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FUTURE OF SPACE PROPULSION

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ABSTRACT

A lot has happened in the area of space propulsion over the last 10 years prompting one to wonder, "Where are we going next?" This paper will first take a quick look back at history and from this perspective postulate the future directions for space propulsion. Topics to be addressed include spacelift and spacecraft propulsion. The future holds many great opportunities but just as many technical challenges.

INTRODUCTION

Significant challenges and advances in space propulsion have occurred over the last ten years. The end of the Cold War has had significant impacts both positive and negative. Operational systems now have to operate well beyond their design life. Parts and technology obsolescence are having a significant impact as are an aging workforce and limited opportunities to develop new systems. The advent of asymmetric warfare is fully upon us. The military has to project power anywhere on the globe. In addition, there is concern that U.S. space assets are vulnerable in this new world. Furthermore, changes in acquisition policy driven by incredible cost and schedule overruns on nearly every space acquisition program will have significant impacts on the future of propulsion. In spacelift, the U.S. once held nearly 80% of the launch market, today only 20%[1]. In addition, the RL-10 has experienced a number of reliability and production problems over the years causing some to question its future viability. The legacy spacelift vehicles built upon the U.S.'s historical ICBM systems are gone and have been replaced by the Delta IV and Atlas V. A number of programs encountered numerous problems with parts and technology obsolescence –the significant downside of keeping some systems operational well beyond their intended lifetimes.

The U.S. has made great strides in technologies for space in the last 10 years. The Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program has reached some significant milestones. Scramjet propulsion saw its first successful flight. Numerous physics based modeling, simulation, and analysis efforts were started to address industry shortfalls when trying to design outside the empirical database of the last 50 years. Many commercial companies have tried their hand at entering the spacelift business with small, "cheap" launch vehicles. Microsatellites have been trying to get a foothold on space and appear to be making some headway.

If we are to understand what the future of propulsion holds we need to understand the recent past from the perspective of both technology development and world affairs. The future holds many great opportunities but just as many technical challenges.

RECENT HISTORY

The goal of the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program is to double U.S. rocket propulsion capability. IHPRPT is a cooperative effort between the Air Force, Navy, Army, NASA, and Office of the Secretary of Defense. IHPRPT has seen some great successes and is continuing to generate great technological advances that are leading to revolutionary capabilities. The Integrated Powerhead Demo (IPD) successfully demonstrated liquid oxygen/liquid hydrogen (LOX/LH2) boost engine technologies that resulted in 100 missions between overhaul and 200 mission life capability for future LOX/LH2 engines. The first U.S.-built Hall Effect (electric propulsion) Thruster is currently flying on TacSat 2. Advances in solid propulsion technologies developed under the IHPRPT program are yielding greater than 50% increase in payloads for small launch vehicles.

Hypersonics continues to show promise for future tactical and space flight applications. NASA flew the first U.S. liquid hydrogen scramjet engines in 2004, on their X-43 Hyper-X research vehicles. The scramjet engines on these vehicles were designed for operating durations of only a few seconds, at flight speeds of Mach 6.8 and 9.6.[2] AFRL and DARPA are on schedule to fly the first X-51, a hydrocarbon-fueled scramjet test vehicle, in 2009. X-51 will demonstrate the ability to transition over a range of Mach speeds. Accomplishing the X-51 program goals will require powered flight durations of several minutes. These milestones are significant if hypersonic scramjet technologies are going to be useful for future launch systems or other applications.

Our legacy launch vehicles, Atlas, Delta, and Titan IV have been retired. These systems were based on the technology developments for the Atlas, Thor, and Titan ballistic missiles. They have been replaced by the Delta IV and Atlas V, both developed under the Evolved Expendable Launch Vehicle (EELV) program which started in 1994. The Atlas V uses a Russian designed and built RD-180 engine since the U.S. has not built a new hydrocarbon engine since the RS-27 in the 1960s. Delta IV uses the RS-68 LOX/LH2 engine. Both launch vehicles use the RL-10 upper stage engine, also developed in the 1960s. The reliability and producibility problems experienced by the RL-10 have been a source of concern. The commercial small launch vehicle market has seen many fits and starts and many failures over the last 10 years. They all attempt to provide "low cost" access to space. Some have had some success; others have learned there is a reason it is called "Rocket Science."

