AN AFFORDABLE FLIGHT DEMONSTRATOR FOR FULLY-REUSABLE ACCESS TO SPACE TECHONOLOGIES

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ABSTRACT

A multi-company team headed by Conceptual Research Corporation is developing a design concept for an affordable rocket-powered flight demonstrator for Fully-reusable Access to Space Technologies (FAST) under funding from USAF-WPAFB, with administrative and technical assistance from the University of Dayton Research Institute. This demonstrator offers affordable and incremental demonstration of responsive space access system concepts and enabling technologies, and will demonstrate high-tempo reusability in an operational environment. To keep the program affordable, the demonstrator will have an empty weight of well under 20,000 lbs yet will be capable of reaching space altitudes and hypersonic speeds.

The demonstrator vehicle is based on a preliminary concept described below for a reusable upper stage, but the demonstrator test results will also be applicable towards a reusable first-stage design. This paper will present the baseline operational vehicle design concept including key issues in configuration integration, and will describe the demonstrator vehicle and program plan.

INTRODUCTION

The USAF has a significant need for space launch capability that is affordable, flexible, and responsive. While the total number of flights per year is small compared to, say, aircraft flights, the military value of those flights is almost immeasurably high. Space assets provide essential capabilities including ISR, SIGINT, communications, navigation, remote sensing, weather prediction, and event detection, and are an integral force multiplier for almost every military operation today.

The desirability of a reusable launch vehicle is to many self-evident. With the exception of portions of the Space Shuttle, the launch vehicles used for USAF space launches are destroyed during each flight. Purchase of vehicle hardware is a substantial portion of the launch cost, unlike aircraft where the air vehicle itself is an amortized and reusable asset.

Disposable launch hardware also has an impact on responsiveness and surge capability. It is unaffordable to keep a number of expendable launch vehicles “at the ready” to respond to an emerging need such as for a reconnaissance asset over a new world trouble spot. Instead, an emerging need must be met by accelerating and rescheduling a launch already “in the queue.” Surge capability is limited by production capacity and the availability of long-lead manufacturing items. This contrasts to aircraft, where an emerging need can be met by using an aircraft in the hanger, and an immediate surge requirement can be met by putting on additional ground crew shifts to turn the aircraft more quickly. Such a capability for the USAF launch vehicle fleet would be highly desirable.

Greater responsiveness and lower price per flight would quite likely further increase the role of space assets in USAF operations, much as the lowered price of GPS receivers has produced an explosion of applications, many not anticipated.

The obvious advantages of reusability must be measured against the negatives. A reusable launch vehicle must be designed to reenter, return to base, and land in some fashion. The thermal protection system, aerodynamic surfaces, control actuation, long-duration subsystems, and landing gear all add weight to the vehicle. Due to the large growth factor inherent in launch vehicle design, the weight penalty is multiplied many times over when applied to a system requirement.

The decision – reusable vs. expendable – depends ultimately upon the available level of technology. Previously, the provision of reusability increased the weight and cost so much that the cost benefits of reusability were swamped by the added costs of the heavier, more-complicated booster. Recent studies by the USAF and others indicate that the tide may have turned, and that a fully-reusable first stage now offers a net benefit for USAF applications.

A number of emerging and enabling technologies for Reusable Access to Space are candidates to be tested with the FAST Demonstrator vehicle. Some of them have to do with reusability itself, such as non-expendable igniters, reusable auxiliary power sources, durable and/or flight line-replaceable TPS, accessible and maintainable avionics, and coking-free LOX-Methane rocket engines, turbo pumps, and RCS thrusters. Some likely test technologies are related to the desire to reduce the logistics trail, such as non-pyrotechnic actuation and avoidance of monopropellants in RCS and APU systems.

Other technologies are enablers for improved operations and reduced design size and cost. These include the potential use of a high angle-of-attack reentry profile, which has been shown to reduce heating which in turn reduces TPS cost and weight. High-α reentry also reduces sonic boom. The FAST Demo will probably be fabricated from composite materials much like modern fighter aircraft, relying upon its TPS for thermal protection. This offers weight and cost savings, and also reduces demonstrator design and fabrication time.

RESULTS AND DISCUSSION

NOTIONAL OPERATIONAL SYSTEMS

While it is not the intent of the FAST program to develop a definitive USAF operational system concept, a notional concept has been developed to guide technology selection and the demonstrator design approach. The basic design concept is of a reusable upper stage (RUS) suitable for use with a reusable first stage booster similar to the recent ARES/HLV or with an advanced expendable first stage.

