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Quicksat: A Two-Stage to Orbit Reusable Launch Vehicle Utilizing Air-Breathing Propulsion for Responsive Space Access

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In order to counter newly emerging threats and offensive posturing from hostile countries, the United States military has identified responsive space access as a necessary capability to provide security and defense for the nation. An option for enabling quick, on-demand space access involves reusable transportation elements. Specifically, elements that incorporate air-breathing propulsion systems to provide multi-role mission capabilities, loiter capability, flyout, and abort options. These capabilities are not generally possible on systems that only utilize rocket propulsion systems. In support of this vision, the Air Force Research Lab has initiated concept development studies in the area of combined-cycle propulsion systems applied to reusable launch vehicles. The first product from this study has resulted in the design of a space operations vehicle (SOV) referred to as the *Quicksat.* This SOV is the first element of a two-stage launch vehicle concept that uses combined-cycle air-breathing propulsion. The nominal system launches and lands horizontally in addition to using non-cryogenic propellants for improved operability in support of on-demand and responsive launch scenarios. Additionally, the unique vehicle is capable of supporting at least three unique missions: a) space maneuvering vehicle (SMV) delivery to orbit, b) a hypersonic strike mission, and c) cargo delivery to LEO and polar orbits.

Nomenclature

ACS	=	*attitude control system*
AFRSI	=	*advanced, flexible reusable surface insulation*
AOA	=	*angle-of-attack (degrees)*
Aref	=	*reference area* (ft^2)
CAV	=	*common aero vehicle*
Ct	=	*thrust coefficient (thrust/q/Aref)*
DMSJ	=	*dual-mode scramjet*
GLOW	=	*gross lift-off weight (lbs)*
GTOW	=	*gross takeoff weight (lbs)*
H_2O_2	=	*hydrogen-peroxide*
Isp	=	*specific impulse (seconds)*
IVHM	=	*integrated vehicle health monitoring*
JP-7	=	*hydrocarbon jet fuel*
LEO	=	*low earth orbit*
MPS	=	*main propulsion system*
MSP	=	*military space plane*
Pc	=	*chamber pressure (psia)*
RDT&E	=	*research, development, test, and evaluation*

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SMV	=	*space maneuvering vehicle*
SOV	=	*space operations vehicle*
TPS	=	*thermal protection system*
TSTO	=	*two stage to orbit*
TUFI	=	*toughened unifibrous flexible insulation*
UHTC	=	*ultra high temperature ceramic*
pcf	=	*pounds per cubic foot*
q	=	*dynamic pressure (psf)*
ε	=	*expansion ratio*

I. Introduction

Over the past few decades, a shift in the perception of outer space has been occurring. New interpretations of space have been coming from both the commercial sector (as seen in the recent phenomenon of space tourism) and from the military[1,2]. An expanding consensus is developing within military circles that views space as equivalent to any existing land and sea battlefield[3,4]. The ultimate manifestation of this may be a "space force" as some have advocated, equivalent to one of the four main branches of the United States military, arising out of major components from the current Air Force.

Recommendations from recent U.S. government commissions including the Commission to Assess United States National Security Space Management and Organization, known as the "Space Commission" and headed by Donald Rumsfeld, have heralded these new perceptions[5]. The commissions have indicated that the United States is more heavily dependent upon resources (i.e. satellite imagery, telecommunications, etc.) from space than ever before and thus has to be concerned about vulnerabilities of those assets. Specific commission findings include[6].

- The extent of U.S. dependence on space and the vulnerabilities it creates demand that space be recognized as a top national security priority.
- The U.S. government is not yet arranged or focused to meet the national security space requirement of this century.
- Throughout history, there has been conflict in every medium (air, land and sea) and space will be no different. The United States must defend against hostile acts in and from space.

At this point however, outer space can be viewed as a location of military infrastructure, and probably potentially less as an actual combat battleground[7]. Multiple countries have reconnaissance assets (some available on the commercial open market) in space and current defensive and offensive capabilities are minimal and most likely non-existent if unclassified sources are correct.

The United States military in particular has been a supplier of both space infrastructure (satellites) and developer of transportation services (X-vehicles, expendable launch vehicles). Ever since the initial development of manned space travel, the U.S. military has considered and invested in a myriad of programs to advance reusable space transportation services (Dynasoar, etc.). As seen in projected budgets for fiscal years 2002 to 2007, the U.S. Air Force (USAF) is projected to spend 86 percent of the Department of Defense's (DoD) total allocated space funding of $165 billion[8]. The latest incarnation of USAF reusable launch vehicle (RLV) plans is embodied in the Space Operations Vehicle (SOV) concept[9,10,11].

During the late 1990s and early 2000s (pre-Exploration Initiative), NASA was investing heavily in the Space Launch Initiative (SLI) and Next Generation Launch Technologies (NGLT) programs. These programs with multi-billion dollar funding levels were to assist in making the decision on whether to replace or upgrade the current Space Shuttle fleet. Several new concepts were being examined for this study, yet the essential requirements for NASA's system are drastically different than those envisioned by the USAF for their SOV.

A Military Space Plane (MSP) is in essence an atmospheric/space delivery architecture that can consist of multiple stages to deliver payloads into space and onto the surface of earth. This system is essentially an RLV specifically designed to support military users. Current perceptions of the first MSP entail development and Initial Operating Capability (IOC) sometime in the 2015-2020 timeframe. This imagined MSP consists of multiple elements coupled together to provide the war fighter with a flexibility of response. The core component of the architecture is a reusable first stage vehicle known as the SOV. The SOV will have the capability of carrying multiple payloads with turnaround times (TATs) measured in hours instead of the current months for the U.S. Space Shuttle. U.S. military scenarios entail building up both a useful demonstrator and full-scale version of the MSP[9]. Concepts within a 5-15 year time horizon most likely will entail some type of Two-Stage-To-Orbit (TSTO) system.

Nominally, the MSP shall be capable of the following[12,13]:

a. The SOV shall be capable of supporting space control, force application, force enhancement, and force support missions by providing low cost, high ops tempo launches of Space Maneuvering Vehicle (SMV), Common Aero Vehicle (CAV), and modular insertion stage payloads to mission orbits or trajectories.
b. Orbit-capable and sub-orbital SOVs shall be capable of executing sub-orbital, pop-up profiles that allow safe launch and recovery from U.S. bases.
c. The MSP System shall be capable of autonomous, virtually commanded, or crewed operations depending on future requirements evolution.
d. The MSP System shall provide aircraft-like levels of operability and maintainability to allow high sortie rates.
e. Orbit-capable SOVs shall be capable of supporting once around missions while returning to their launch site.

SpaceWorks Engineering, Inc. (SEI) and the Air Force Research Lab (AFRL) at Wright-Patterson Air Force Base have embarked on a coordinated effort to examine the potential of combined-cycle propulsion systems towards meeting and/or exceeding the nominal attributes of the envisioned MSP. The first phase of this effort has involved the examination of a vehicle concept that includes a turbine-based combined cycle (TBCC) propulsion system with dual-mode hydrocarbon-fueled scramjet engines. The scramjet engines used for this study represent one potential application of the current research being conducted by the U.S. Air Force in the HyTech program. The primary goal of this joint SEI-AFRL effort is to establish a vision and roadmap for the future application of hydrocarbon scramjet engine technologies.

II. *Quicksat* Concept Overview

The *Quicksat* SOV is the first element of a two-stage MSP concept that uses combined-cycle air-breathing propulsion (see Figure 1). The nominal system, which takes off and lands horizontally, uses non-cryogenic propellants for improved operability in support of on-demand and responsive launch scenarios. Additionally, this booster is capable of supporting three different missions by configuring the upperstage with mission-specific hardware. The primary missions supported by the *Quicksat* include: a) space maneuvering vehicle (SMV) delivery to orbit, b) a hypersonic strike mission, and c) cargo delivery to LEO and polar orbits. The various upperstage configurations will be detailed in a later section.

Figure 1. *Quicksat* Launch from Notional Military Facility.