The once dominating U.S. launch business has been undercut by the development of foreign launch capabilities. The U.S.'s rocket scientists have been retiring and the pool of available next generation rocket scientists is not nearly as deep as one would desire. In addition, nearly gone are the years and years of build'em & bust'em experience our greybeards have held. The build'em and bust'em era, although being replaced by efficient modeling and simulation integration, created a historic testing database and personal experience that may never be seen again. The Saturn V F-1 engine conducted over 5000 component tests and 900 engine development and qualification tests alone. The tools used by the industry are based on an extensive history of rocket engine developments in the 1950s, 60s, and 70s. The extensive testing program the F-1 engine, Minuteman, and others went through are just not affordable any more. To address some of these issues AFRL initiated a number of efforts to integrate physics based models into the U.S.'s modeling, simulation, and analysis capability; these models are now beginning to have significant payoffs. These capabilities are being addressed under the Upper Stage Engine Technology (USET) program and others.

Technology and component obsolescence has been a major problem since the end of the Cold War. The Department of Defense is no longer developing and buying enough new systems, resulting in many companies transitioning from being heavily defense related to being primarily driven by the commercial market or outright going out of business. Another fall-out of the end of the Cold War was the dictate to keep systems flying two to three times beyond their design life. This exacerbates the parts obsolescence issue. Both also affect the talent pool of scientists, engineers, and manufacturing experts. People are looking elsewhere for the challenge and the money – the commercial market place. Technology and component obsolescence will continue to be a challenge for the future.

Asymmetric warfare is another challenge for the future. Many adversaries see the U.S. as the dominant power in the world and know they cannot compete head-to-head without going bankrupt. They have chosen to counter U.S. strengths by trying to attack what they perceive as weaknesses and vulnerabilities. The U.S. depends heavily on its space assets and has learned a great deal since the first Gulf War 16 years ago. Commanders in the field know about space and want the capabilities space can provide and they want it under their control. Adversaries see opportunity in the dependence on space capabilities. AFRL is developing the propulsion technologies to address warfighter needs for responsive spacecraft and responsive spacelift.

Space is not an inexpensive endeavor. The 2003 GAO report on Space Acquisition Policy reported a number of space acquisition programs with repeated significant cost and schedule overruns in the past 10 years. Some of this is attributed to those programs relying on "immature" technologies.[4] Compare the development of a reusable launch vehicle with an advanced aircraft and an expendable launch vehicle. The F-22 cost $33B[3] and about 20 years to develop. The Evolved Expendable Launch Vehicle programs cost $1.8B[5] and about 6 years – with technologies considered mature and off-the-shelf. There is disagreement on how quickly and at what cost a reusable launch vehicle which experiences a much more demanding flight environment than either example above can be developed. Policy changes have occurred regarding the inclusion of technologies into an acquisition system. Each technology must be certified to be at a Technology Readiness Level of 6 or greater prior to Keyt Decision Point B. This will require acquisition programs and planning efforts to consider technology developments and maturity much earlier in the development cycle.

AFRL and AFSPC have been working hard over the last 10 years to obtain long-range strategic plans identifying the capabilities AFSPC desires over a moving 30 year window of time. Of course near-term needs are easy to identify and quantify but it is usually too late for S&T to have much of an impact unless researchers had the foresight to already be working those technologies. Long-range desired capabilities are harder to identify and quantify but can be greatly affected by S&T investments. AFRL doesn't seek single design points but rather a vector (e.g. responsive, reusable spacelift) and rough design space (e.g. turn-time in hours to weeks vice 6 to 12 months) within which to develop technology options. Why does AFRL need 30 year roadmaps? Because it can take 5, 10, even 15 years of S&T development to ensure the technology is ready when the User finally puts the money down to actually buy a system.