There are a number of launchers in roughly the 5,000 lb payload category, including the Delta and Titan which have been extensively used by the USAF. This was assumed as the required payload to orbit, along with recovery of the payload in abort scenarios. Based on various studies and other available information it was determined and/or assumed that a future USAF reusable first stage would be capable of lifting a second stage with a GLOW of 110,000 lbs which was therefore used as the FAST-RUS design weight.

Two baseline configuration concepts for the FAST-RUS were developed (Figure 1). Baseline 1 features tip-mounted vertical tails, whereas Baseline 2 has V-tails mounted on the fuselage. Otherwise the design concepts are virtually identical.

The fuselage arrangement is straightforward, with most of the volume taken up by propellant tanks and the payload bay. The use of an internal payload bay rather than an external payload arrangement was studied previously, where it was determined that the GLOW and performance were similar but that the external shroud required for payload survival in an abort scenario would add a greater element of non-reusability.

Composite primary structure is assumed, with a tile or blanket thermal protection system plus carbon-carbon nose cap and leading edges. Tanks are load bearing and are of composite integral construction, actually forming the primary load-bearing structure of the fuselage in that area.

Engines are at the back, attached to a conical composite load transfer structure which in turn attaches to the aft propellant tank. Previous optimization indicated that a four engine arrangement provides acceptable engine-out performance and reduces the total vehicle length while imposing only a small weight penalty compared to a single engine. The engines are pump-fed, LOX-Methane notional engines as defined by XCOR in a prior contract.

These vehicles are about 68 feet in length, with a body diameter of 12.3 feet. The wingspan is 29 feet for the tip-mounted tail design, and 24 feet for the design with tails on the fuselage.

Trajectory analysis was done using a module of the RDS-Professional[6] design program called “ROAST” (RDS Optimal AeroSpace Trajectories”). This is based on the equations and methods in Sutton[1], Bate[2], Griffin[3], and Koelle[4] and follows the vehicle through time step integration of *F=ma*.

The trajectory analysis assumed first stage separation conditions of 6,000 fps at 200,000 ft altitude. The target orbit for the 5,000 lb payload is a 100 nmi circular orbit from a due-East Canaveral launch. Trajectory results indicate that the baseline Reusable Upper Stage attains this target orbit with this payload.

More details about the design and analysis of the FAST-RUS are available in the contract final report[5].

FAST DEMONSTRATOR BASELINE

The FAST demonstration program will include ground-based demonstrations of structure, systems, TPS, and propulsion/tanks, followed by a flight demonstration vehicle capable of replicating all FAST system flight envelope points and validating key technologies. The FAST Demonstrator vehicle design was based on the RUS designs above, sized to permit self-launch for flight envelope expansion followed by boost to reentry speeds on a 1st stage launch vehicle. Successful completion of the FAST Demonstrator program would mature relevant technologies, explore high-payoff system concepts, and significantly reduce the risk of developing the desired USAF operational capabilities including reusable first and second stages.

The overall goals of the FAST Demonstrator vehicle can be summarized as follows:

1. Build national confidence in the feasibility, utility, and affordability of reusable military launch vehicle systems
2. Minimize future system development risk and cost
3. Mature key technologies applicable to all such systems
4. Validate the particular FAST concept solution

To attain these goals, the following specific demonstrator requirements are defined:

	Threshold	Goal	
Altitude (self-boost)	150,000	300,000	ft
V-max (self-boost)	3,000	6,000	fps
M-max (booster launch)	10	25	
Landing Mode	V or H	V and H	
PMF	60%	90%	
Payload mass (unassigned)	1,000	2,000	lb
Payload volume	25	50	ft^3

The FAST Demonstrator was configured as a subscale version of the FAST Reusable Upper Stage as described above. The initial tip-mounted tail configuration is shown in Figure 2. The version with fuselage-mounted tails is similar (see below).

The FAST demonstrator does not have the internal payload bay seen on the operational RUS. The technology of incorporating a payload bay is well understood based on Space Shuttle experience, and the structural effects can readily be calculated using modern FEA methods. This is a beneficial decision, allowing sufficient propellant volume in a design which is essentially a photographic scaling of the RUS design. The square-cube law would predict disproportionately reduced internal volume as the vehicle is photographically scaled down, making it otherwise difficult to obtain sufficient propellant volume.