The *Quicksat* concept is enabled through the use of numerous technology advances in the areas of propulsion, materials, structures, avionics, and integrated vehicle health monitoring (IVHM). In the propulsion area, the vehicle uses Mach 3+ capable turbine engines, an endothermically fueled Mach 8 dual-mode scramjet system, and a bank of tail-rockets that utilize a monopropellant catalyst-bed for powering four closed-cycle liquid rocket engines. All of these engines are fully reusable and require minimal maintenance between flights. Advanced composite and metal-alloys materials are used for a number of key structural elements to reduce system weight and protect against high temperatures. Structural designs that maximize airframe stiffness while minimizing weight and intrusions into the airframe are required due to the high loading conditions during various flight maneuvers (takeoff, pull-up, max-q, etc.). Multi-redundant avionics and flight systems capable of fully autonomous or virtual operations from takeoff to landing are used. Additionally, through the use of imbedded sensors and detection systems the IVHM provides constant assessment of the vehicle's subsystems as well as flight conditions. Allowing for immediate identification of failing systems or violated operating conditions. This contributes greatly to the reduced ground processing times.

Current launch scenarios have space-access missions being conducted from a spaceport facility at Cape Canaveral in Florida or Vandenberg Air Force Base in California. Figure 1 provides an illustration of the hangar facilities and the *Quicksat* system during takeoff from a notional military base to perform a space-access mission.

III. Concept Analysis Methods

The complex vehicle architecture was designed and analyzed using a collaborative, distributed framework known as ModelCenter© available from Phoenix Integration, Inc.[14]. A number of industry standard analysis tools were utilized, along with numerous in-house codes developed at SEI.

Industry codes included:

- POST — 3-degree of freedom trajectory simulation code[15]
- APAS - S/HABP — aerodynamic and aeroheating load predictions[16]
- NASCART-GT — 3-D Euler with external flowfield analysis[17]
- NEPP — turbine system performance tool[18]
- SRGULL — scramjet engine performance analysis
- Solid Edge — configuration layout and center-of-gravity assessments
- NAFCOM — research, development, test, & evaluation (RDT&E) and acquisition costs[19]

Codes developed by SEI include:

- REDTOP — attitude control system (ACS) performance predictions[20]
- REDTOP-2 — liquid rocket engine design[21]
- SEI-Sizer — airframe, tank, and subsystem weight modeling and system sizing
- TCAT-II — transient, 1-D aeroheating analysis and thermal protection system design/sizing
- SESAW — avionics subsystems
- CABAM — economics assessment
- GTSafety-II — vehicle safety and reliability metrics
- TAPS — turnaround activity and processing

The disciplinary tools with tightly coupled variables (between multiple disciplines) were integrated together to create an automated system closure model. Non-dimensional parameters like the aerodynamic coefficients and air-breathing propulsion system thrust coefficient permit scaling within reasonable ranges through normalization with a reference area. Computing platforms used within the distributed framework included: an SGI Octane Workstation, a dual 1.8Ghz 64-bit G5 Macintosh, and two 3.2Ghz Dell Pentium-4 PCs.

IV. Upperstage Configurations and Attributes

The *Quicksat* vehicle is designed to support three primary missions. They include: a) a space maneuvering vehicle (SMV) deployment to orbit, b) a hypersonic strike mission, and c) cargo delivery to LEO and polar orbits. For each of these missions, the booster stage (*Quicksat*) is identical but the upperstage configuration is unique. The three upperstage options and specifications will be provided next.

A. Space Maneuver Vehicle (SMV) Delivery

The nominal mission for the *Quicksat* is the delivery of an SMV to orbit. The SMV is a reusable vehicle capable of remaining on-orbit for extended periods of time[22,23]. The vehicle features a small, kerosene/H_2O_2 liquid rocket engine (Rocketdyne AR2-3) for on-orbit maneuvering. The total vehicle weight is 13,090 lbs, which includes an experiment bay with up to 500 lbs. of payload. The length from nose-to-tail is 27.5 ft and the wingspan is 15.0 ft.

The SMV is deployed by an expendable rocket-powered upperstage. This stage consists of 3 propellant tanks, an attitude control system (ACS), flight controller, thermal protection system (TPS) blankets, and a single liquid rocket engine. The SMV is attached at its base to the forward section of a truss structure. The upperstage, which carries and accelerates the SMV from Mach 8 to orbital velocities, utilizes JP-7 and H_2O_2 propellants. Figure 2 shows an external view of the SMV and the SMV attached to the expendable upperstage system.

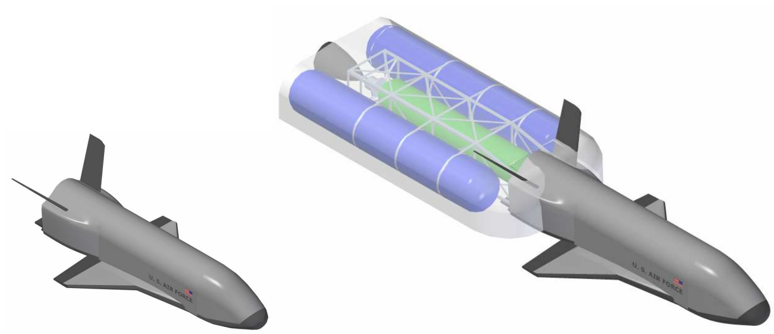


Figure 2. SMV and SMV+Upperstage System

The expendable upperstage hardware elements are designed with limited reliance on new technology developments to keep the recurring system costs to a minimum. The engine is a derivative of the reusable engines on the *Quicksat* booster (to be detailed later) and the propellant tanks are all constructed from aluminum. The ACS is a simple blow-down, pressure-fed, monopropellant arrangement using H_2O_2. The upper half of the body is covered in thermal blankets to protect the hardware during the ascent, prior to booster release. Since the system is unmanned, minimal system redundancy has been used. Table 1 provides a top-level listing of the main hardware elements and associated weights for the upperstage and SMV. The integrated system has a combined weight of 90,215 lbs. when loaded with the SMV and all fluids contained in Table 2. The total stage length is 52.2 ft with the SMV.

Table 1. SMV and Upperstage System

Hardware Element	Weight (lbs)
Airframe Structure (truss, tanks, etc.)	1,200
Thermal Protection (AFRSI blankets)	285
Main Propulsion (rocket engine)	1,940
Attitude Control Systems (ACS)	185
Subsystems (avionics, EPC&D, etc.)	665
Total Hardware	**4,275**
Total Hardware + Fluids + SMV	**90,215**

Table 2. Upperstage Propulsion Fluids

Category	Weight (lbs)
Residuals	75
Reserves	550
Attitude Control Systems (ACS)	480
Unusables	715
Ascent Fuel (JP-7)	8,830
Ascent Oxidizer (H_2O_2)	61,500
Startup Losses	700
Total All Propulsive Fluids	**72,850**

B. Hypersonic Strike Mission with ECAV Delivery

The *Quicksat* booster is capable of acting as a long-range strike system. One strike-mission of interest and the focus of current research and development activities in the joint DARPA and Air Force Force Application and Launch from Continental United States (FALCON) program, is the deployment of Enhanced Common Aero Vehicles (ECAVs) [24]. To perform this type of mission, the *Quicksat* upperstage can be outfitted with a conformal fuel tank and two banks of 3 ECAVs (6 total). The ECAVs are unpowered hypersonic gliders, equipped with a 1,000 lbs. munition and a nominal weight of 2,000 lbs each. When released at high Mach conditions, it is desired that they be capable of impacting targets 6,000-9,000 nmi. downrange. Figure 3 provides an aft-section view of the *Quicksat* integrated with a conformal fuel tank and 6 ECAVs. Note that the ECAVs are notionally represented as triangular shaped volumes and are not representative of any specific design concept.

