Heavy Lift
Reusable Launch Vehicles

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Abstract

This paper analyzes recent developments in launch vehicle design engineering science as they apply to basic launch vehicle design theory and expendable launch vehicle evolution towards the penultimate conclusions of modern future reusable heavy lift launch vehicles.

Scientific Position

This author is of the opinion that two urgent environmental problems that have risen to the level of national security issues – global warming and orbital debris, not only demand the immediate cessation of the offending processes, atmospheric carbon combustion on the one hand, and expendable launch vehicles, upper stages and their satellite payloads, but also require immediate active mitigation such as reducing the atmospheric carbon dioxide levels and removing a large amount of the at risk and high risk orbital debris.

The sheer magnitude of these problems demands immediate national efforts similar to the Manhattan project at the condensed matter physics level, or the Apollo moon landings at the space science and astrophysics level, in order to solve and implement the solutions.

The Obama administration intends to pursue a 'simpler' heavy lift launch vehicle effort signaling a willingness to entertain new or alternative heavy lift launch vehicle designs, in addition to wrapping the described problems up into a national space science initiative tied directly to new national education, infrastructure development and jobs programs. Meaningful progress in these areas requires the quality assurance and design oversight that is best provided by modern practitioners of the new domain of engineering science.

The Scope of the Problem

Modern rocket science and engineering has now matured to the level of conceptual and practical advancement, such that one may proceed directly to new clean sheet designs. However, existing expendable medium lift launch vehicle capabilities now exceed their market demand in both capacity and flight rate, and there is no consumer demand for new clean sheet expendable heavy lift launch vehicle designs; beyond government subsidized efforts predicated upon future requirements for global planetary engineering solutions to: near term environmental and natural hazards such as global warming and climate change; near Earth orbital debris proliferation; earthquake, tsunami and asteroid impact response; terrorism and nuclear proliferation; and financial insolvency related to economic decline, job losses, escalating fuel costs and carbon and hydrocarbon based energy dependencies; and associated pollution and environmental degradation effects these situations hazard.

Human space flight suffers from a public perception of irrelevance to modern societal problems, in sharp contrast to its necessity for solving present day threats to civilization. This poor perception has roots in the diminishing educational opportunities and real life experiences for a growing fraction of people on an overpopulated and resource stretched planet, rapidly approaching critical thresholds in almost every aspect of day-to-day life.

Likewise, space science and astronautics also suffers from a poor understanding among the general scientific community of the value of government to government collaboration and the huge impacts to society, the positive effects on education, and the great benefits for international diplomacy that have resulted from a minimal investment in space flight. Furthermore, many imagined or predicted futuristic and large scale discretionary science projects such as orbiting extrasolar planetary telescopes and observatories, interplanetary spacecraft and missions and further development of near Earth space solar power stations may very well require the additional lift and flight rate capacities that heavy lift provides.

The potential for human space flight to revolutionize the quality of life for large fractions of the global population rivals the effects that semiconductors and condensed matter and quantum physics has had on industrialized society, but remains as yet, not fully realized, generally unrecognized, and under appreciated by ordinary citizens and scientists alike. The unique abilities of space flight activities and infrastructure to detect, prevent, resolve and respond to modern and future global and international problems such as natural and man made disasters, remains ignored and neglected primarily because of its application to situations and conditions which are not immediately addressable or confrontable, appear as distant in space or remote in time, or are perceived to be insoluble or intractable. Thus, the prospect of space flight as a tool for economic stability and global security is not yet widely understood, recognized, acknowledged or accepted as an obvious observable fact, and a deep skepticism of its value, and a lack of appreciation for its utility still persists.

The solution to the credibility gap that exists for evolutionary heavy lift launch vehicle development is a clear demonstration of its relevance to solving the seemingly insoluble problems of modern civilization, and a critical review of its abilities to evolve into the fully recoverable, retrofitable and reusable systems demanded by economic necessity.

Time and Funding Constraints

Complementary to our present space launch and orbital infrastructure are the anticipated and future funding profiles and the timelines associated with the magnitude and severity of the various national and global problems that are expected to be confronted and solved by a robust and well funded international space program. Clearly the clock is still ticking.

When the problems of heavy lift launch vehicle development are cast into this basic form, fundamental solutions are then amenable to simple geometric and mechanical methods using existing launch vehicle assets and current state of the art as the initial starting point.

Time and funding constraints simply dictate the amount of time and money necessary to validate new core and stacking arrangements with their engine plumbing configurations in terms of analytical structural, fluid dynamical, thermodynamic and fuel flow models, and then constructing and testing necessary tools and techniques for orbital disassembly and reassembly of the volatile safed attitude controlled space rated core stage and engine.

