Solution Space Screening of a Hypersonic Endurance Demonstrator

Amit Oza, Gary Coleman, Lex Gonzalez, Bernd Chudoba

Mechanical and Aerospace Engineering Department
University of Texas at Arlington

Paul Czysz

Hypertech Concepts LLC
St. Louis, MO

Abstract

The Solution Space Screening for a Hypersonic Endurance Demonstrator program was a two and one-half month study to:

- Demonstrate the Aerospace Vehicle Design (AVD) Laboratory sizing process applied to a fast turnaround project by using a dedicated knowledge-harvesting approach coupled with a unique sizing methodology to represent the first step in the conceptual design phase.
- Identify and visualize the solution space available for a hypersonic endurance (20 to 30 min) demonstrator that employs an air-breathing propulsion system.
- Propose prospective baseline vehicle(s) based on (1) available industry capability and (2) high-priority research (technology) required.
- Demonstrate a best-practice product development and technology forecasting environment that integrates the key team members, including (1) manager (decision maker), (2) synthesis specialist (integrator), and (3) technologist (disciplinary researcher).

In an effort to increase the air-breathing endurance capability of current hypersonic research aircraft (i.e., X-43, 7 seconds; X-51, 5 minutes), the NASA Langley Research Center (LaRC) Vehicle Analysis Branch (VAB) has tasked the Aerospace Vehicle Design (AVD) Laboratory at the University of Texas Arlington (UTA) with exploring the technical and operational solution space for a 20 minute to 30 minute cruise endurance demonstrator operating at Mach 6 to Mach 8. The primary challenge has been to explore that portion of the available industry capability that will require future technology complementation, with the aim of arriving at a technically feasible demonstrator within a given time frame and

budget. Consequently, this study necessitated the use of a simulation capability to assess and visualize the physical design drivers and sensitivities of the operational and technical domain.

The overall goal of the project has been the development of a concept for an airbreathing hypersonic endurance flight vehicle to increase our existing understanding and knowledge-base regarding air-breathing propulsion, associated thermal protection systems (TPS), and any operational peculiarities of long-duration hypersonic flight (e.g., maintenance, turnaround, practical range, etc.).

This report introduces the AVD Laboratory's product development and technology forecasting methodology as applied to the problem introduced above. Because the focus of this activity has been on the exploration of the available solution space, a unique screening process has been employed to assess the implication of (a) the mission, (b) the baseline vehicle, and (c) the operational scenarios on key research objectives to be defined.

This study concludes that an air-launched, liquid-hydrogen-fueled, 30 minute Mach 6 demonstrator (with 10 minute Mach 8 capability) provides the largest feasible solution space of the trades that have been examined (i.e., largest design margins with lowest technical risk) when compared with a kerosene-fueled equivalent.

Mission Requirements and Research Objective

The overall objective of this study is to explore and visualize the technical solution space for a hypersonic endurance demonstrator.

The NASA VAB operational and technology requirements for this demonstrator are:

- scramjet test vehicle
- reusable
- unmanned
- multiple aircraft (at least three test articles)
- entry into service circa 2020

To evaluate the technical feasibility of such a research vehicle, the following mission requirements are selected by NASA VAB:

- design speed: Mach 6 to 8 (possibly Mach 12)
- maximum endurance: 20 to 30 minutes
- payload: test instrumentation
- fuel selection: hydrogen or kerosene
- operation: straight line or point-to-point

The broad direction specified by VAB in June 2010 translates into a large *n*-dimensional design trade space. Please note that the VAB-defined design mission is considered a starting point only, thus the mission itself is a variable. Since the targeted flight regime is novel terrain for the designer, it is essential to trade flight vehicles capable of satisfying alternative missions. Clearly, the sizing exposure will iteratively enable the designer to define and justify a feasible baseline mission and baseline vehicle combination.

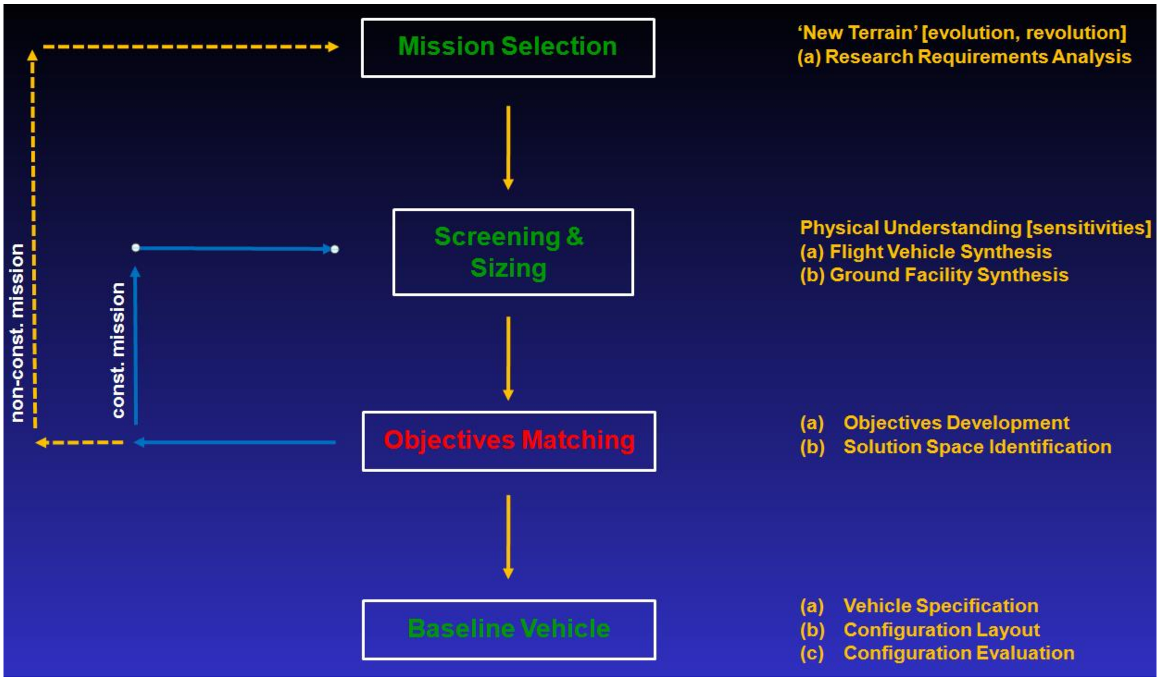


Figure 1. Iterative nature of the mission & objectives & baseline vehicle(s) selection process.