When performing this mission, the nominal space-access flight profile for the *Quicksat* is expanded to include a supersonic cruise segment. The vehicle takes off from a military complex outfitted with up to 6 ECAVs. The ECAVs are attached to the top of the vehicle via a small truss structure. Release mechanisms are also included for the separation of the gliders. The flight profile up to the cruise condition is identical to the space-access mission, with tail-rocket assist through transonic. As the velocity approaches the cruise Mach number, the vehicle performs some maneuvering to obtain the desired cruise altitude at a lower dynamic pressure. The *Quicksat* then remains on the constant-altitude and Mach number path until the desired range is achieved. Propellants for the cruise portion are used from the external, conformal tank and/or the nominal flyback fuel tank. After the cruise phase, the vehicle resumes the space-access flight profile, accelerating to Mach 8 and executing a hard pull-up maneuver. At Mach 9, the booster will release the ECAVs, which can then presumably travel an additional 1,500 nmi. to the intended target. Depending on the distance from the launch base at separation, the *Quicksat* can return to the launch complex, refuel aerially with subsonic flyback, or proceed to a downrange base. Alternate strike missions could involve shorter strike ranges and/or dropping any variety of munitions, of up to 12,000 lbs., capable of sustaining supersonic release conditions.

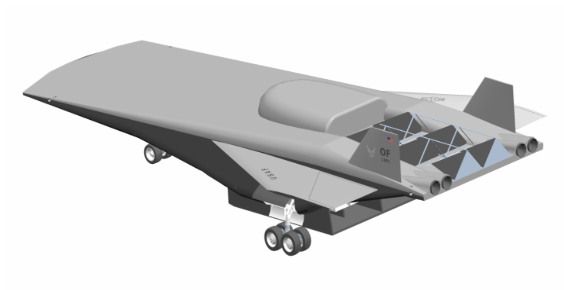


Figure 3. *Quicksat* HSM Configuration

The optimal conditions for achieving maximum range occur at Mach 5 (dual-mode scramjet (DMSJ) propulsion) at an altitude of 95,000 ft. These conditions result in a total range of 4,440 nmi. from the launch site to the ground target. This range is well short of the desired 'global-reach' capability for the FALCON program at 9,000 nmi. The *Quicksat* is designed foremost as a space-access vehicle and system compromises were not made to result in a greater strike-mission capability.

C. Cargo Payload Delivery
The *Quicksat* vehicle can also be configured to support general cargo delivery missions to low-earth orbit (LEO). In this configuration, the SMV is replaced with a similarly shaped payload fairing. This fairing, which has an internal volume of 950 ft^3 and weighs 2,500 lbs, allows for up to 10,020 lbs. of payload to be transported to orbit.

V. Booster Performance Attributes
The tools and processes outlined in Section III were used to design a feasible and viable vehicle concept. During the course of the design process, a number of one-variable at a time performance trades were conducted to identify locally optimum configurations. Parameters considered included: rocket engine characteristics (chamber pressure (Pc), mixture ratio, expansion ratio (ε), and thrust level), maximum dynamic pressure (q_{max}), turbine-to-DMSJ transition point, transonic rocket-assist Mach number range, and the staging velocity. Computing resources and expense were limiting factors in performing a global optimization of the system with ten or more design variables. The nominal mission is designed to support delivery of an SMV to LEO. This was selected as the driving mission for the booster and all other missions are then constrained to the booster's payload capability resulting from supporting this mission.

A. Configuration and System Hardware Layout
The *Quicksat* is configured as a lifting-body design, derived from the National Aerospace Plane (NASP) program vehicle configurations and similar to the ongoing NASA Hyper-X (X-43) integrated-scramjet flight test program[25]. Upperstage modules are located on the leeward, aft portion of the vehicle in a partially recessed cavity. The air-breathing propulsion systems are arranged in an over-under configuration with turbine-engines embedded in the vehicle airframe and an underslung DMSJ system. These engines share a common external compression system (i.e. the vehicle forebody) and aftbody expansion zones. In addition to providing engine airflow matching and optimal flow expansion, the variable geometry inlet and exit ramps can shield the turbine systems from the freestream flow when not being operated. All propulsion system elements use JP-7 hydrocarbon fuel. The rocket systems also use a hydrogen-peroxide (H_2O_2 at a 95% purity level) oxidizer. Figure 4 presents various profiles of the external vehicle shape and design.

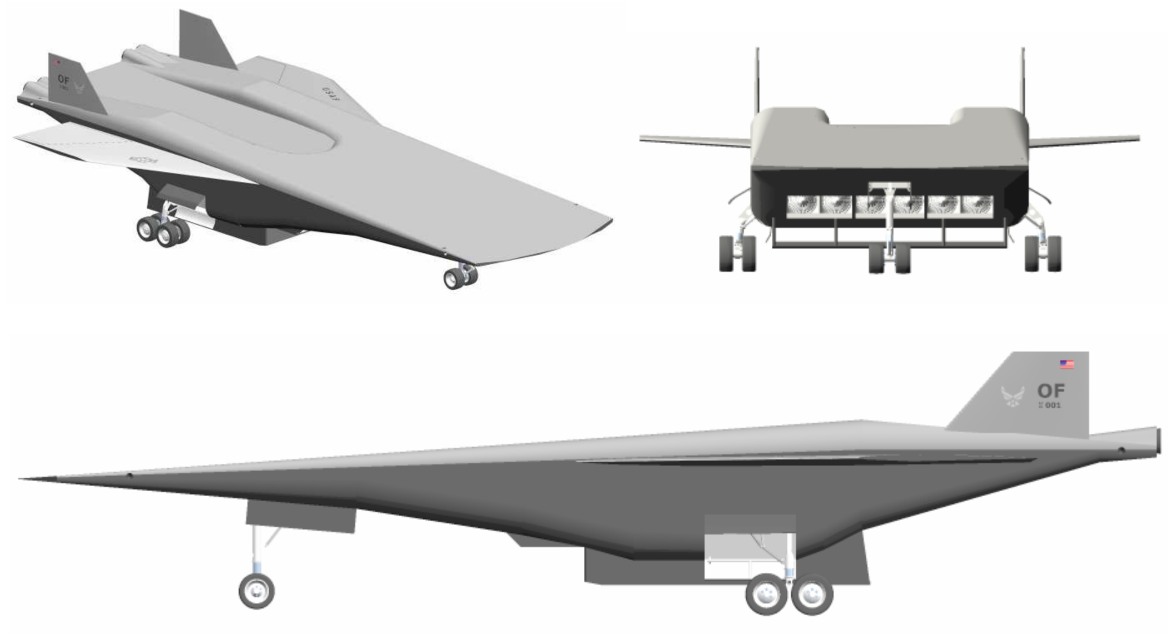


Figure 4. *Quicksat* External Views.

The feasibility and viability of the *Quicksat* system is dependent upon technology advances in a number of key areas. Specific technologies and features unique to the booster system include:

- Graphite-epoxy airframe primary and secondary structures
- Titanium-aluminide wing and tail hot structures
- Cylindrical, non-integral Gr-Ep fuel tanks
- Cylindrical, non-integral aluminum oxidizer tanks
- Electro-hydraulic actuators (EHAs) for control surfaces, propulsion system ramps, landing gear/doors
- All-moving vertical tails
- Pressure-fed, monopropellant ACS
- Lightweight, retractable landing gear and high-speed tires

The internal airframe components were arranged to provide the best overall packaging efficiency while not compromising the ability to access and inspect the vehicle's propellant tanks, feed lines, propulsion systems, and subsystems. Additionally, denser items such as oxidizer tanks and subsystems were located as far forward as possible to prevent the vehicle center-of-gravity (C.G.) from being located to far aft. Figure 5 provides various transparent views of the airframe and internal systems.