This kind of work defines human space flight, and thus there are no outstanding reasons why these procedures will not be amenable to engineering science methods, and the cycle of design, validate, construct, test and launch cannot be closed and driven into periods which produce yearly test flights and satisfactory results within four year election cycles. The existing budget is adequate to support initiation of the program with existing assets, and the on orbit facility we have is more than adequate to support any in situ simulations.

Engine and Booster Limitations

I have recently described the viability and ease of single stage to orbit test flights of new space shuttle main engine (SSME) powered core stages of solid rocket booster (SRB) and hydrocarbon liquid reusable booster (LRB) assisted stage and a half to orbit architectures without the need for upper stages and with heavy lift class cargo capacities to an existing orbital space port, easily capable of handling the tasks of the orbital recovery, retrofit and reuse of heavy core stages, engines and payloads - the International Space Station (ISS).

Remarkably, shuttle derived inline heavy lift launch vehicles with space rated core stages could ideally be flown concurrently with our existing space shuttles, allowing immediate engine retrieval of expensive and delicate reusable space shuttle main engines from orbit. By developing tools and procedures to remove engines in orbit, while docked to the ISS, and returning them to Earth in the cargo bay of the shuttles, great advances can be made in reusability and cost reductions while greatly enhancing the value and utility of the ISS.

Even absent space shuttle availability to return test flight engines from low Earth orbit, initial test flights may also proceed sequentially with STS retirement with single engine flights on five meter core stages flown to low Earth orbit or extinction, whichever comes first, or with the use of commonly available booster augmentation. These vehicles would have the payload capacities of the Ares I without the burden of numerous engineering and logistical problems associated with the refurbishment of segmented solid rocket boosters.

Existing Contractual Obligations

Constellation program contracts consist of an engine contract for a high energy cryogenic upper stage engine with Pratt & Whitney Rocketdyne, the reengineered 1.3 MegaNewton J2-X interplanetary class vacuum restartable engine, the associated test stands at Stennis, along with a 5.5 meter upper core stage from Boeing and a five segment SRB from ATK. Also on hand and in service are in excess of a dozen flight worthy SSMEs, with enough spares for dozens of SSME equivalent flights, a few space shuttle ETs and four segment SRBs all available for the immediate development and fabrication of flight test hardware.

Upper stages with the thrust levels of the J2-X and payload capacities of the heavy SRBs are not expected to be needed for quite some time, as the timeframes for the ET derived engine clustered heavy lift launch vehicles are exceptionally long, and require extensive redesigns and modifications to the 8.4 meter external tanks in order to proceed. Similarly, five meter single engine ground started variants of the Ares I upper stage will also require an extensive redesign and modifications as well, but new hybrid spin forming and friction stir welding technologies promise to greatly reduce weight and speed up the development of five meter EELV class core stages. Thus, a rational method of proceeding would be to renegotiate the Ares upper stage fabrication contracts with Boeing, and then proceed with development of rapid turnaround structural and thermodynamic analysis and validation methods, procedures and techniques for multi-diameter variable length cryogenic stages, amenable to the booster configurations appropriate to the vehicle diameter and length. This would allow development of the long lead time propulsion elements to be relaxed and the immediate and urgent program of SSME liquid core stage development to begin.

Resource and Center Management Issues

Once a decision has been made to retain advanced cryogenic hydrogen launch vehicles, and to continue national involvement in next generation reusable launch vehicle research, then SSME powered, cryogenic single stage to orbit core stage development can proceed. Initial hardware development, fabrication and test flight operations should be restricted to the rapid deployment of 5.5 meter, all liquid powered, Ares I heritage EELV derivatives, consisting only of demonstration flights which are complementary to existing commercial and industry efforts rather than competing directly against them. These efforts should not diminish the long term necessity for new engine and booster stage elements as well as the upper stage extensions to the robust low Earth orbit infrastructure necessary to solve the relevant and serious societal and national security problems anticipated in the near future. At risk NASA centers and their constituencies should be held accountable to their unique abilities to administrate, develop, fabricate, test, launch and operate these future systems.

An implicit understanding must be developed among the relevant center administrators and directors that the resulting technology development efforts must produce systems that represent incremental advances to existing state of the art in commercial launch vehicles, and that fiscal realities and national priorities will be invoked to demand system recovery, retrofitability and reusability at the highest levels in the mission requirements hierarchy, such that fielding advanced future launch vehicle demonstrations may proceed posthaste.