Figure 1 illustrates the iterative nature of the mission selection process. The unknown-terrain nature of a 20 to 30 minutes air-breathing demonstrator requires a modification of the traditionally utilized product development procedures. As shown in this figure, the AVD Laboratory screening & sizing methodology is the primary tool utilized to arrive at a (a) baseline mission which harmonizes with (b) the overall research objectives and (c) the baseline vehicle.

The sizing team is tasked to execute alternative missions resulting in prospective baseline vehicle(s). Throughout the sizing phase, the involved mindsets (*managerial* (M), *synthesis* (S), *technology* (T)) are successively gaining physical insight into the characteristic of the product. Consequently, true product understanding is evolving while the solution space alternatives are perturbed. The mission-trading needs to happen during the *parametric sizing* (PS) phase, an essential task before a baseline objectives catalogue can be formally defined. Clearly, the traditional notion of pre-defining the mission and objectives is not feasible with a product of such novel characteristics. The screening & sizing approach becomes the enabling means to arrive at a balanced set of (a) mission, (b) objectives, and (c) baseline vehicle(s).

Due to project time constraints, the present research undertaking excludes the research objectives development and matching step. Figure 2 illustrates the finally implemented baseline vehicle development sequence for the present study by omitting the *objectives matching* step shown in Figure 2. It is recommended to formally complement the existing study at a later step by including the *objectives matching* logic as an essential ingredient supporting decision-making.

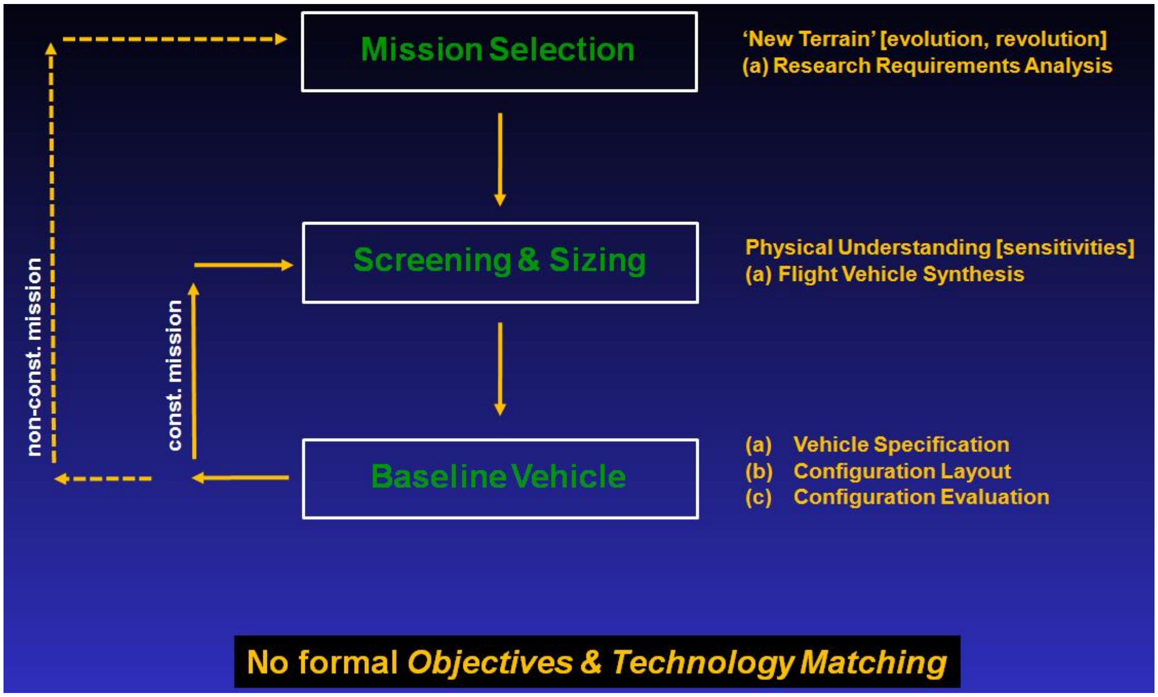


Figure 2. VAB/AVD Laboratory baseline vehicle development sequence.

Data-Base and Knowledge-Base Review of Hypersonic Demonstrators

A key component enabling the development of hypersonic flight test vehicles is effective management of the knowledge-generation and knowledge-preservation activity. As illustrated before, the research approach implemented places emphasis on elevating the understanding with regards to project aims and objectives, overall resulting in an informed and structured approach. In the present context, the research challenge is best formulated with the question: How to efficiently synchronize the *understanding available* with the *understanding required* to specify a feasible air-breathing hypersonic demonstrator with the technical resources, team support and time available? Due to the limited timeframe available, the DB and KB assistances have become indispensable to expedite the learning process.

The scope and complexity of the present research undertaking is seen as *catalyst opportunity*, which translates into a chance to evaluate past and present data and knowledge for its utilization in the context of a technically demanding demonstrator with not seen-before performance capability. Table

1 lists high-speed flight vehicles of direct relevance in the context of a future endurance testbed.

The following two sub-chapters present the flight vehicle conceptual design data-base (DB) and knowledge-base (KB) as developed and utilized for the present research undertaking. The main flight vehicle research & design work is directly benefitting from this dedicated DB & KB foundation.