This FAST demonstrator is designed to the maximum GLOW of 25,000 lbs with a length of 31.6 ft., a span of 11.3 ft and a body diameter of 5.8 ft. In ongoing studies the demonstrator design has been rescaled to a greater GLOW allowing incorporation of either four Chase-10 engines or a single Space-X Merlin (see Figure 6). The Chase-10 is interesting because it is LOX-Methane powered and offers deep throttling. The Merlin is also interesting, because it is a modern but off-the-shelf LOX-RP design of the right thrust class.

Initial aerodynamic calculations were performed using RDS-Professional[6], based largely upon classical analytical methods as described in Raymer[7]. Detailed aerodynamic and stability calculations including tail sizing trade studies were conducted by subcontractor Analytical Methods Inc of Redmond, WA.

Demonstrator weights were estimated by a variety of methods (Figure 4). The structural weights are based upon previous structural design and FEM analysis performed under subcontract by Convergence Engineering Inc. Structural weight includes a weight penalty for attachment of the demonstrator to a first-stage booster or to another demonstrator in a BiMese configuration. Subsystem weights are based on a buildup previously prepared under a previous contract. Other weights are based upon off-the-shelf equipment, statistical analysis, and in some cases, expert opinion.

Since the demonstrator is to be built in the near future, no adjustments for future technologies were made. For a demonstrator GLOW of 25,000 lbs, an empty weight of 7,017 lbs is estimated leaving a boost propellant weight of 15,358 lbs for a PMF of 66.6%. This is substantially below the estimated PMF for the operational RUS, which benefits from scaling effects and also from more advanced technology assumptions.

Trajectory analysis results are shown in Figure 5 for a ground self-launch. For a single vehicle launch an altitude of nearly 200,000 feet and a speed of 3300 fps is attained. When a BiMese launch is used the upper stage reaches over 300,000 ft and attains a speed of about 6300 fps. This illustrates the performance potential of this design and its ability to perform envelope expansion and technology test via self-launch from the ground.

FAST DEMONSTRATOR SCALABILITY

The issue of scalability looms large over any proposed demonstrator program. While advocates of various technologies and system concepts always want to fly a “proof-of-concept” vehicle as early as possible, those paying the bills need to balance the expense against the likely “learning” to be obtained.

To a large extent, this is driven by technical and cost considerations. If the demonstrator vehicle is too small or excessively compromised by cost considerations, it might end up being just a “model airplane” rather than a true representation of the technologies and concepts under consideration. An example is the 60%-scale proof-of-concept vehicle for the T-46 program. While the POC vehicle was large enough to be manned and looked virtually identical to the production aircraft design, it was fabricated in a completely different manner and the chosen engine was different from that used on the full-scale design. When the full scale vehicle was built it was found to be 7% over the desired empty weight resulting in a significant loss of useful load, and its drag was 40% higher than expected due to the required redesign of the inlet system to integrate the actual engine. This plus cost considerations led to the cancellation of the T-46 program.

On the other hand, many demonstrator vehicles have been very successful and have led to excellent operational vehicles. One example little-known in the USA is the 70%-scale SAAB 210 “Little Dragon” which first flew the double-delta wing design in 1952. It was used to work out the flight characteristics of the double-delta and to find the best inlet-wing integration scheme, and led directly to the Mach 2 SAAB 35 Draken (“Dragon”). This first flew in 1955 and was operational until 1993.

The current FAST contract included a study of the demonstrator scalability issue, both qualitatively and quantitatively. There are a number of reasons to believe that the weights and systems performance proven on the FAST demonstrator will be trustworthy for predictions of an operational system. First, the demonstrator is physically almost a photo-scaled version of operational RUS vehicle. Like a good wind tunnel model, standard analytical scaling equations will permit reducing flight test data to high-quality predictions concerning the operational vehicle’s aerodynamics and stability.

This is also true for the FAST demonstrator structural concept – it is virtually identical to the proposed operational structural concept. The demonstrator design is about 50% of the length of the current operational RUS design, which is close enough that even the detailed parts designs will be almost a photo-scale of the demonstrator parts. The operational system will be designed and built about 5-10 years after the demonstrator so there will be an opportunity to insert relevant technological improvements such as more-advanced matrix materials, but these are not expected to change the overall structural concept nor invalidate the “learning” obtained from the demonstrator.