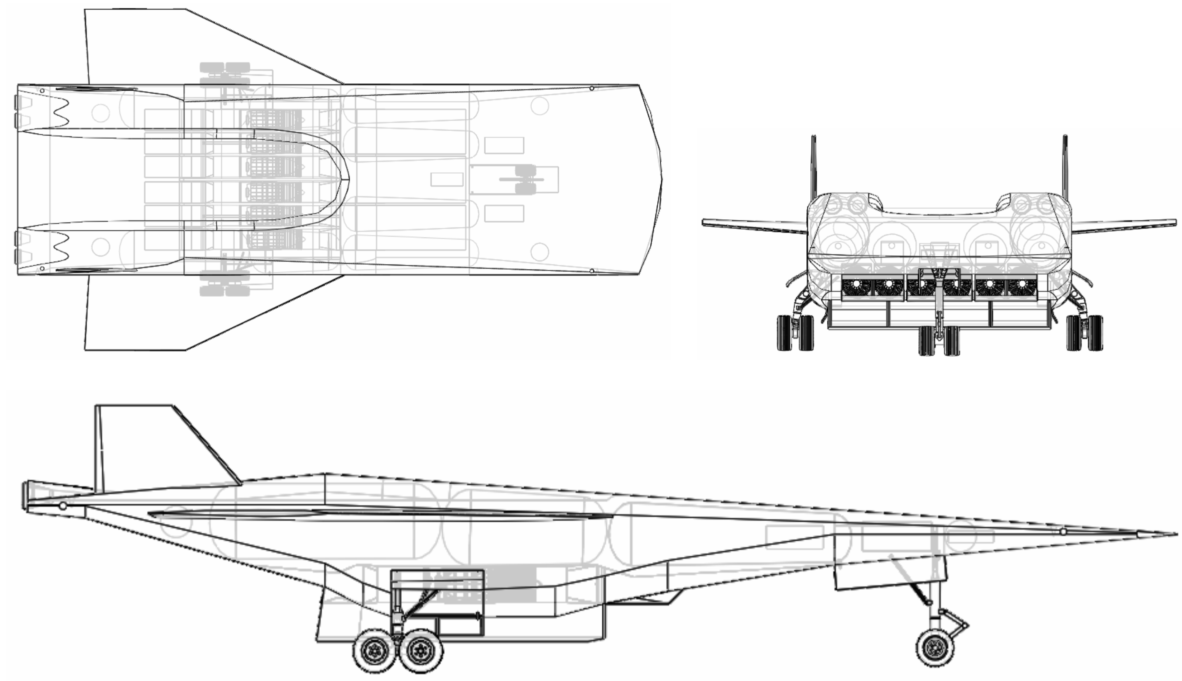


Figure 5. *Quicksat* Internal Views.

The length of the *Quicksat*, from the nose-to-tail section is 123.6 feet, with a wingspan of 65 feet and tail height of 26 feet. The weight of the booster, without propulsive fluids, is 167,840 lbs. Table 3 provides a top-level weight summary for key system hardware elements. Without an upperstage module, the weight of the fully loaded booster with the JP-7 fuel and H_2O_2 oxidizer propellants is 651,455 lbs, yielding a total gross takeoff weight (GTOW) of 741,670 lbs. (less startup losses) for the SMV deployment mission. Table 4 provides a breakdown of the fluid weights on the booster. In addition to the propellant volumes, an ullage volume of 3% per tank is present.

Table 3. *Quicksat* Hardware Weights.

Hardware Element	Weight (lbs)
Wings and Tails	16,240
Airframe (aeroshell, tanks, bulkheads, etc.)	44,970
Thermal Protections Systems	16,180
Landing Gear	16,815
MPS	
Turbines	41,435
DMSJ	15,685
Tail-Rockets	6,425
Attitude Control System (ACS)	840
Subsystems (avionics, EPC&D, EHAs, etc.)	9,250
Total Hardware	**167,840**
Total Hardware + Fluids + Upperstage	**741,670**

Table 4. *Quicksat* Fluid Weights

Fluids	Weight (lbs)
Residuals	1,035
Reserves	3,750
Flyback	25,780
Attitude Control System (ACS)	4,855
Unusables	13,280
Ascent Fuel (JP-7)	312,875
Ascent Oxidizer (H_2O_2)	122,040
Startup Losses	4,430
Total All Propulsive Fluids	488,045

B. Mission Profile and Flight Dynamics

A typical space access mission for the *Quicksat* is comprised of a number of key events that must occur throughout the flight profile. For the SMV-deployment mission, the system nominally launches from Cape Canaveral, located at approximately 28.5^{o} latitude. For the takeoff run the six turbine engines (each with 65,660 lbs. thrust) provide power to accelerate the vehicle down a 14,000 ft runway. Pitching up to a 15^{o} angle-of-attack (AOA) and with the wing control surfaces fully deflected, the vehicle is able to generate enough lift to leave the ground at 297 kts after traveling 7,050 ft. The autonomous flight system directs the vehicle to an altitude of 11,000 ft. at Mach 0.8 and signals the tail-rocket ignition. The four tail-rockets on the booster are instantly ramped up to full-throttle and provide the additional thrust needed to efficiently drive the vehicle through the transonic flight regime. At Mach 1.4 the control system signals the shutdown of the tail-rockets and the turbine engines are then used to continue along an 1,600 psf dynamic pressure to Mach 3.75[26].

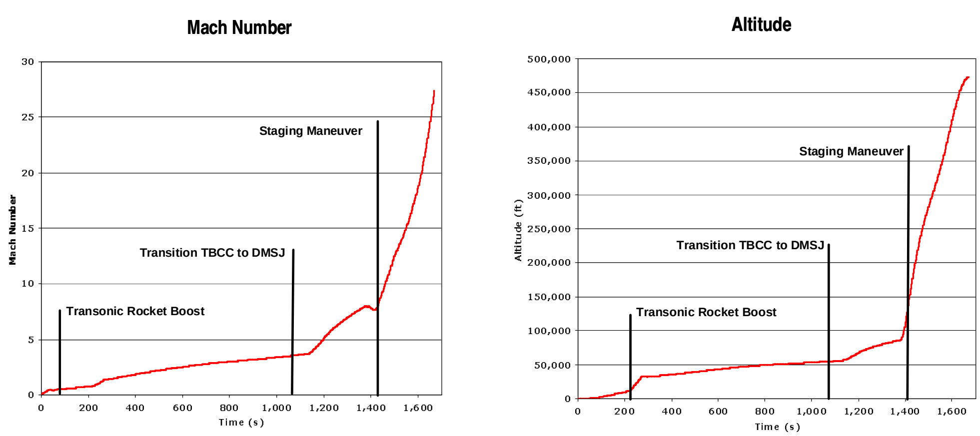
At this point in the mission, the vehicle transitions from its low-speed propulsion system to the high-speed system. To accomplish this, a very rapid sequence of shut-down procedures must occur on the turbine system with simultaneous power-up commands to the DMSJ system. The inlet ramps to the turbine engines are retracted to cut off the air inflow, fuel flow is gradually reduced to permit additional cooling, and the nozzle ramps are finally closed. Simultaneously, the JP-7 fuel flowrate to the DMSJ engines is rapidly increased. The inlet ramps and fuel injectors respond to the instantaneous flight conditions and adjust to provide the necessary thrust levels. The DMSJ engines operate in a fuel-lean mode until the flight speed increases enough to maintain the thermal choke at the nominal fuel-rich (φ=1.1) conditions. The vehicle operates under DMSJ power and along a dynamic pressure boundary of 2,000 psf up to Mach 8.

Upon reaching Mach 8, the vehicle departs from the q-boundary and begins a sharp pull-up maneuver to setup the staging event. Within a few seconds the dynamic pressure drops below 500 psf and the controller signals the tail-rocket re-ignition. The Mach number at this point is still approximately 8 due to atmospheric impacts on the speed of sound. The tail-rockets are then used to boost the vehicle to the Mach 9 staging condition at an altitude of 250,000 ft (q=25 psf).

At the staging point, the attach clamps for the upperstage are released and the single tail-rocket is ignited. Simultaneously, the *Quicksat* reduces its speed and flight path angle, initiating the separation of the two stages. Under all-rocket propulsion, the upperstage continues to the insertion velocity at an altitude of 70 nmi. This results in the SMV deployment to an elliptic 70x197 nmi. orbit at a 28.5^{o} inclination. The SMV is released from the expendable upperstage hardware elements (tanks, avionics, engine, etc.) and proceeds to conduct its primary mission. The remaining upperstage elements then use the ACS to pitch over and perform a small delta-V of 100 fps for deorbit and atmospheric disposal.