Table 1. Past Hypersonic Demonstrator Projects and Programs

Start Date	End Date	Project/Program	Organization	Description
1952	1968	X-15	North American/NASA/USAF	Mach 6 to 8 rocket powered hypersonic research vehicle. 3 test vehicles, 199 flights
1957	1959	Griffon 02	Nord Aviation	Manned ramjet demonstrator
1962	1971	D-21	Lockheed	Mach 4 ram-jet UAV launched from the SR-71
1964	1965	MHCV	Lockheed	*Manned Hypersonic Cruise Vehicle*, some description of a demonstrator
1967	1968	UHTV	Vought	*Universal Hypersonic Test Vehicle*, flexible and modular hypersonic test vehicle
1967	1969	X-15 Delta	North American/NASA	Delta wing X-15
1969	1970	HYFAC	MAC/NASA	*HYpersonic FACilities* study, 32 rocket/air-breather configurations explored
1969	1969	X-15 SERJ	Marquardt	*Super Charged Ejector Ramjet* (RJ) X-15
1969	1969	X-15 Scram	Boeing	Scramjet (SJ) X-15
1970	1972	IGV	MAC/USAF	Incremental growth vehicle
1972	1972	PPD Scramjet Test Vehicle		*Propulsion Performance Demonstrator*, vertical takeoff cone with four scramjets around its periphery; rocket acceleration to test speed
1975	1977	X-24C NHFRF	Lockheed/NASA	*National Hypersonic Flight Research Facility*, B-52 launched, Mach-4.8 70,000 lbs vehicle; envisioned as a X-15 type flight operation
1976	1980	ASALM	Martin	Hydrocarbon fuel air-launched cruise missile
1980	1981	SLRV		*Shuttle Launch Research Vehicle*, Mach 8 aerodynamic configuration demonstrator
1985	1985	RSFTP		*Ramjet/Scramjet Flight Test Program*, M 4-7 F-15 launched vehicle
1989	1990	HYPAC	MBB	Sänger demonstrator study
1990	1995	BMFT	MBB/UK/UT/Dornier/MTU	Hypersonic technology program, HYTEX and RADUGA D2
1996	2004	X-43A	NASA LaRC/NASA Dryden	Scaled hypersonic scramjet demonstrator
1999	1999	SSTO Demonstrator	Hyper Tec	RBCC hypersonic demonstrators based on HYFAC Studies
1999	1999	Trailblazer	NASA Glenn	Modification of the NASA wing body to include RBCC and TBCC
2000	2002	X-43B	NASA LaRC/NASA Dryden	Reusable combined cycle demonstrator
2001	2002	X-43C	NASA LaRC/NASA Dryden	Hydrocarbon variant of the X-43A, RJ/SJ
2002	Present	HYFLY	Boeing/DARPA	Mach 6 ramjet powered cruise missile demonstrator
2003	Present	X-51A	Boeing	Scramjet propulsion research vehicle
2005	2007	X-43D	NASA LaRC/NASA Dryden	HYFLITE III, M 12 variant of the X-43A
2007	2007	HyCAUSE	DARPA/ADST	2-stage sounding rocket for hypersonic propulsion demonstration
2007	2008	Falcon HTV-3X	Lockheed/DARPA	TBCC hydrocarbon hypersonic demonstrator

Overall and Reduced Trade Space

The challenge of designing a 20 to 30 minutes hypersonic endurance demonstrator is embodied in the fundamentally unknown vehicle solution space and solution topography. Based on the best understanding available at the outset, it is required to define an initial or 'start' trade-space by taking relevant constraints and requirements into account.

Table 2. Overall Trade-Space Concepts, Categories and Options

CONCEPT/CONFIGURATION	CATEGORIES	TOTAL TRADE OPTIONS	SELECTED TRADES
Mission Concept	Mach number and duration	design Mach 6	design Mach 6
		design Mach 8	design Mach 8
		design Mach 12	
		test duration	0 to 30 minutes
	test range options	point-to-point	point-to-point
		fly-back	fly-back
Staging Configuration	SSTC	integrated booster, propellant and oxidizer tanks	
	TSTC	air launch	air launch
		expendable booster	expendable booster
		oxidizer drop tanks	
	MSTC	any combination of TSTC options	
Operations Concept	launch	HTO	
		VTO	
	recovery	HL	
Hardware Concept	lift & volume supply	lifting body	lifting body
		wing body	
	propulsion concept: (accelerator engine)	RKT	RKT
		TJ	
		RBCC	
		PDE	
	propulsion concept: (cruise engine)	SJ	
		dual mode RJ/SJ	dual mode RJ/SJ
		RKT	
	fuel selection	hydrogen	hydrogen
		methane	
		kerosene	kerosene
	primary & secondary controls	aerodynamic	
		mix	mix

It is to be expected that this initial trade-space, with associated constraints & requirements, will naturally mature during the configuration exploration phase. The configuration exploration phase is tasked to identify two primary solution-space areas of significance: (a) the solution space area based on presently available industry capability, and (b) the solution space area requiring prospective future technologies. Dependent on the establishment of overall project objectives (technology development, low-cost & risk demonstrator, etc.), the physical understanding generated will help to refine the initial trade-space scope.

Clearly, the early identification of the *correct* trade-space and technology combinations requires using logic, organization and transparency before any baseline design can be selected. This approach will provide the greatest insight into the design problem within the time assigned.

The process of rectifying thus reducing the theoretical trade-space available consists of: **(a)** Formulate a classification scheme for the design options available. **(b)** Focus the DB/KB development and team learning on relevant design trade-studies. **(c)** Harmonize pre-selected trades with VAB's team's long-term research objectives.

Table 2 presents the overall trade-space adopted classification scheme addressing (1) *mission concept*, (2) *staging configuration*, (3) *operations concept*, and (4) *hardware concept*. If all of the options shown in this general trade-space Table 2 would be executed, the total number of trades would exceed $90{,}000^{+}$ cases.

Applying the DB/KB lessons-learned and harmonization with VAB's research objects further allows reducing and focusing the trade-space:

1. ***Mission Concepts*:** Mach 6 and Mach 8 design trades are given priority; point to point and fly-back options are explored. Mach 12 has been eliminated.

2. ***Staging Configurations and Operational Concepts*:** HyFAC (Reference 3) determined that air-launch and vertical take-off provide the largest research value for a hypersonic demonstrator relative to horizontal takeoff and single-stage vehicles. Air-launch and vertical takeoff with a booster allow for smaller and lighter demonstrators which can focus on testing the high-speed regime. Consequently, the trades selected will focuse on air-launch and vertical takeoff options.

3. ***Hardware Concepts*:** Alternative vehicle concepts have been grouped as follows:

    a. *Lifting body* - for this speed range, the lifting body provides improved volumetric efficiency over wing bodies; therefore, the lifting body has been selected as the sole volume supply option (Reference 3, 4).
    b. *Off-the-shelf accelerator rocket* – the off-the-shelf rocket motor (low risk item) is selected to accelerate the ramjet to start Mach number.
    c. *Dual-mode ramjet cruise engine* - the dual mode ramjet/scramjet is selected to allow for testing of both modes with a single vehicle.
    d. *Fuel selection limited to liquid hydrogen and kerosene* - the fuel selection is determined by the operational vehicle envisioned; for possible reusable TSTC launch vehicles, hydrogen appears to be the most likely choice. Kerosene appears to be an operationally practical option for a military hypersonic point-to-point vehicle. Consequently, both options (hydrogen and kerosene) are explored.

The above reasoning is reducing the overall trade-space to 10 trade studies, consisting of a constant test vehicle concept (lifting body, dual mode ramjet/scramjet, horizontal landing) with varying (a) design Mach number, (b) endurance, and (c) launch concept. The reduced trade-space is introduced with Table 3 and Figure 3.