The FAST demonstrator will be able to explore the entire operational vehicle flight envelope including launch, orbit, reentry, and recovery. Therefore, the demonstrator will employ fully-capable propulsion, subsystems, avionics, and TPS. These will be as close to the operational vehicle designs as possible rather than “dummies” or near-term work-arounds.

To provide a quantitative assessment of the scalability issue, CRC subcontractor Convergence Engineering was tasked with scaling the demonstrator baseline FEA model up to an operational size vehicle, making appropriate modifications to represent the payload bay and other differences between the demonstrator and the operational vehicle. To this FEM, they applied operational loading conditions and performed structural analysis and weight estimation. The results indicate that the demonstrator design scales to an operational sized vehicle with reasonable per-unit weight reductions due to economies of scale when compared by either surface area or part volume, both of which are often used as preliminary weights estimation methods. This provides an analytical indication that the structural design of the FAST demonstrator should scale very well to the operational system.

DEMONSTRATOR PROGRAM PLAN

A tentative schedule for the FAST demonstrator program is shown as Figure 7. This includes demonstrator design, fabrication, and test, as well as a near-term structural article fabrication and test effort. The schedule begins with the continuation of concept development studies through the end of FY07 to mature the design and address certain areas of concern. Starting in FY07, a structural test article (see below) would be designed and fabricated for test at government facilities at WPAFB. This would be similar to the eventual flight-capable structure, and would include TPS in certain regions for testing in the 2009-2010 timeframe. At the end of 2011, the flight demonstrator program would begin in earnest with a contract award. PDR would occur 8 months later, followed by CDR, fabrication, and checkout. Flight test would begin at the end of 2014. Engine development would occur in parallel with vehicle development.

A key part of this program is the structural test article to be built for ground testing of the structure, tanks, and TPS. This article would be full size and complete, but would be somewhat simplified compared to the actual flight hardware to save cost and accelerate the schedule. For example, the structure would not include all attachment fittings and hard points. Structural thicknesses would not be fully optimized for expected flight loads, instead relying upon a reduced amount of optimization with constant skin thicknesses over fairly large regions. However, the basic geometry would be identical to the expected flight hardware and the flight structure would later be built on the same molds and tooling, after further design optimization and incorporation of lessons-learned.

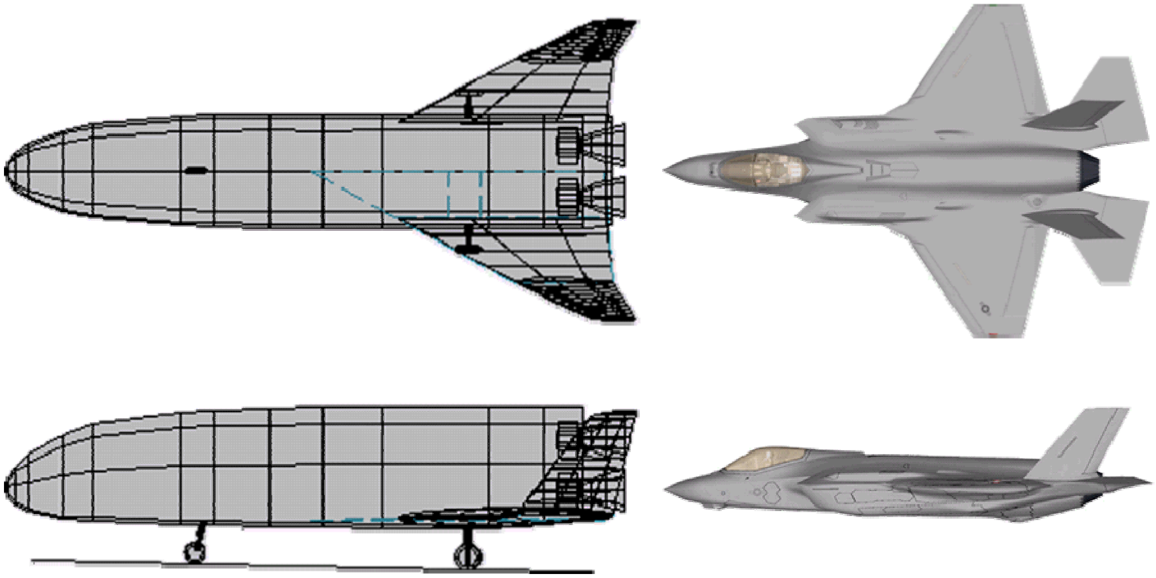
Testing of the resulting structure article would begin with pressure and cryogenic testing of the integral tanks. Next, simulated air, inertial, propulsion, actuation, and landing gear loads would be applied using the facilities at WPAFB. This would include a reasonable amount of fatigue testing as well. Localized TPS testing would occur using the WPAFB heating and acoustic generation capabilities. Finally, landing gear would be simulated and drop tests conducted.