After staging, the *Quicksat* continues to reduce its speed and performs an unpowered turn towards the launch site. When the vehicle has reduced its speed and altitude to Mach 5 at an altitude of 95,000 ft (q~500 psf), the DMSJ engines are restarted and used to fly the vehicle back to the launch site. The total flyback distance of 800 nmi. requires 0.26 hours to complete.

Figures 6 and 7 provide time histories for the Mach number and altitude during the mission. The total ascent time-to-orbit for the SMV is 0.47 hours from launch, with the staging maneuver occurring at 0.4 hours into the mission. In the event that the vehicle can return to a downrange base for service and propellant resupply, a partial amount of the flyback propellants can be used to either loiter or phase-up with a desired orbital plane.



Figures 6 and 7. Mach Number and Altitude Histories for SMV-Deployment Mission

C. Propulsion System Characteristics

The *Quicksat* incorporates a number of propulsion systems that enable mission flexibility as well as provide numerous abort scenarios. The air-breathing engine systems use a number of advanced technologies, to either improve performance or reduce weight, that are currently being developed in a number of government funded technology development programs.

Low-Speed Systems

The low-speed engines operate from takeoff to Mach 3.75 and consist of 6 advanced, low-bypass ratio turbofan engines. The engines, which use JP-7 fuel, are grouped in pairs and each pair shares a common inlet and nozzle ramp. During takeoff, each engine can generate 65,660 lbs. of thrust using the afterburner with a corresponding Isp of 1,895 s. The engines have an uninstalled, sea-level-static thrust-to-weight ratio of 15:1, resulting in an installed T/W ratio of 9.96. Table 5 provides a summary of key engine parameters for the *Quicksat* and Figure 8 shows the main engine components (compressor, combustor, turbine, and afterburner) integrated in the booster figure.

Table 5. Turbine Engine Specifications.

Parameter	Value
SLS Thrust (lbs)	65,660
SLS Isp (s)	1,895
Uninstalled Length (ft)	12.6
Compressor Diameter (ft)	4.2
Hub-to-Tip Ratio	0.20
Bypass Ratio	1:1
Max. Turbine-Inlet-Temperature (R)	3,660
Max. Equivalence Ratio	0.95
Overall Pressure Ratio (OPR)	17.5

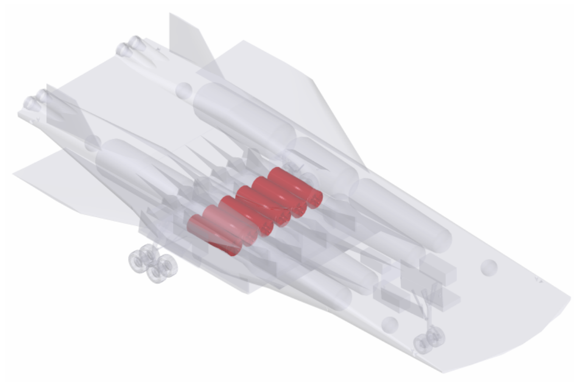


Figure 8. *Quicksat* Turbofan Engines.

High-Speed Systems

The high-speed engines operate from Mach 3.75 to Mach 8 and consist of 4 dual-mode scramjet (DMSJ) engines. The engines are regeneratively cooled, use JP-7 fuel, feature variable geometry inlets, and include a thermal-choke in the nozzle system. Achieving and maintaining the thermal choke enable operation at lower Mach number flight conditions keeps engine weight to a minimum by elimination of a mechanical-choke nozzle. The engine controller requires input from numerous engine sensors to assess the correct fuel flowrate and injection location to maximize operating performance. Table 6 provides a summary of the engine performance in terms of thrust coefficient (Ct) and Isp versus Mach number and Figure 9 shows the engines location on the airframe. All data shown corresponds to a vehicle AOA of 0^o and dynamic pressure of 2,000 psf.

Table 6. DMSJ Performance Specifications.

Mach Number	Ct	Isp (s)
4	0.82	1,628
5	0.91	1,412
6	0.59	975
7	0.51	859
8	0.43	771

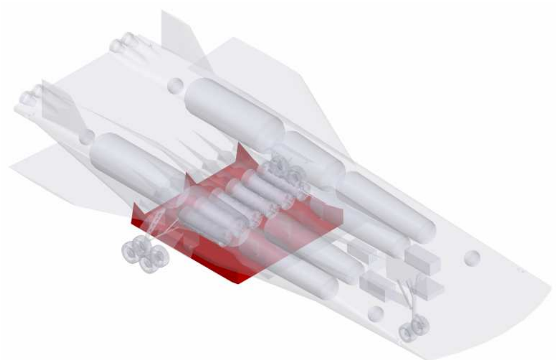


Figure 9. *Quicksat* DMSJ Engines.

Exo-Atmospheric Systems

The *Quicksat* features 4 tail-rockets for additional thrust during the transonic flight regime and the final pull-up maneuver before staging. As the main low and high speed propulsion systems are air-breathing, the tail-rockets are needed to facilitate a low-q staging exo-atmospherically. Additionally, the use of rockets during transonic greatly reduces system risk and performance demands on the turbine engines.

The tail-rockets use JP-7 and H_2O_2 propellants, both non-cryogenic fluids for ease in handling and extended ground-hold times. The engines are a closed-cycle design with parallel flow turbine gases that are derived from a hydrogen-peroxide catalyst pack. The configuration reduces pump weight by eliminating the need to boost the fuel to excessively high pressures normally required for a bipropellant preburner design. The engines are capable of multiple restarts and are capable of being gimbaled. Table 7 provides some key engine performance parameters. The engines provide a vehicle thrust-to-weight (T/W) ratio of 0.475 at takeoff conditions. This provides a similar thrust level as the turbine system used during takeoff. In the event of a turbine-engine failure during takeoff and climbout the tail-rockets can be used to facilitate a mission abort.

Table 7. *Quicksat* Tail-Rockets.

Parameter	Value
Vacuum Thrust (lbs)	107,520
Vacuum Isp (s)	329.9
SLS Thrust (lbs)	88,073
SLS Isp (s)	270.2
Vacuum T/W	90.5
Expansion Ratio	50 : 1
Mixture Ratio	7.0
Chamber Pressure (psi)	2,200

Table 8. Upperstage Rocket Engine.

Parameter	Value
Vacuum Thrust (lbs)	102,940
Vacuum Isp (s)	336.1
Vacuum T/W	73.9
Expansion Ratio	100 : 1

As previously mentioned a derivative of this engine is used on the expendable upperstage system. The upperstage version uses a slightly smaller engine powerhead with a larger expansion ratio nozzl. The engine provides a system thrust-to-weight ratio of 1.15 at the Mach 9 ignition and staging condition. Table 8 provides a performance summary for this engine system. The synergy between these two engines results in a significant reduction in the propulsion development costs and program risk.

D. Aerodynamics

The *Quicksat* booster is a two-dimensional lifting-body design. This shape is not particularly efficient aerodynamically at subsonic speeds, but offers a number of advantages at supersonic and hypersonic speeds. The forebody is designed to minimize flow non-uniformity and provide a high mass capture and total pressure recovery to the engines. The compression ramp angles and lengths result in a shock-on-lip (SOL) condition at Mach 8.5, with an initial turn angle of 5^o and a maximum turning angle of 11^o. The leeward surface of the vehicle is designed to nominally provide a zero-incidence surface during flight for minimum drag. It is not possible to completely shadow the upperstage, thus a small drag penalty is always incurred. The aft, underside section of the vehicle is designed to provide efficient flow expansion area for the turbine and DMSJ engine exhaust.