Table 3. Summary of Design Trades Executed

	MISSION				**STAGING CONFIGURATION**		**OPERATIONS CONCEPT**		**HARDWARE CONCEPT**		
	Atmospheric			Test Range Options	TSTC		Launch		Fuel Selection		
Trade #	design Mach 6	design Mach 8	test duration	point-to-point	air launch	expendable booster	HTO	VTO	hydrogen	kerosene	dual fuel
1	x		0 - 30 min	x	x		x		x		
2		x	0 - 30 min	x	x		x		x		
3	x		0 - 30 min	x	x		x			x	
4		x	0 - 30 min	x	x		x			x	
5	x		0 - 30 min	x	x		x				x
6		x	0 - 30 min	x	x		x				x
7	x		0 - 30 min	x		x		x	x		
8		x	0 - 30 min	x		x		x	x		
9	x		0 - 30 min	x		x		x		x	
10		x	0 - 30 min	x		x		x		x	

For each individual trade study, the total system design solution space is identified and visualized with the AVD Laboratory parametric sizing program AVD^{sizing}. This 'best practice' sizing approach has been developed through a thorough review of parametric sizing processes and methods from the 1960s to present for subsonic to hypersonic vehicles, see Reference 5. With this framework in place, the available solution space is identified considering both technical and operational constraints.

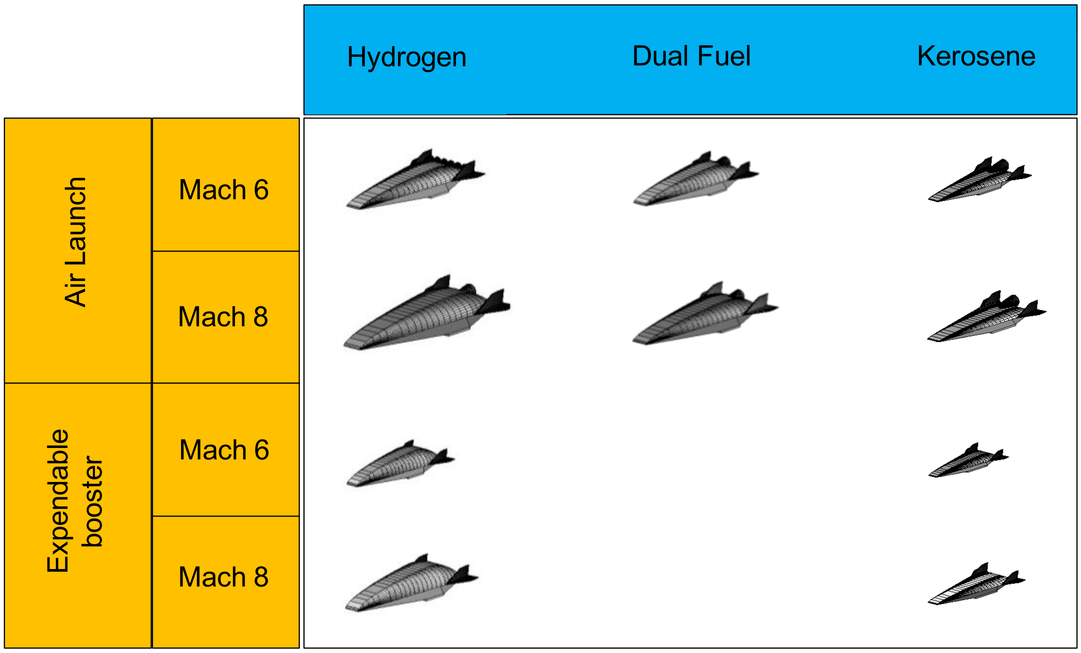


Figure 3. Reduced trade-space explored.

Parametric Sizing and Solution Space Screening

AVD Sizing Process Summary

AVD^{sizing} is a constant mission sizing process capable of first-order solution space screening of a wide variety of conventional and unconventional vehicle configurations. Solution space screening implies an overall focus on visualizing multi-disciplinary design interactions and trends. AVD^{sizing} is based on the *Hypersonic Convergence* sizing approach for transonic to hypersonic vehicle applications as developed at formerly McDonnell Aircraft Company between 1970 and 1990, see Reference 6. The modular process implemented with AVD^{sizing} relies upon a robust disciplinary methods library for analysis and a unique multi-disciplinary analysis (MDA) sizing logic and software kernel enabling data storage, design iterations, and process convergence. The integration of the disciplinary methods library and the generic multi-disciplinary sizing logic enables the consistent evaluation and comparison of radically different flight vehicles, see References 7, 8. The flight vehicle configuration independent implementation of AVD^{sizing} allows for rapid parametric exploration of the complete flight vehicle system via a convergence check to mission. Figure 4 visualizes the top level sizing process implemented.

At the heart of the process is the weight and balance budget. The results from the geometry, performance constraint and trajectory modules (weight ratio, required T/W ratio, and vehicle geometry) are provided to a weight & volume available and required logic. For a given vehicle slenderness parameter $(\tau = V_{total}/S_{pln}^{1.5})$, the planform area is iterated through the total design process until weight & volume available equal weight & volume required.