Completion of this ground structural testing would increase confidence and reduce risk for the subsequent flight test program. Another complete vehicle structure would be built, incorporating further optimization and design detailing, into which the systems, propulsion, avionics, and other flight equipment would be installed. Flight test could commence in about 2014. To save up-front expenses, certain technologies and components could be left off the vehicle for initial flight testing then added later after basic flight envelope expansion has been completed. For example, the real TPS is only required for high Mach and reentry flights. Early flights could be done with “dummy” TPS made of expanded foam or similar material.

(The above program plan and schedule represents CRC suggestions to the government and has not been endorsed by USAF personnel.)

SUMMARY AND CONCLUSIONS

The FAST rocket powered demonstrator concept offers a timely and affordable means for technology and system concept validation. Since the demonstrator is self-powered, envelope expansion could be conducted gradually and with minimum risk. Initial testing would focus on the basic technologies and demonstrator itself, with later testing turning attention towards the problems of orbital Mach reentry.



Size Comparison : FAST RUS vs. F-35

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FIGURES

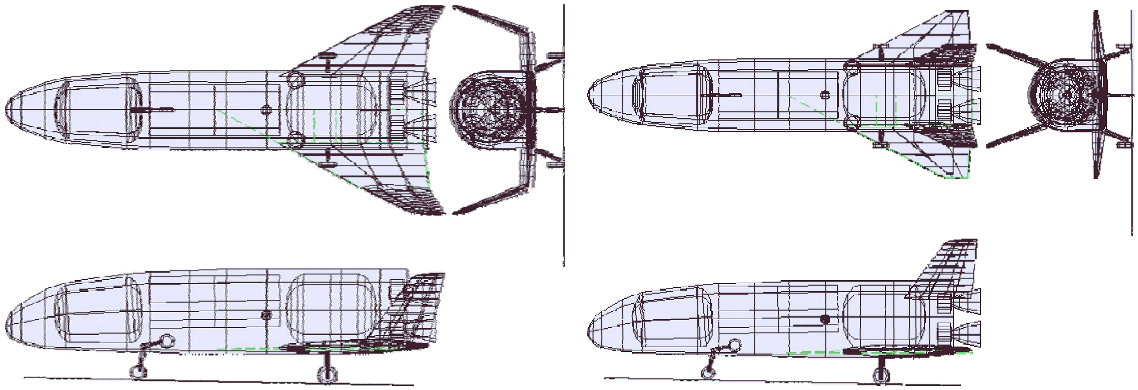

Figure 1. FAST-RUS Baseline 1 and Baseline 2

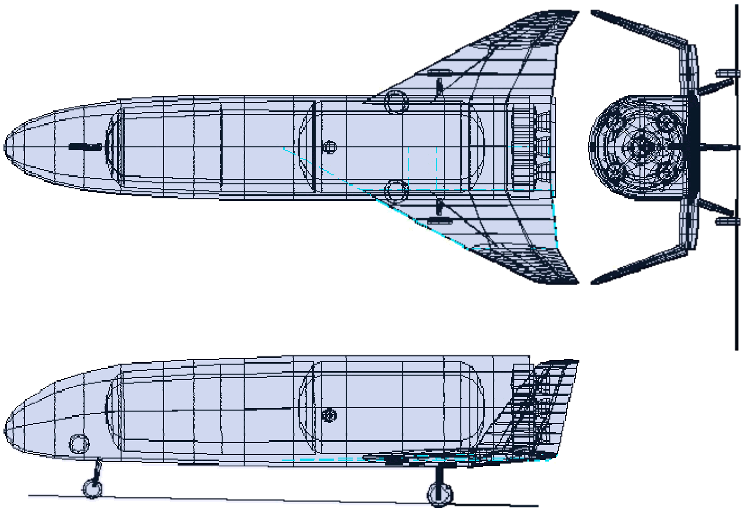

Figure 2. FAST Demonstrator Preliminary Baseline (Tip-mounted Tails)