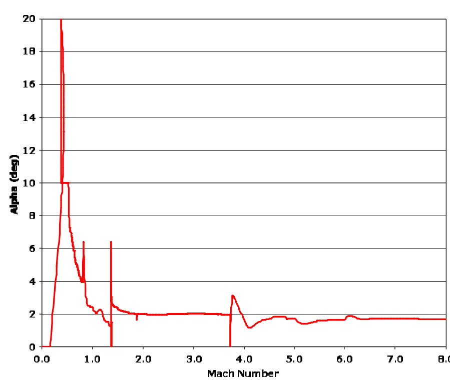


Figure 10. Alpha vs. Flight Mach Number

The wing size is dictated by a requirement to keep takeoff speeds under 300 kts and shaped for high-speed flight. The wing characteristics include a sweep angle of 65^o, a taper ratio of 0.2, a span of 52.6 ft, and a variable thicknessto-chord ratio of 0.04 at the root and 0.02 at the tip. The wing structure is designed to sustain a load factor of 1.75 times the GTOW of the system.

Figure 10 provides the angle-of-attack (AOA) profile for the simulated flight path as a function of flight Mach number. The AOA profile is determined using a Linear Feedback Controller (LFC) which minimizes the error with the desired and actual q-boundary. The AOA spikes that appear are attributable to thrust deltas during the ignition or shut-down of tail-rockets and TBCC to DMSJ transition point. The LFC response to a thrust-delta is not instantaneous and requires a few seconds to damp out the vehicle impact. For the majority of the flight, the vehicle experiences an average AOA of 2.5^{o}. Figures 11 provides the corresponding aerodynamic lift and drag coefficients for the simulated flight path as a function of Mach number. The intermittent spikes in the aerodynamic coefficients coincide with the AOA spikes, whose cause has already been explained. Additionally, the large increase in the drag coefficient through the transonic flight regime is evident, illustrating the need for the tail-rocket assistance in this Mach number envelope.

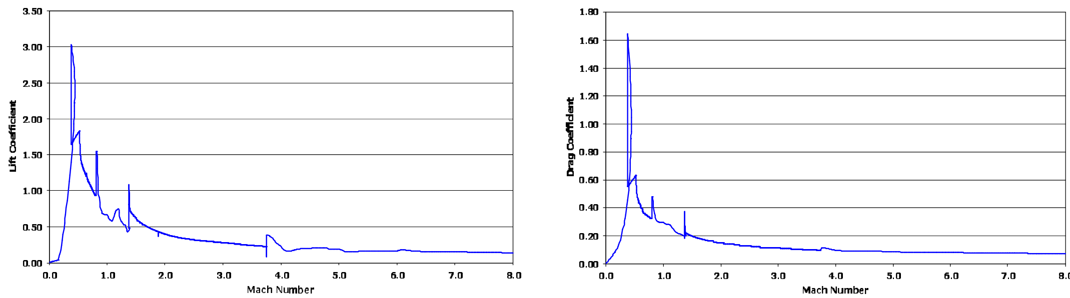


Figure 11. Lift and Drag Coefficients vs. Flight Mach Number

E. Aeroheating and Thermal Protection Systems

As the vehicle accelerates into the high Mach number flight regime, the flowfield temperatures around the *Quicksat* begin to increase and quickly exceed the material limits of the aluminum and Gr/Ep airframe structure. All external surfaces are required to be covered with high-temperature materials to protect the vehicle. Fortunately, due to the relatively low hypersonic Mach number envelope, all thermal protection systems are passive (i.e. no active cooling required).

The airframes windward surfaces and aftbody are covered with a ceramic tile known as Toughened Unifibrous Flexible Insulation (TUFI) using the AETB (8 pcf) type fibrous insulation substrate[27]. Strain Isolation Pads (SIPs) are used in conjunction with a room temperature vulcanizing (RTV-560) silicone adhesive to attach each tile to the airframe. The leeward surfaces of the airframe are covered with a silica-based batting called Advanced Flexible Reusable Surface Insulation (AFRSI) blankets. These blankets are attached with mechanical fasteners to the airframe. The vehicle has sharp leading edge radius of 2 inches which results in stagnation point temperatures exceeding 3,820 R and requires the use of a hafnium-diboride (HfB_2) Ultra High Temperature Ceramic (UHTC).

The bulk area of the upper and lower wing and tail surfaces are covered with a material called Conformal Reusable Insulation (CRI), while the control surfaces have a Carbon/Silicon-Carbide (C/SiC) face sheet and the leading edges are covered with the HfB_2 UHTC.

The TPS materials are designed to ensure the backside temperature that interfaces with the airframe structure does not exceed 760 R and the wings do not exceed 950 R. The transition line between the placement of TUFI tiles and AFRSI blankets is based on the maximum surface temperature encountered at that location on the vehicle and maximum temperature limits of the TPS material. The average weight of all the TPS materials is 1.239 lbs/ft^2.

VI. *Quicksat* Operations, Safety/Reliability, and Mission Effectiveness

A. Operational Assessment

Aggressive processing advantages (inherent IVHM, fast integration, access, leak checking) were assumed throughout the system. The overall operational approach is to have a three-process facility dis-aggregating some top-level turnaround functions. The envisioned facilities include a main hanger, pre-flight propellant-loading canopy, and post flight purge/safing exposed canopy. Specific activities such as vehicle integration, propulsion checkout, and TPS maintenance occur in the main hanger. Purging of the multiple propulsion systems occur in the canopies as well as loading of all main propellants. This scenario enables the main turnaround functions to be separate from purging sand propellant loading, activities that would normally shut down a vehicle processing facility. Specific activity categories envisioned in this flow include the following:

- Ferry From Landing to Post Flight Canopy
- Purging/Safing in Post Flight Canopy
- Ferry to Main Hanger
- Ground Processing In Main Hanger
  - TPS Post Flight Inspection and Repair
  - Other Subsystems Post Flight Inspection and Repair
  - ACS Bank Catalyst Pack Inspection and Repair
  - Booster Tail Rocket Inspection
  - Turbine Engine Inspection
  - DMSJ Inspection
  - Upperstage + SMV Integration
- Ferry to Propellant Loading Canopy
- Total Propellant Loading (all propellants) in Pre Flight Canopy
  - Booster JP-7 Propellant
  - Booster Main H_20_2 Propellant
  - Booster ACS H_20_2 Propellant
  - Upperstage JP-7 Propellant
  - Upperstage H_20_2 Propellant

Aggressive operational assumptions were made for most of the above activities, including assumptions of parallel processing when appropriate. Fast turnaround is possible given automated checkout capability (i.e. IVHM), clear access, and parallel processing.

B. Safety and Reliability

The top-level safety assessment determined Loss of Mission (LOM) and Loss of Vehicle (LOV). Aggressive subsystem safety assumptions (such as 75% improvement from expendable launch vehicle subsystem failure rates) were assumed. Substantial abort and landing area flexibility advantages with turbine engine systems were available, relative to other space access systems. Table 9 shows the overall LOM and LOV for the *Quicksat* TSTO architecture. Given the flyback capability of the *Quicksat* booster, its overall reliability is substantially higher than that for the Upperstage. The LOV is around one thousand flights, 4-5 times better than the current Space Shuttle, for the entire system. The large number of engines in one reason for the lower than expected LOM and LOV metrics. Decreasing the overall number of engines, increasing each engine's reliability, and improving overall subsystem reliability would help to improve overall safety.

Table 9. *Quicksat* TSTO Baseline: Reliability Assessment†.