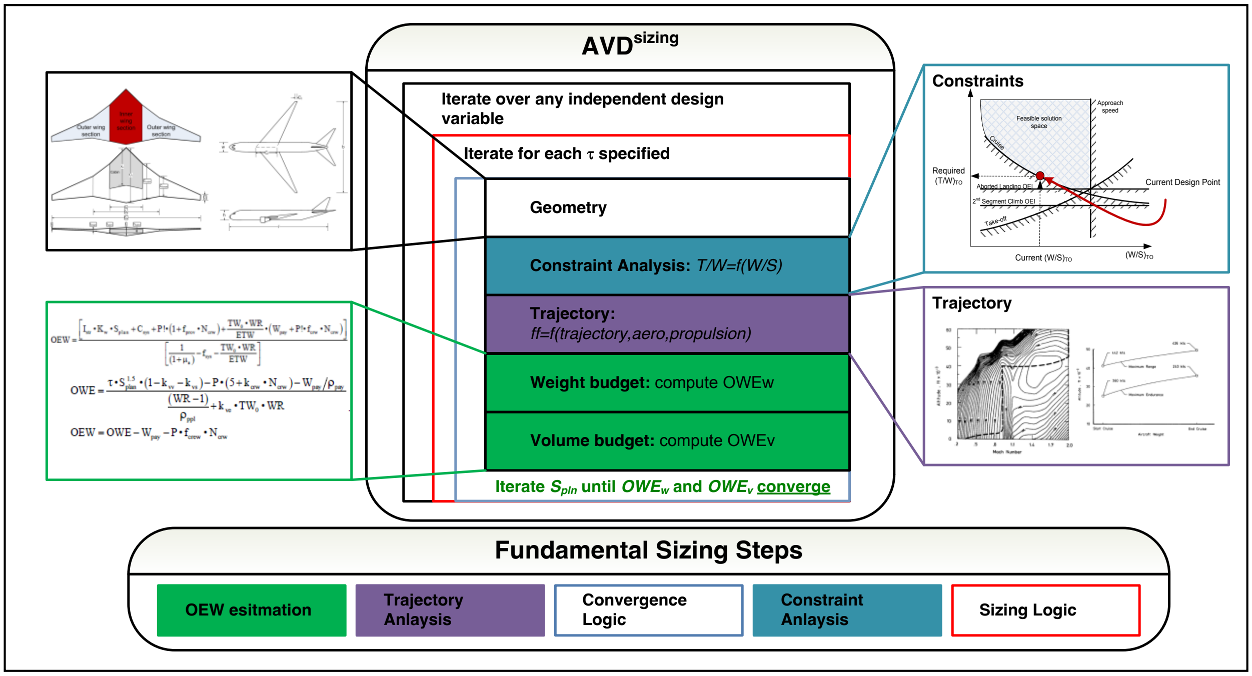


Figure 4. AVDsizing methodology visualized via Nassi-Schneidermann structogram.

Disciplinary Methods Library Overview

The following methods are utilized from the disciplinary methods library for this hypersonic demonstrator study, see Reference 5. The methods selected are of consistent first-order nature, including empirical, semi-empirical and reduced-order analytical types. Table 4 summarizes the disciplinary methods used for this study.

Table 4. Summary of Disciplinary Methods

DISCIPLINE	METHOD TITLE	DESCRIPTION	REFERENCE
Geometry	Planform	Vehicle length, span and spatular width for current planform area based on constant leading edge sweep and c/s.	Czysz [6]
	Bottom Surface	Total volume and dimensions determined from non-dimensional engine constants.	Appendix A
	Top Surface	Total volume, dimensions and wetted area computed for a compound elliptical cross-section. Top surface height determined from specified slenderness parameter.	Appendix A

Aerodynamics	Drag Polar	McDonnell-Douglas empirical correlations (circa 1970) based on vehicle slenderness, frontal area and wetted area with spatular corrections from Pike. $C_{D_0} = f(\tau, c/s, S_{wet}, S_{front}, Mach,\ Configuration)$ $L' = f(Mach, Configuration)$	HyFAC [3] Pike [10]
	Lift-Curve Slope	McDonnell-Douglas empirical correlations (circa 1970) of all-body hypersonic vehicles. $C_{L_\alpha} = f(Mach, Configuration)$	HyFAC [3]
	Maximum Lift (low speed)	FDL-7 wind tunnel data.	FDL-7 report
Propulsion	Scramjet - Modified 1-D Cycle Analysis	1-D stream thrust analysis with corrections inlet spillage drag. RSM from Bradford used for truncated SERN nozzle performance.	Heiser and Pratt [12], Bradford [13]
	Ramjet – Marquardt Data	Representative data from Marquardt study (circa 1960).	Marquardt [14]
	Rocket – Pratt & Whitney Method	Analytic off-design performance estimation of rocket thrust and I_{sp} based on ideal rocket equation.	Czysz [6]
Performance	Landing	Wing loading requirement for given stall speed and maximum trimmed lift coefficient.	Coleman [5]
	Trajectory	2-D energy integration method (altitude and velocity), constant q trajectory to cruise velocity, cruise climb, maximum L/D descent.	Appendix A
Stability and Control	Trim effects	Engine cowl location effect on trim drag.	HyFAC [3] Czysz [6]
Weight and Volume	Hypersonic Convergence Weight and Volume Budget	Empirical weight and volume estimation of structure, systems, payload and propellant.	Appendix A

Description of Solution Space Visualization

The overall product solution space consists of individually converged total flight vehicle design points. For a fixed vehicle slenderness parameter (τ), the complete weight breakdown and trajectory are computed for every individual vehicle planform iteration. The process is repeated until the weight and volume required meet the weight and volume available, see Figure 5.

A vehicle geometry solution space contour or topography is determined by varying the vehicle slenderness and re-converging each design point. The operational mission solution space is created by varying cruise time and re-converging each solution contour. The result is a continuous carpet plot comparing individually converged flight vehicle solutions based on structural index, I_{str}, and *TOGW*, see Figure 6. The structural index, I_{str}, is a metric of the structural efficiency of the concept, and is defined as structural weight per unit wetted area. This parameter will be further discussed when addressing the description of the solution space constraints.

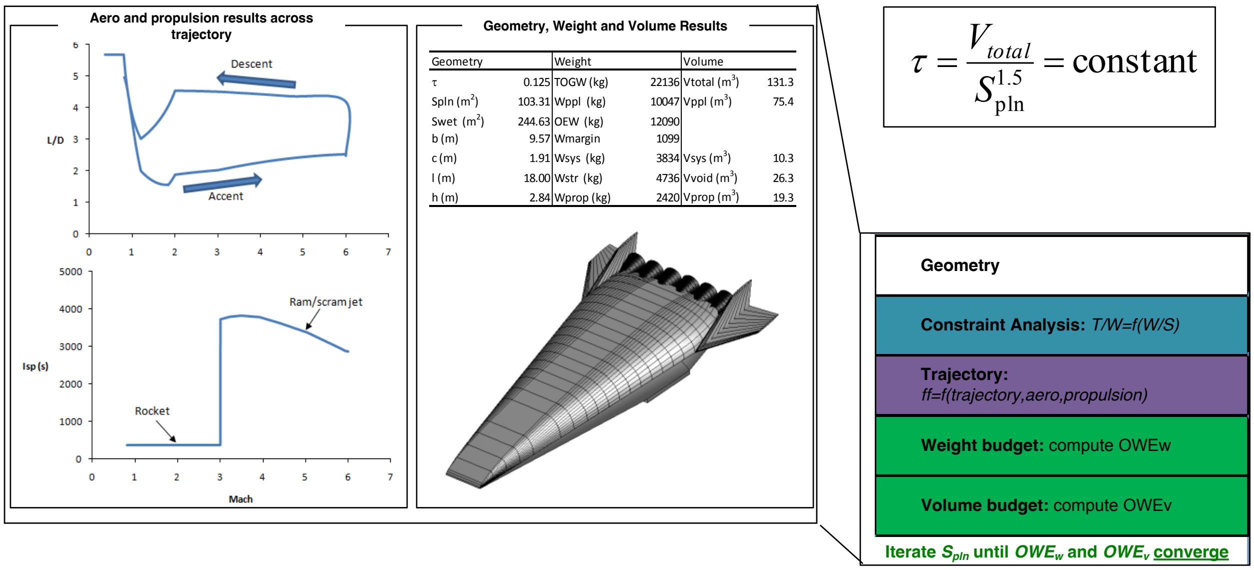


Figure 5. Each design point represents a converged complete hypersonic vehicle (Example: Mach-6, 30 minutes, cruiser configuration).