	FAST-DEMO
W-gross	25000
W-empty	7017
W-payload	2000
W-misc UL	624
W-propellant	15359
PMF	61.4%
# engines	5
T per engine	7000
T/W	1.4
Length	31.6
Diameter	5.8

	HorizSurf	Tails
Area Sref	111.32	19.04
Aspect Ratio	1.153	1.6
Taper Ratio	0.333	0.44
Sweep (LE)	61.213	35
Sweep (c/4)	54.199	30.057
Thickness t/c	10%	12%
Dihedral	3	-20
Twist	-2	0
Span	11.329	5.52
Root Chord	14.737	4.791
Tip Chord	4.915	2.108
Mean Chord	10.644	3.624
Y-bar	2.36	2.402

Figure 3. FAST Demonstrator Design Data

	Weight lbs	Loc ft	Moment ft-lbs
STRUCTURES	**3098**		**52072**
Horiz Surface	120	22.3	2687
			0
Wing (carry-through)	52	22.3	1160
Tails	94	28.4	2665
Fuselage	869	17.5	15212
			0
Body Flaps	43	29.7	1270
Integral Tanks	588	16.4	9645
			0
			0
Landing Gear	397	16.0	6358
TPS	934	14.0	13076
			0
PROPULSION	**1260**		**31919**
Engines (5)	780	28.9	22542
Mount & Misc Install	175	25.0	4375
			0
			0
			0
			0
Prop Pressurization	130	16.4	2132
Propellant Insulation	175	16.4	2870
			0

	Weight lbs	Loc ft	Moment ft-lbs
EQUIPMENT	**2325**		**36064**
Flight Controls (EMA)	757	20.0	15140
Instrumentation	14	4.0	55
Wiring	381	18.0	6862
Electrical (Power)	46	5.0	230
Avionics - Fwd Bay	106	4.7	500
Avionics - Engine Bay	329	26.0	8542
Avionics - Thermal Mgmt	412	5.0	2060
Battery	162	5.0	808
			0
Misc Equipment	0		0
RCS System	119	15.7	1867.79
(% We Allowance)	5		
Empty Weight Allowance	334	18.0	6003
TOTAL WEIGHT EMPTY	**7017**	**18.0**	126058
USEFUL LOAD	**17983**		
Start & Residual Prop	374	16.4	6142
Boost Propellant	15358	16.4	251873
RCS Propellant	250	15.7	3925
Land Propellant			0
Payload	2000	15.3	30600
TAKEOFF GROSS WEIGHT	**25000**	**16.7**	418598
Wo - No Propellant	9642	17.3	166725

Figure 4. FAST Demonstrator Weights

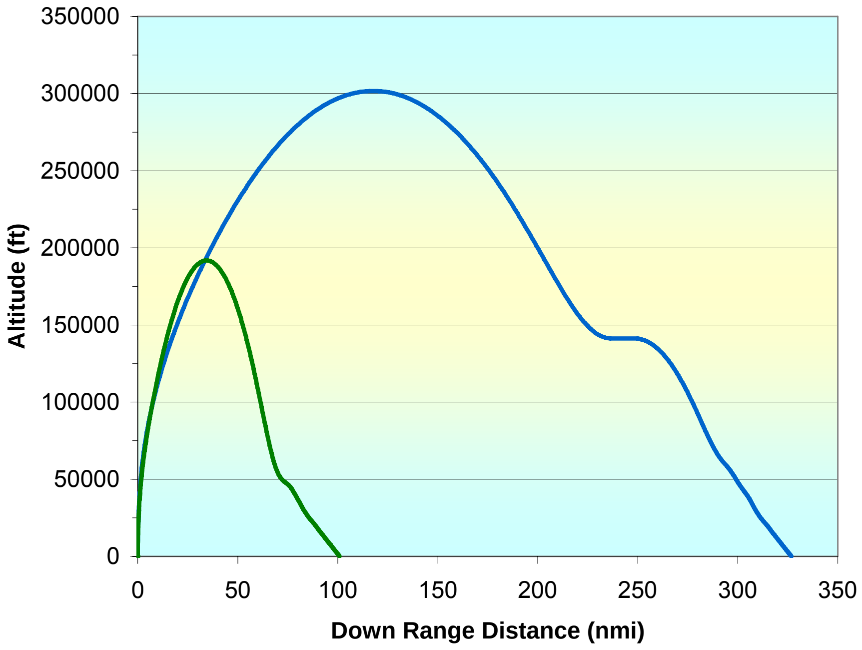

Figure 5. FAST Demonstrator Self-Launch Trajectory Analysis: Altitude vs. Distance