An example of the above is AFRL and AFSPC have been working over the last 7 years to develop the requirements and S&T efforts required to eventually field a responsive, reusable launch vehicle. They have learned from NASA's experiences and used sound systems engineering. The final point solution has gone through some permutations progress continues. The hardest part was getting AFSPC to define "responsive." In those days AFSPC did not want to define "Requirements" as they have very formal processes for "big R" requirements and did not at the time have a process for defining "little r" requirements or better yet desired capabilities. However, AFRL needed to know the scope, the design space, the capability they needed to address. The technology challenges for 6-12 month turn-time are significantly different than those for achieving turn-times measured in hours or days. Even as AFSPC and the U.S. work through the processes of defining the future of spacelift AFRL continues to work the technologies required to address the design space sought, ensuring the technologies are ready when the acquisition program needs the technologies. If AFRL did not do so AFSPC would have to work into their acquisition timeline an additional 8-10 years prior to Key Decision Point B for technology development or accept whatever capability they could achieve using off the shelf technologies (currently 40 years old).

THE FUTURE

The past has seen a lot of success and accomplishment in the area of space propulsion. What does the future hold for space propulsion? One thing is certain, decreasing budgets will require smarter planning – strategic, acquisition, and technical, and leveraging early S&T to ensure technology is available when people realize that COTS is only good when the store is fully stocked and the supply chain is stable.

Space Lift

The U.S. will continue to have a need for responsively placing assets into space to support commanders in the field or to quickly replace or gap-fill satellite capabilities that have been degraded or lost. This is a significant capability increase over what can be done today. It does not require advanced concepts that rewrite the laws of physics or require 800 seconds of Isp. These revolutionary capabilities are possible through evolutionary developments. Satellites can vary greatly in weight. Some can be handled using small launch vehicles, either solid rocket based or liquid engine based. Others will require a larger system, either highly reusable and responsive or a responsive expendable. The U.S. will also continue to have launch-on-schedule satellites like many of the current systems. These could be launched on either a reusable or expendable launch vehicle. Nothing in the U.S. inventory beats solid rockets for responsiveness or for helping to break the gravity well and they are currently used in systems like the Minotaur family of launch vehicles. Liquid rocket systems have greater Isp than solids and hydrocarbon engine based systems are the choice over hydrogen engine based vehicles for responsive spacelift. Launch vehicles using hydrocarbon engines are more responsive and smaller and thus easier to handle. The current fuel of choice is RP (Rocket Propellant) of which there are two variants, RP-1 and RP-2. Other hydrocarbon fuels that could be used include Propane and Methane. However, it is yet to be determined if there is any real life cycle cost differences between RP and any these other fuels.

AFRL technology development efforts like the IPD and USET projects are feeding advanced hydrocarbon boost technology developments. The Hydrocarbon Boost Demo will demonstrate long life, responsive booster engine technologies far beyond anything currently operating or planned: 15% better Isp, 60% increase in thrust to weight, 100 mission life, 50 missions between overhaul, and 30% lower cost. The technologies will feed all future U.S. hydrocarbon engine developments – responsive, reusable boost as well as expendable boost. The Hydrocarbon Boost Demo technology demonstrator was awarded in January 2007 and will deliver technologies matured to Technology Readiness Level (TRL) 5 around 2015.

AFRL also has a roadmap to achieve fully reusable access to space using scramjet/rocket engines to further improve the responsiveness and reduce the cost of future launch systems. The rocket and scramjet engine technologies will be integrated into Rocket-Based Combined Cycle (RBCC) engines, optimized for efficient operation at a variety of flight conditions. Historical RBCC developments have employed the rockets for boost (Mach 0-4+) and have then used the hypersonic scramjet propulsion technologies for higher speeds (up to Mach 10+). Independent analyses by AFRL, ASC/XR, and SMC/XR have identified significant value in a different type of RBCC – one that uses scramjet engines for flight at speeds from Mach 5 to 10+, and then transitions to rocket operation for ascent to orbit. This change in mind-set, from booster to upper stage applications, has already had a significant impact in AFRL's propulsion technology development strategy.