Solution Space Constraint Description: Having generated a carpet plot consisting of individually converged flight vehicles of varying vehicle slenderness (τ) and cruise time, the next step is to superimpose the aborted landing constraint, the thrust minus drag (*T-D*) constraint and the structural technology level available (I_{str}). The landing constraint is computed from the prescribed approach speed, which translates to the required 1g stall speed and required stall wing loading. Additionally, mapping the required wing loading to the *TOGW* and I_{str}, the *T-D* constraint can be added to the solutions, see Figure 7.

The *T-D* constraint represents the highest τ allowable which will still have positive acceleration during the ascent portion of the trajectory. If the vehicle is stouter (reduced planform area and increased vehicle height), then this limits the wave drag increase and the reduced capture area results in negative thrust, see Figure 7.

Figure 7 represents the structural weight per wetted area required to converge the configuration to each specific slenderness value (τ). When superimposing relevant material and structural concept technology levels onto the vehicle structural index carpet plot, the left boundaries of the solution space are determined. For vehicle slenderness parameters which require structural indices beyond this limit, the structural and shingle material are not feasible, see Figure 8. Figure 9 documents the structural indices utilized to derive the technology solution space boundaries pertinent to the flight mission.

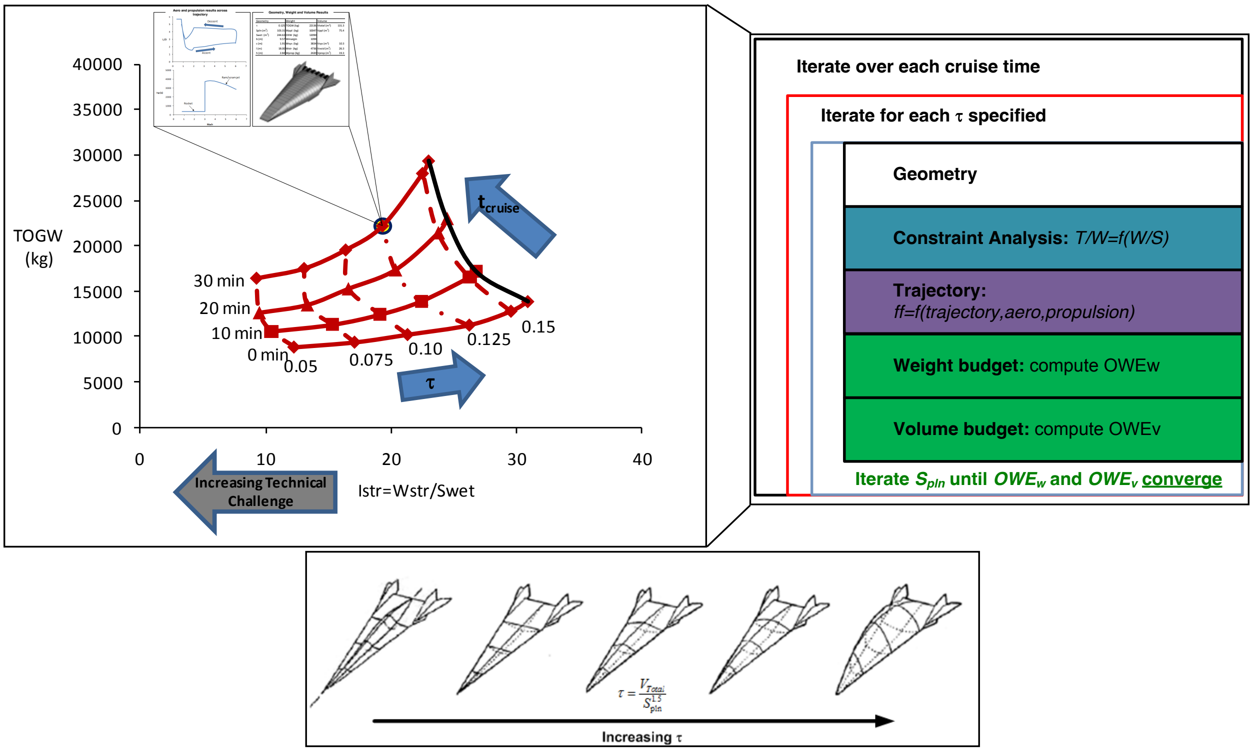


Figure 6. Solution space plot of TOGW and Istr for varying vehicle slenderness and cruise time.

The final constraints of relevance for identifying the solution space include: (a) launch vehicle load capability, (b) geometry limits for the carrier (air-launch) aircraft, and (c) expendable booster staging options. Options for the air-launched carrier vehicle are the B747-100SCA and B-52H; both options have been explored as possibilities. The B-52H employs an under wing mount constrained by: (a) the maximum load of the pylon, and (b) the geometric boundaries between the fuselage and inboard engine, the test vehicle wing and engine exhaust plum. The X-24C was intended to be the largest vehicle to possibly fit under the B-52H wing mount. Therefore, the X-24C's *TOGW*, length and width represent a guide for the maximum capability of the B-52H air-launcher for this investigation, see Figure 10. The B747-SCA is a modified B747-100 designed to carry the Space Shuttle Orbiter. For this study, the *OEW*, length and span of the Space Shuttle Orbiter are used as a guide for the maximum air-lift capability of the B747-SCA, see Figure 11.