Item	*Quicksat*	Upperstage	Total
Loss of Mission (LOM) [Mean Time Between Sorties]	1,928 sorties	738 sorties	534 sorties
Loss of Vehicle (LOV) [Mean Sorties Before Loss]	3,893 sorties	1,329 sorties	991 sorties

† - 3 *Quicksat* Booster fleet performing 50 sorties per year operating for 15 years

C. Mission Capture Analysis for Uncertain Future Demand

A mission capture assessment was performed to determine the cost to meet various operational requirements for future peace and wartime scenarios. The important parameter being examined here is mission capture rate or the percentage of required sorties flown. This is dependent upon the turnaround time (between when a vehicle lands and then next takes off) of an individual vehicle and the number of available vehicles in the fleet. The sortie capture rate is directly proportional to fleet size and inversely proportional to turnaround time. The fundamental question being addressed here is the following: can a given fleet of military space planes (such as the *Quicksat*) with a given turnaround time, meet the required number of sorties (capture rate) for various envisioned future demand scenarios? Previously developed MSP requirements were used for this analysis (see Table 10). These requirements indicate the required number of sorties during various future environments, whether during peacetime, exercises, or war (either sustained, surge, or in an emergency capacity). The particular missions modeled here were those for rapid strike rather than space access. SMV delivery is not envisioned to take more than several flights per year. Monte Carlo simulation was used to place ranges on the types and length of future wars. These distributions were applied on parameters such as the number of wars, starting date, duration, and sortie rate (see Table 11). Thus for a particular combination of vehicle turnaround time and fleet size, a Monte Carlo simulation was performed to see how much of that "future demand" the fleet is able to meet (the capture rate).

The assessment process included the creation of a flight capture model in MS Excel and ModelCenter© collaborative design environment for probabilistic simulation of future demand. Two design variables were used consisting of fleet size and turnaround time (days) with 4 settings for each variable (16 runs x 1,000 simulations = 16,000 model function calls) requiring approximately 14 hours of computation time for all function calls (average Pentium PCs with ~1GB RAM).

Table 10. Military Space Plane (MSP) Mission Requirements[12].

Requirement	Threshold	Objective
SORTIE UTILIZATION RATES (for each MSP)		
Peacetime Sustained (sorties/day)	0.10	0.20
War/exercise sustained – 30 days (sorties/day)	0.33	0.50
War Exercise surge – 7 days (sorties/day)	0.50	1.00
Emergency Surge (sorties/day)	3.00	4.00
TURN TIMES		
Emergency war or peace (hours)	8	2
Peacetime sustained (hours)	48	24
War/exercise sustained – 39 days (hours)	18	12
War/exercise surge – 7 days (hours)	12	8
SYSTEM AVAILABILITY	0.80	0.95

Large fleets will be required to meet the specific future demand as projected in this analysis. Figure 14 displays the probabilistic output for one of the Monte Carlo cases, where turnaround time for a vehicle is 4 hours in a fleet of 2. Table 12 gives the complete results for all the cases. For a fleet of 2 Quicksat boosters, each with a turnaround time of 4 hours, only slightly more than one third (38.5%) of the missions can be captured (with a 90% certainty). For a fleet of 14 Quicksat boosters, each with a turnaround time of 24 hours, only slightly more than half (54.6%) of the missions can be captured (with a 90% certainty).

Table 11. Noise Variable Probability Distributions.

Item	Distribution Type	Minimum	Most Likely	Maximum
Number of Wars (in 30 years)	Uniform	5	-----	15
War Starting Date	Uniform	1/1/2025	-----	12/31/2050
War Duration (days)	Triangular	7	30	365
War Flight Rate-for all MSPs (sorties per day)	Triangular	0.33	10	60

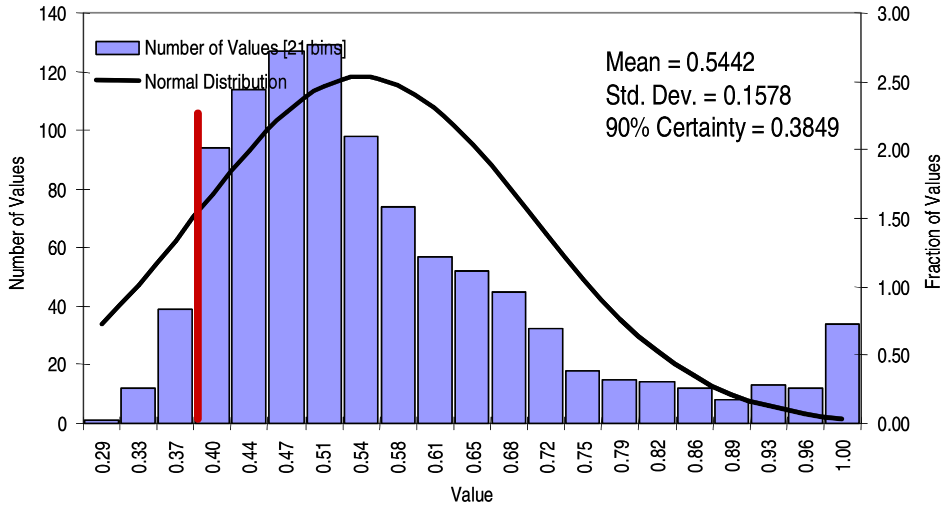


Figure 12. Mission Capture Rate (1,000 Monte Carlo Simulations): Frequency Distribution for Turnaround Time of 4 hours and Fleet Size of 2

Table 12. Mission Capture Rate versus Turnaround Time and Fleet Size.

90% Capture Rate Certainty (1,000 Monte Carlo Simulations)					
		Turnaround Time (Hours)			
		4	**8**	**12**	**24**
Quicksat Fleet Size	**2**	0.385	0.223	0.165	0.101
	6	0.850	0.577	0.433	0.276
	10	0.986	0.794	0.642	0.425
	14	1.000	0.919	0.781	0.546

VII. System Trade Studies

A series of trade-studies have been conducted to ascertain the expanded capabilities as well as impacts to the *Quicksat* based on a number of design features in the nominal system. These studies included an examination of new orbits, alternative low-speed propulsion systems, staging conditions, and propellant options.

A. Polar Mission Capability

While the nominal *Quicksat* design is capable of placing either an SMV or 10,020 lbs. of cargo into LEO at a 28.5^{o} inclination, the capability to place cargo into polar orbits was evaluated. For these missions, the *Quicksat* will launch from Vandenberg Air Force Base in California. The target orbit is slightly retrograde at a 98.7^{o} inclination. An identical upperstage to that used for the LEO cargo missions is used for these missions, thus the payload capability varies depending upon the desired final circular altitude. Table 13 provides the payload capability versus altitude for the polar missions. For all cases, an aluminum payload fairing with a weight of 1,535 lbs. is assumed.

Table 13. Polar Mission Payload Delivery.

Altitude (nmi)	Payload (lbs)
150	8,900
200	8,650
300	8,055
450	6,895
600	5,465

For the sun-synchronous orbit at 450 nmi, the *Quicksat* can deliver 6,895 lbs. of payload. When conducting this mission, the upperstage is required to perform an additional insertion burn to circularize the orbit after the main engine cut-off (MECO) injection point. Removal of the expendable upperstage hardware from orbit is accomplished in a separate delta-V (100 fps) maneuver after cargo release. The propellants required for these maneuvers are within those available from the current upperstage design.

B. Alternate Low-Speed Engines

An alternate set of turbine engines were considered for the *Quicksat* design. These engines are currently at a higher technology readiness level (TRL) than the nominal engines and are derived from work under the Air Force Versatile Affordable Advanced Turbine Engine (VAATE) program[28]. At sea-level conditions, the thrust output of these engines is approximately 27% lower than the nominal engines. The alternate engines also have a lower T/W than the nominal due to a more conservative approach towards material selection and availability.

The six engines on the *Quicksat* were replaced with this alternative VAATE set. It was evident that the thrust reduction experienced with these engines was going to significantly impact the acceleration, thus the *Quicksat's* tail-rockets were employed at their half-throttle setting from Mach 1.4 till the DMSJ transition at Mach 3.75. This extended rocket burn required the addition of oxidizer mass on the vehicle. While this increased the system GTOW, the rocket burn resulted in a significant reduction in the time to staging, thus the vehicle achieved more optimal acceleration levels and reduced propellant requirements due to the shorter flyback range requirements. This effect helped to offset the impact of carrying additional oxidizer for the rocket burn and lower turbine engine T/W, when coupled with a denser vehicle due to the high oxidizer fraction. Table 14 provides a comparison of the nominal *Quicksat* and the booster configured with the alternate turbine engines.