AFRL's RBCC efforts build, in a stepping stone approach, on hypersonic propulsion developments on-going under the X-51 program and the subsequent Robust Scramjet program. The result is a technology maturation plan that will result in larger and more operable engines, for both expendable and reusable applications. AFRL's RBCC efforts will combine the scramjet developments with rocket technology developed under the USET and Hydrocarbon Boost Demo efforts. The target applications will require substantial scale-up, from today's small-scale X-51 engine that uses about 10 lb_m/sec of air, to future large-scale RBCCs that will use about 1000 lb_m/sec of air. Because of the scale-up challenges, this technology will not be ready for large-scale applications until around 2025 or later, although RBCC engines for smaller launch vehicles and tactical applications could be developed after 2015.

The U.S. will continue to seek true aircraft-like operations to space. Current aircraft systems use a block upgrade strategy. Will that strategy carry over to highly reusable spacelift systems? Will there be drop-in replacement hydrocarbon engines in the future or will whole new launch vehicles have to be built? Will the commercial sector leverage these technology developments or go their own direction? Challenges lie in achieving the high mission life and mean time between overhaul at low engine costs which the Hydrocarbon Boost Demo is trying to achieve. Real aircraft like operations would require even higher operability, maintainability, and supportability. One of the benefits offered by RBCC propulsion is the combination of high performance (payload mass fraction) with high levels of reusability and maintainability. Rocket performance is limited by currently known chemistry and physics but AFRL continues to explore new and advanced fuels that could yield higher performance, knowing that even a few seconds of Isp results in thousands of pounds of additional payload to orbit – increased capability. This will be needed as a majority of satellites continue to grow in size.

The physics based modeling, simulation, and analysis tool developments under the USET program are enabling engineers to decrease the cycle time to explore new engine designs by 70%. They are able to explore orders of magnitude more engine designs, resulting in much more mature, robust, lower cost designs than ever could be explored using the old empirically based design tools. These tools are already being used across the U.S. with over 28 examples of technology transition. The tools can be used throughout an engine development process from conceptual design to preliminary and critical design review to final testing. The program will complete in 2010 with validation efforts carried out on full-scale hardware that was designed using the tools, TRL 4-5.

The retired Minuteman II and Peacekeeper assets are currently being used to build the Minotaur family of launch vehicles. Eventually these assets will be consumed and replacement vehicles will have to be built. AFRL is continuing development of solid rocket technologies that will continue to increase the payload delivered by small spacelift vehicles eventually replacing the Minotaur family with a family of vehicles capable of greater than 50% increase in payload to orbit and at 35% lower cost. These motors can also support hybrid partially reusable launch vehicles providing the upper stages to a fully reusable first stage launch vehicle. There are still significant gains to be made in performance and cost improvements. There is no more responsive a system than an all solid rocket system.

Will the current commercial spacelift efforts continue or will they too pass into history as many others have – Conestoga, Roton, BA-2, etc.? These efforts can be broken into two classes, those trying to put satellites into orbit and space tourism. Space tourism companies are only trying to take their passengers sub-orbital, about 65 miles into orbit, a much "easier" job than trying to put the same weight into orbit at 300-800 miles, if anything about rocket science can be said to be "easy." Both groups will benefit greatly from work under the Hydrocarbon Boost Demo and USET efforts and eventually the scramjet development efforts. The drive to get to space will continue and entrepreneurs will continue to fund efforts to tap into that drive and potential marketplace.