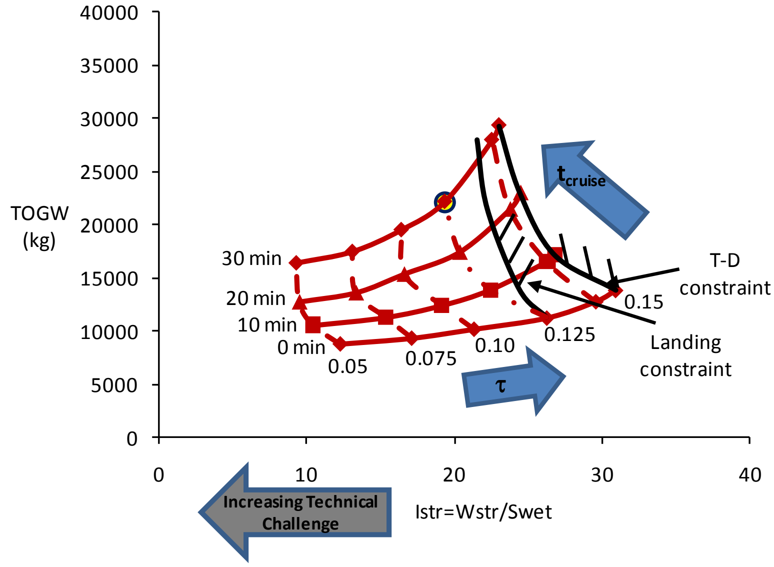


Figure 7. Landing and T-D constraints imposed on the solution space. For the Mach 6 demonstrator, the landing constraint is more constraining than T-D.

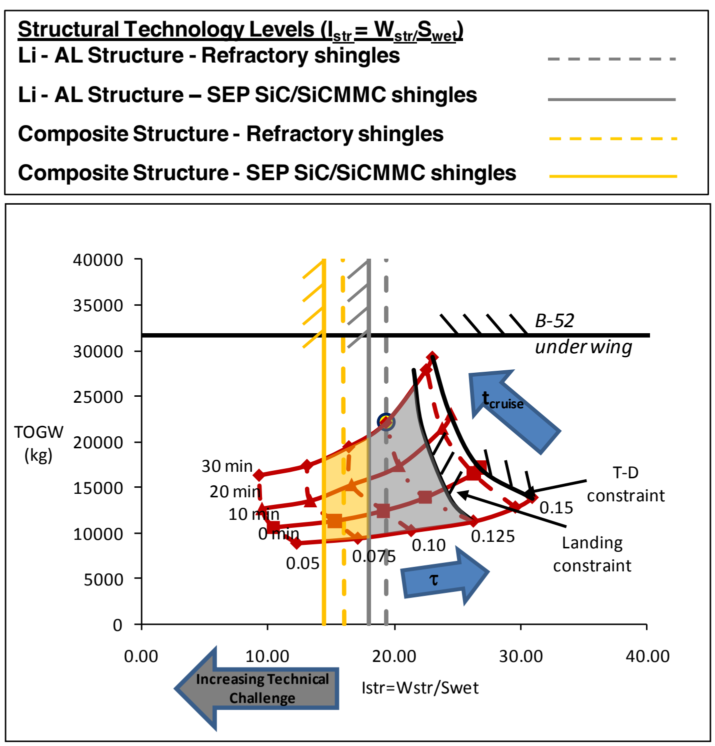
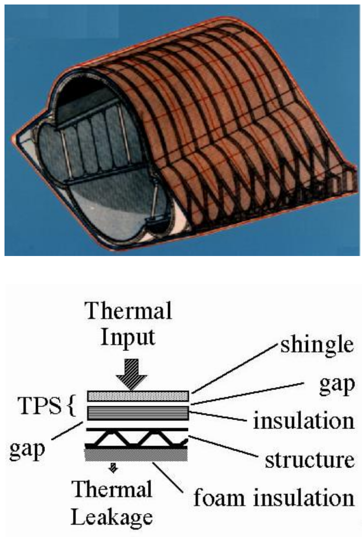


Figure 8. Superposition of structural indices provides the final constraint to determine the technical solution space.

Integral fuel Tank Structural constant (MAC circa 1970)



Break-down of industrial capability index

Integral Hydrogen Fuel tank

	Li-AL structure		Composite strucutre	
	Refractory shingles	Advanced schingles	Refractory shingles	Advanced schingles
	kg/m^2	kg/m^2	kg/m^2	kg/m^2
Shingle	6.30	4.88	6.30	4.88
Insulation	4.39	4.39	4.39	4.39
Structure	7.08	7.08	3.61	3.61
Foam insulation	1.61	1.61	1.61	1.61
total	***19.38***	***17.97***	***15.92***	***14.50***

Integral Kerosene fuel tank

	Li-AL structure		Composite strucutre	
	Refractory shingles	Advanced schingles	Refractory shingles	Advanced schingles
	kg/m^2	kg/m^2	kg/m^2	kg/m^2
Shingle	6.30	4.88	6.30	4.88
Insulation	4.39	4.39	4.39	4.39
Structure	7.08	7.08	3.61	3.61
Foam insulation	0.00	0.00	0.00	0.00
total	***17.77***	***16.36***	***14.31***	***12.89***

Figure 9. Definition of structural capability indices used for this study. (Ref 6)

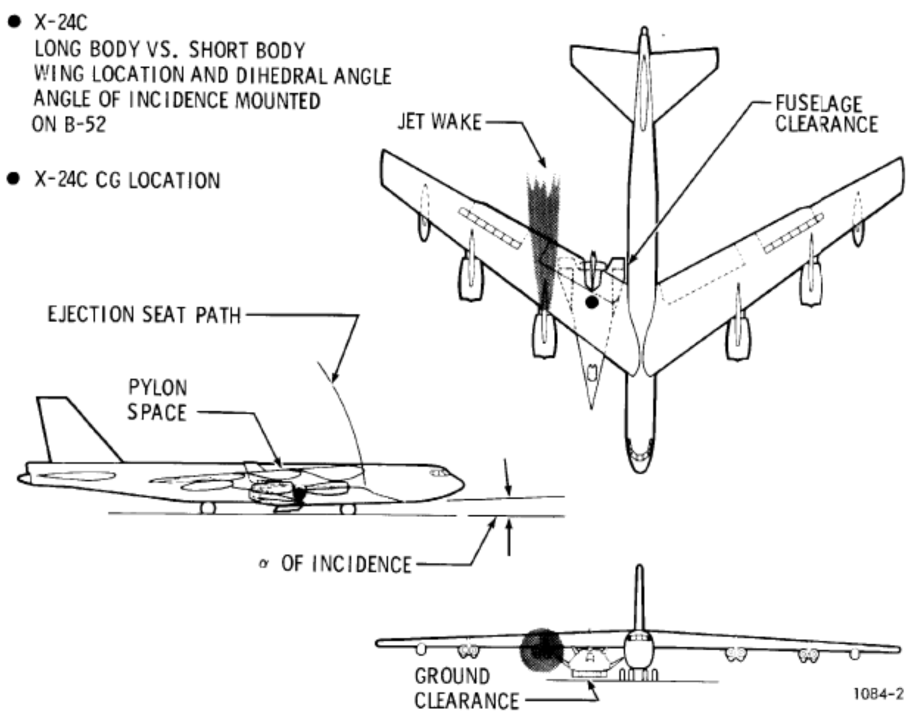


Figure 10. B-52H under-wing mount geometric constraints. (Ref 15)