Five Meters - Single Engine EELV Form Factors

Single stage to orbit space flight was first accomplished in 1958, with the flight of an Atlas B on Project SCORE. Although technically not an SSTO, the core stage was still ground started and then flew directly to low Earth orbit, with the assistance of side mounted boosters, in this case outboard engines. The modern version of this rocket may very well be called an EELV hybrid – a Delta IV core stage reengined with a space shuttle main engine, and boosted with a pair of side mounted Atlas Vs.

Clearly it's not as simple as reengining and space rating a Delta IV core stage, but we've already made substantial investments in high energy upper stages with the Ares I, and the inevitability of new cooperative second generation heavy EELV programs is undeniable. The key to making an expendable launch vehicle program affordable and sustainable is to make each individual element of it - the core stage, engines, boosters and payload carrier - reusable, with increased payload capacities and decreased costs over existing offerings.

Economic, fiscal and temporal realities will demand that any second generation reusable launch vehicles will also necessarily involve recovery, retrofit and reuse of redesigned, stretched and reengined core and upper stage elements of the total system, adapted to the evolutionary engineering and scientific advances of the day, month, year and/or decade. Only the increased efficiency, reduced weight, closed cycle and regenerative cooling of hydrogen powered space shuttle main engines makes these single stage to orbit scenarios possible, thus affording order of magnitude improvements in the logistics of space flight. The immediate application of modern new Al-Li spin forming and friction stir welding technologies to EELV sized core stages exemplified by the Ares I upper stage will enable the eventual development of reusable heavy lift launch vehicles using 8.4 meter tankage.

8.4 Meters - Two and Four Engine ET Form Factors

Only when routine, high flight rate, all liquid fueled, stage and a half and booster assisted space flight is achieved, should the economies of scale afforded by wide tankage, engine clustered, heavy lift launch be pursued. By applying existing and competent - operational, government, industry and commercial manufacturing infrastructure and resources, and by demanding logistical expediency and cost reductions of recovery, retrofit and reusability, we should be able to attain the order of magnitude improvements necessary in low Earth orbital transport capabilities required to address and confront any of the future problems which may be encountered by an industrial civilization, on a terrestrial planet, many of which are now well underway, approaching the level of severe national security issues.

External tank derived straight stack launch vehicles assisted by segmented solid rocket boosters are amenable to opposing pairs of space shuttle main engines, either a single pair flying with reduced fuel loads, or in a square configuration of four engines in two groups. This particular geometry allows for terminal acceleration shutdown of a pair of engines for thrust reduction, or a single engine within a pair, albeit with some asymmetric thrust. Presumably such a large core stage could also be boosted with liquid reusable boosters, at the expense of a somewhat reduced payload, and such a system also approaches single stage to orbit capabilities without the worries of exceeding the SSME acceleration limits.

However, one can immediately recognize how quickly development and operational costs escalate with these large core stages and their complicated SRB integration procedures, and how flight rate would be diminished over smaller and simpler single engine designs where other methods exist for reducing terminal accelerations of five meters core stages. Furthermore, the fuel needs of four engines will require a tank stretch, and the insulation needed for a larger volume of the cryogenic hydrogen fuel is proportionately increased.

Ten Meters - Five and Seven Engine Cluster Form Factors

Extrapolating to the ten meter tank diameter range of the Saturn V - also envisioned by NASA to feed the very large and heavy RS-68s in Ares V designs – the smaller, lighter, more efficient and regeneratively cooled nozzles of the space shuttle main engines can be supported in clusters of five and seven, which necessarily involves engines three abreast. These large future heavy lift designs are possible if problems of cryogenic fuel insulation are solved such that the engines can be recovered in orbit, and tankage can be retrofitted into the large low earth orbit space ports, hotels, observatories and the interplanetary craft envisioned for the future. Clearly also are the anticipated high costs of such an endeavor far beyond any funds currently available, and any timeframes are well beyond reasonable.

Nevertheless, the geometric and mechanical advantages of such large engine clusters are readily apparent – ample payload in volume and mass, generous engine out capabilities, multiple sequential engine shutdown options, and a ground started center engine available to function as an upper stage, optimized for vacuum operation or with nozzle extensions. The ability to monitor, throttle and shut down individual engines according to their health provides a method to limit high terminal accelerations often encountered in space flight.

Conclusions

Engineering science has now subsumed the role of systems engineering as the top level domain for the conceptualization, representation and execution of complex programs. Whereas systems engineers would argue that the missions dictate the launch vehicles, the engineering scientist would argue the reasons for going into space, and then presume that propulsion and launch vehicles would be fundamental prerequisites for all that follows. Missions would merely be engineering projects within programs, and the goal would be to satisfy the arguments - hypotheses, that were originally made to justify the endeavor.