Table 14. Alternate Turbine Engine Study.

Parameter	Nominal System	with Alternate Engines	Relative Difference (%)
System GTOW (lbs)	741,670	909,515	+ 22.6 %
Booster Dry Weight (lbs)	167,840	197,940	+ 17.9 %
Upperstage GLOW (lbs)	89,515	86,685	-3.2 %
Upperstage Dry Weight (lbs)	4,275	4,165	-2.6 %
Total Length (ft)	123.6	130.9	+5.9 %

C. Staging Mach Number Sensitivity

The nominal *Quicksat* vehicle is designed to release the upperstage system at a Mach number of 9.0. This important parameter can have a strong impact on the overall size and weight of the system. A higher release Mach number will put the performance burden on the booster instead of the upperstage. This reduces the amount of expendable hardware and subsequently recurring cost by allowing for a smaller upperstage system. This gain is metered though by the resultant larger booster, which typically increases RDT&E costs for the program. Additionally, the ability to obtain low-q (<25 psf) staging conditions is also impacted by the staging Mach number.

Table 15. Staging Mach Number Sensitivity.

Parameter	Mach 8	Mach 9 (Nominal)	Mach 10
System GTOW (lbs)	684,308	741,760	910,666
Booster Dry Weight (lbs)	154,670	167,840	199,110
Upperstage GLOW (lbs)	95,115	89,515	80,456
Upperstage Dry Weight (lbs)	4,492	4,273	3,917
Total Length (ft)	118.3	123.6	134.6

Two alternate staging scenarios were considered for the *Quicksat* performing the SMV deployment mission. The first was for a Mach 10 staging condition, accelerating for two Mach numbers on the tail-rockets after initiating the pullup maneuver off the high-q flight path at Mach 8. The second scenario was to initiate the pullup maneuver one Mach number sooner (Mach 7) than the nominal and attempt to release the Upperstage at Mach 8 with q<25 psf. The results of these two cases are presented in Table 15.

The vehicle GTOW increased by 23% and booster dry weight by 18.6% when staging at Mach 10. For the Mach 8 staging case, the impact to the system appears to be less drastic, with only a 7.7% reduction in system GTOW and 7.8% booster dry weight reduction. For both scenarios, the upperstage was less sensitive to these perturbations, resulting in a gross weight increase of 6.3% for the lower Mach number staging and a reduction of 10% in the higher Mach number staging scenario. Based on these results, it is likely that the choice of staging Mach number will not have a significant impact on the recurring cost of the upperstage, but will be an important factor for the RDT&E costs for the booster.

D. Alternate Propellant Combination

To facilitate the responsive nature of the system, easily storable and non-cryogenic fluids were selected for use on the *Quicksat* system. Using this category of fluids comes at the expense of engine performance. To characterize this impact, the use of liquid oxygen (LOX) instead of H_2O_2 as the oxidizing agent was examined. LOX will offer a higher engine specific impulse for the rocket systems, but will come at the expense of tank insulation weight, lower density (71.2 vs. 89.5 pcf), and more complex main propulsion system (MPS) and ACS flowpaths. For the SMV delivery mission, the *Quicksat* was redesigned using LOX instead of H_2O_2. Staging conditions of Mach 9 (the nominal flight path) and Mach 10 were examined. Table 16 provides a comparison of this vehicle system relative to the nominal propellant scenario.

Table 16. Oxidizer Study Results.

Parameter	MACH 9 STAGING		MACH 10 STAGING	
	JP-7 and H_2O_2 Propellants	JP-7 and LOX Propellants	JP-7 and H_2O_2 Propellants	JP-7 and LOX Propellants
System GTOW (lbs)	741,760	691,130	910,666	771,975
Booster Dry Weight (lbs)	167,840	164,025	199,110	181,220
Upperstage GLOW (lbs)	89,515	83,385	80,456	72,615
Upperstage Dry Weight (lbs)	4,275	4,410	3,917	3,935
Total Length (ft)	123.6	122.6	134.6	129.1
Booster Engine Vacuum T/W	90.1		90.1	
Upperstage Engine Vacuum T/W	75.1		75.1	
Booster Engine Vacuum Isp (s)	329.9	343.8	329.9	343.8
Upperstage Engine Vacuum Isp (s)	336.1	353.4	336.1	353.4

Of considerable interest is the staging Mach number sensitivity. The results indicate that when staging at higher Mach numbers, the tail-rocket performance becomes a critical driving factor. The performance benefit in terms of

GTOW was a reduction of 15.2% for utilizing LOX instead of H_2O_2 at Mach 9 and 6.8% when staging at Mach 10. Comparing the staging Mach number sensitivity, while the H_2O_2 oxidizer resulted in a 22.7% performance hit when staging at Mach 10 instead of Mach 9, the use of LOX results in only a 11.7% increase in GTOW. Thus, the LOX oxidizer substitution appears to be less sensitive to the staging Mach number than H_2O_2. Additionally, the upperstage gross weight was reduced by only 10.1% for the H_2O_2 oxidizer, but LOX case results in a 12.9% reduction. In terms of upperstage hardware, the LOX case reduced this weight by 10.7% compared to 8.4% for H_2O_2.

VIII. Summary and Conclusions

The *Quicksat* vehicle as illustrated in Figure 13 is a promising candidate for meeting the future space-access needs of the United States military. With assumptions regarding technology maturation, a system configured to deploy a SMV to LEO has a gross takeoff weight of 741,670 lbs. While the expendable upperstage has a total gross weight of 89,515 including the SMV payload, the throw-away hardware only comprises 4,275 lbs. of this total. A number of design decisions and compromises have been made to facilitate a more operationally responsive system. These include:

- Selection of a horizontal takeoff and landing configuration for aircraft-like operations
- Use of non-cryogenic propellants
- Utilization of a 95% pure hydrogen-peroxide instead of demanding a higher purity grade
- Simplified, hydrogen-peroxide monopropellant ACS systems
- Use of an all-passive TPS
- Extensive utilization of IVHM

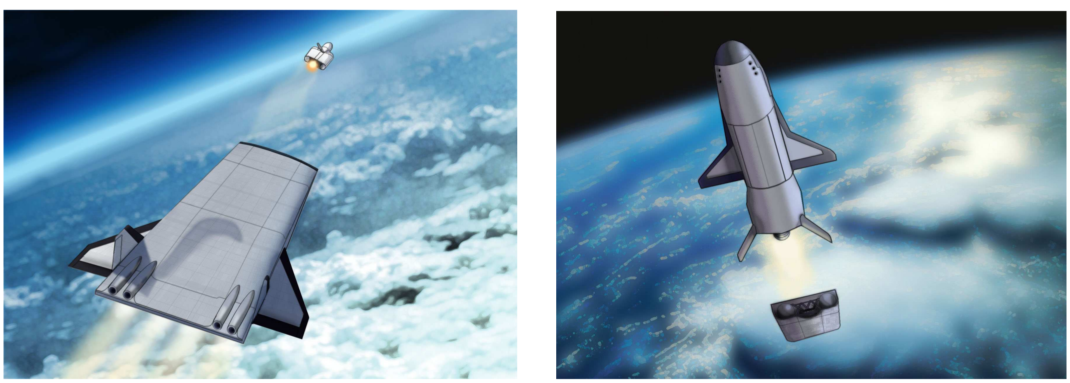


Figure 13. *Quicksat* Flight Illustrations

The flexibility of the system was illustrated as it applies to supporting a variety of missions. Among the highlighted capabilities of the vehicle are: a) ability to deploy a 13,090 lbs SMV to LEO, b) support for hypersonic strike missions and delivery of up to 6 ECAVs at a 4,440 nmi. range, c) transportation of 10,020 lbs. of cargo to LEO, and d) ability to perform polar-orbit insertions at a variety of altitudes for payloads ranging from 5,500 to 8,900 lbs.

IX. Acknowledgements

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