Rocket science is difficult and can be dangerous. SpaceX has experienced set-backs and failures. Scaled Composites recently saw several of their team killed in an industrial accident related to their space tourism launch vehicle development program. Others struggle to obtain funding to continue their system development and overcome the problems they have encountered. Challenges for the commercial small launch vehicle community lie in a number of areas. They need to achieve a breakpoint where the performance of their rocket engines is robust enough to put up meaningfully sized payloads. They need to leverage the many lessons the early rocket pioneers learned. Those lessons were not come by easily. It is a dangerous business. Physics works against them; the gravity-well is great at holding everything on the Earth which is what makes it so difficult to put anything into orbit.

Spacecraft

Freedom to operate in space is of paramount interest to the U.S. The Air Force, Army, and Navy have set out to explore the development of "tactical" satellites that could be under the control of warfighting commanders. These systems require responsive launch vehicles and they have their own propulsion needs. Some of these needs include significant maneuvering, significant drag makeup, and low power consumption, high efficiency, and light weight due to being on such a small satellite bus. In addition, the recent Chinese anti-satellite test flight has the world concerned that satellites and constellations already on-orbit could be vulnerable. Future satellites may require additional propulsion capability to allow them to maneuver away from hostile vehicles. Finally, satellites require more maneuvering capability to enable them to perform more orbit rephasings while maintaining total on-orbit life. This allows the satellites to move back and forth covering multiple geographic regions of interest. The challenge is to have a propulsion system that operates in a very high efficiency mode most of its life yet has the capability, when needed, to operate in a way that allows for great speed. AFRL is pursuing high thrust-to-power electric propulsion and multi-mode propulsion technologies to address these challenges. Despite the growing interest in microsatellites, they can only perform certain missions and the more typical classes of large satellites flying today will still be developed for the foreseeable future.

Acquisition

Technology and parts obsolescence will continue to be a significant issue for space systems. There are many contributors to this problem: 1) satellite systems lasting longer than expected, 2) satellites are expensive to build and launch, 3) there is not enough motivation or gain in capability to drive replacing satellites not for age but for cause, 4) there just are not enough satellites being built. Many of these play off each other in a "chicken and egg" scenario. The people buying and building military satellites do not have to pay for the launch so they care little about the cost of launch today or tomorrow. They do care about how much capability they can get on orbit and how much it costs to build the satellite. Some people have the mindset that the best satellite would be one that lasts 40 years. This would completely wipe out the satellite industrial base. No one would know how to do, for example, the "Position, Navigation, and Timing" (PNT = GPS) mission 30 years from now. The U.S. would have to set out on a 30 year research and development program starting with basic research to develop a whole new way to do the PNT mission. Companies are in the business to make money. If there are no satellites to build they will get out of the business. These problems cannot be solved at the individual program office level. The U.S. must develop a national strategy covering everything from science and technology development to systems acquisition to operations, for both spacelift as well as the satellites themselves.

CONCLUSION

Nothing that moves in or through space does so without propulsion. Investment in propulsion research and development will need to continue. As the potential commercial small launch vehicle vendors are learning, there is a reason it is called "Rocket Science." It is not easy and requires significantly more investment than many think or want to believe. Propulsion is a mission enabler providing increased payload (capability), range, and lower costs.

There will continue to be a push to more responsive spacelift and missions like space tourism. These will eventually lead to real, aircraft-like operations to space with its commensurate challenges for the propulsion systems required. Great strides will be made in small spacelift – both solid and liquid propulsion based. Spacecraft propulsion will span the gamut from microsatellites to large satellites. They will need to maneuver many times during their mission life.

AFSPC and AFRL will continue to develop the necessary long-range plans and identifying the necessary S&T efforts to satisfy the warfighter's capability needs. This will provide the desired vector and capability AFRL should be pursuing in their technology development efforts. AFRL will continue to fill the "designer's toolbox," increasing the design space of the possible ensuring the technologies needed by AFSPC are ready when needed. AFRL will also continue to conduct technology push looking for those new ideas that will revolutionize how people view propulsion and what they can do through it.

The future holds many great opportunities but just as many technical challenges.

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