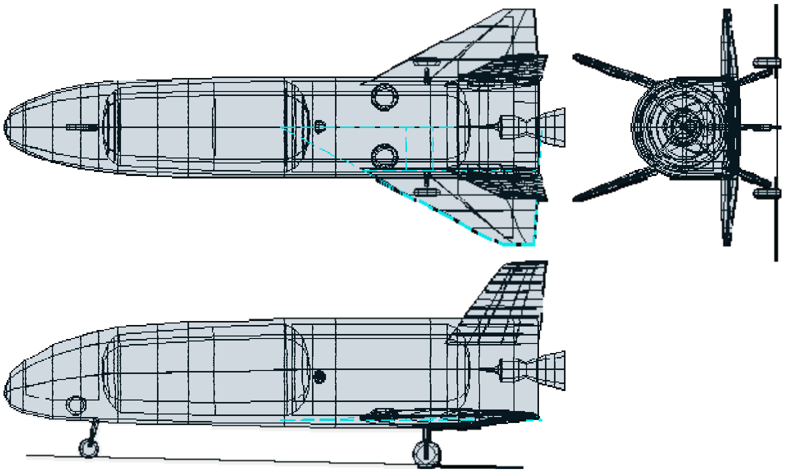

Figure 6. FAST Demonstrator – Single Merlin Engine

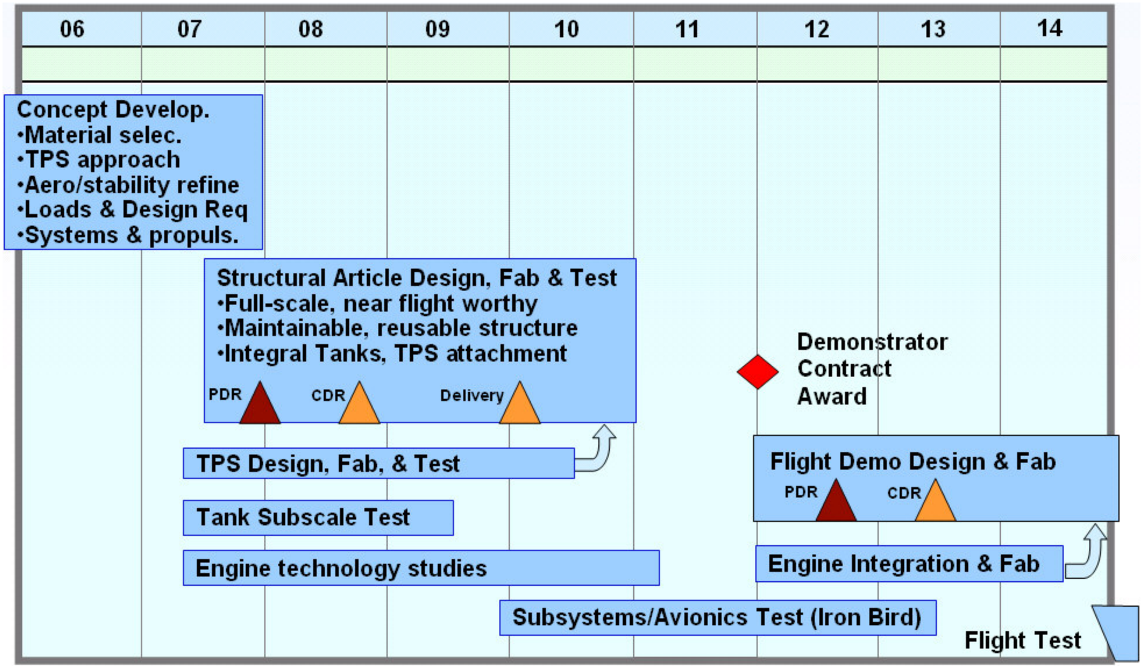

Figure 7. Tentative Demonstrator Program Schedule