In the same manner that general relativity doesn't invalidate the classical mechanics used in our day to day engineering tasks, this paradigm shift does not diminish the veracity of systems engineering methods and techniques to specify the requirements and procedures necessary in order to implement the complex systems of modern human space flight - particularly low Earth orbit flight, rather it develops the reasoning behind the endeavor itself, and then designs appropriate scientific and engineering experiments, conducted at costs commensurate with the value of the questions answered, and the problems solved.

Comparing the five meter reusable EELV hybrid designs outlined here, to the previously proposed heavy lift launch vehicle architectures, although they appear as small launchers, in actuality these are core stages intrinsically possessing single stage to orbit capabilities, assisted by extremely powerful twin side mounted kerosene boosters with relatively short burn times, rendering them amenable to simple robust reentry and recovery procedures. This is in contrast to the relative complexity of the preengineered tank designs necessary to allow adaptation of the bulk of the propulsion and guidance, navigation and attitude control system to the lower energy budget of orbital space flight, and the thermal and fuel management techniques which must be implemented in order to ensure that the stage is able to reach its destination, and is safed and space rated shortly after main engine cutoff.

Astonishingly, the fundamental Earth to low Earth orbit concepts laid out here (Figure 1) can be scaled down into the minimum possible launch vehicles capable of reaching orbit, a region in phase space that we've only just begun to explore, putting the realm of space within the grasp of individual and small groups, including small corporations and nations. It is thus essential that this transition to commercial space flight be well managed by the appropriate institutions and their international counterparts, with the explicit legal, civil and government oversight authority, such that space is efficiently utilized, the public is sufficiently protected, and existing debris is monitored and removed in a timely fashion.

References

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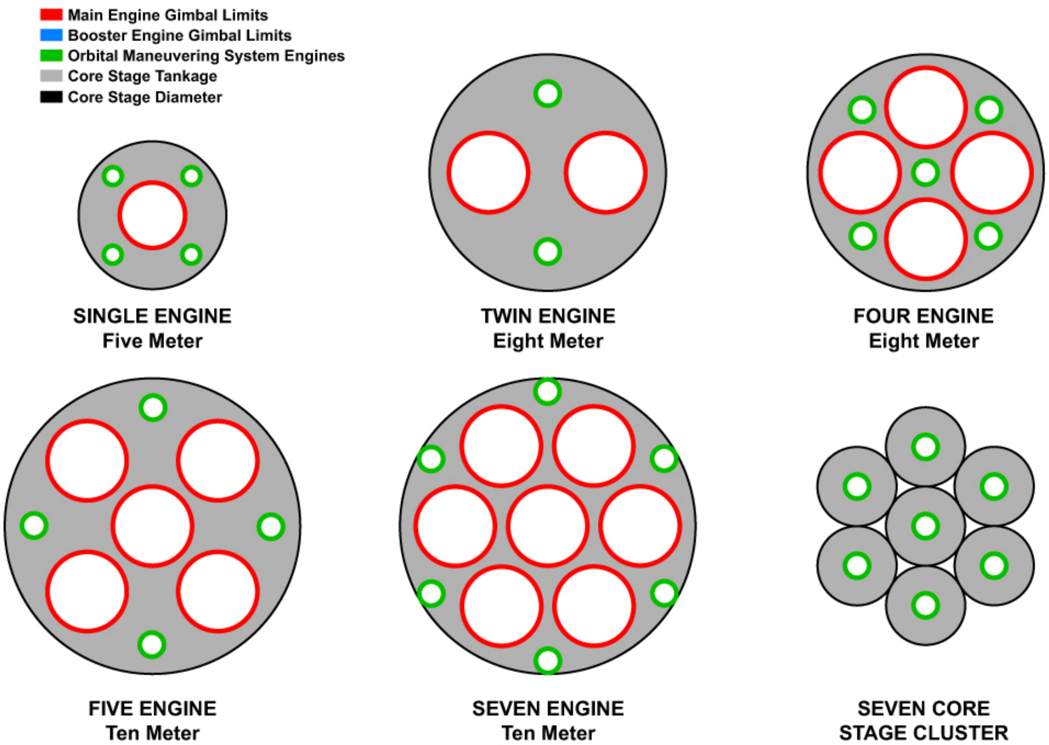
Figure 1. Five, Eight, and Ten Meter Launch Vehicle Engine Cluster Diagrams



Pathfinder Launch Vehicle Demonstration Missions