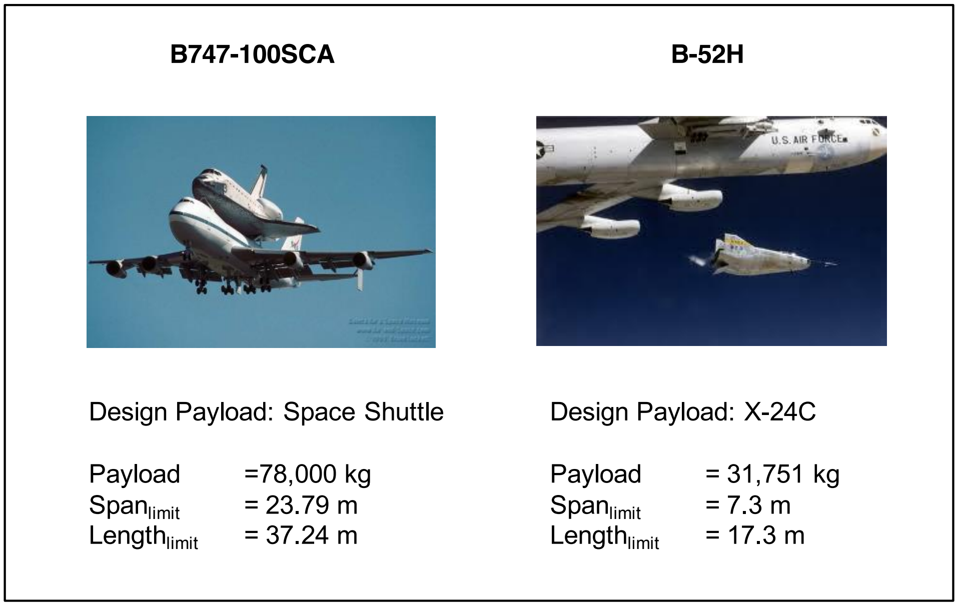


Figure 11. Summary of B747-SCA and B-52H constraints for the hypersonic demonstrator study. (Ref 15,16)

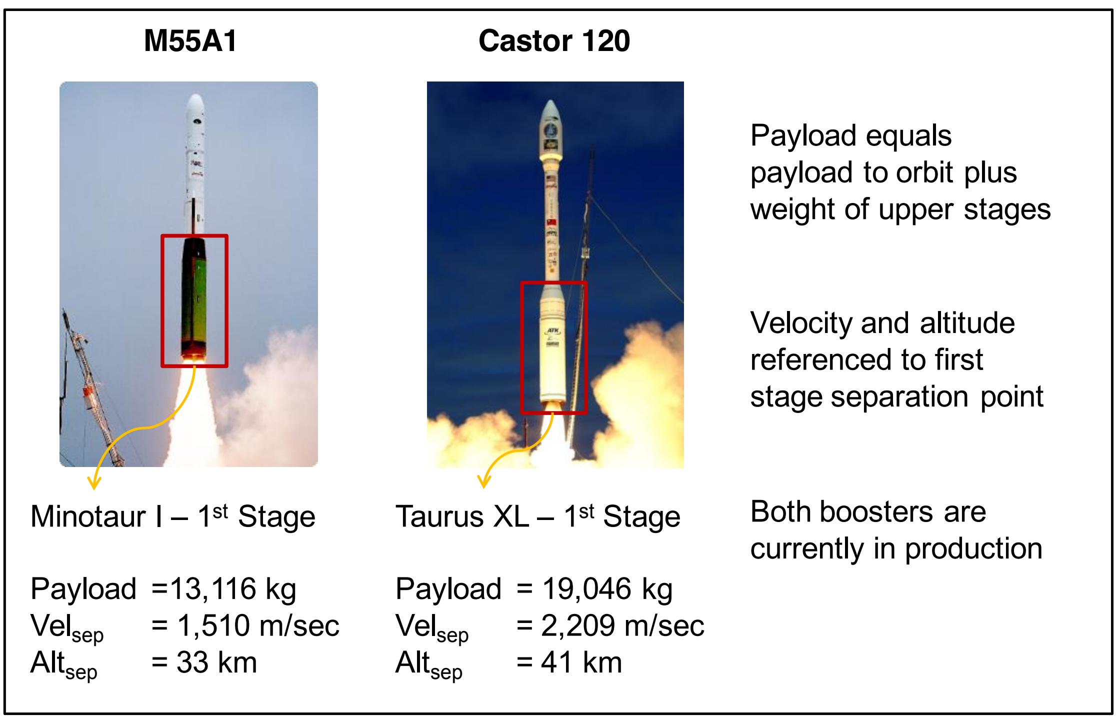


Figure 12. Summary of Minotaur I and Taurus XL 1st stage constraints for the hypersonic

When considering expendable boosters as the launch method for the hypersonic demonstrator, the boosters are found to fit the hypersonic demonstrator options as the 2nd-stage of either the *Minotaur I* or *Taurus XL* launch vehicles. These representative boosters are selected based on their maximum payload weight, separation velocity and separation altitude, see Figure 12. The maximum payload weight capacity of the booster 1st stage is taken to be the maximum payload to orbit, plus the weight of the upper stages.

During the screening process, each solution space is bounded by operational factors and technology factors for landing, *T-D*, and structural index. Next, the carrier/launch vehicle constraints are examined to determine the appropriate air-launch vehicle options for each trade.

Solution Space Screening

The selection of the trade-space and the accompanying trade-matrix results in a solution space screening activity overall consisting of two (2) launch options, two (2) cruise Mach numbers, and three (3) fuel combinations. The solution space deliverables for each option are visualized relative to each other with Figure 13. For each trade, the cruise time will be increased from 0 min to 30 min in increments of 10 min while vehicle slenderness is varied, generating the distinct solution space carpet plot. Since Figure 13 compares discrete flight vehicle types (launch method, Mach number, fuel), note that the ten (10) identified and visualized trade solution spaces demonstrate regions of operational and technical feasibility with a varying TOGW y-axis scale. In total, 237 flight vehicle design solutions have been converged.

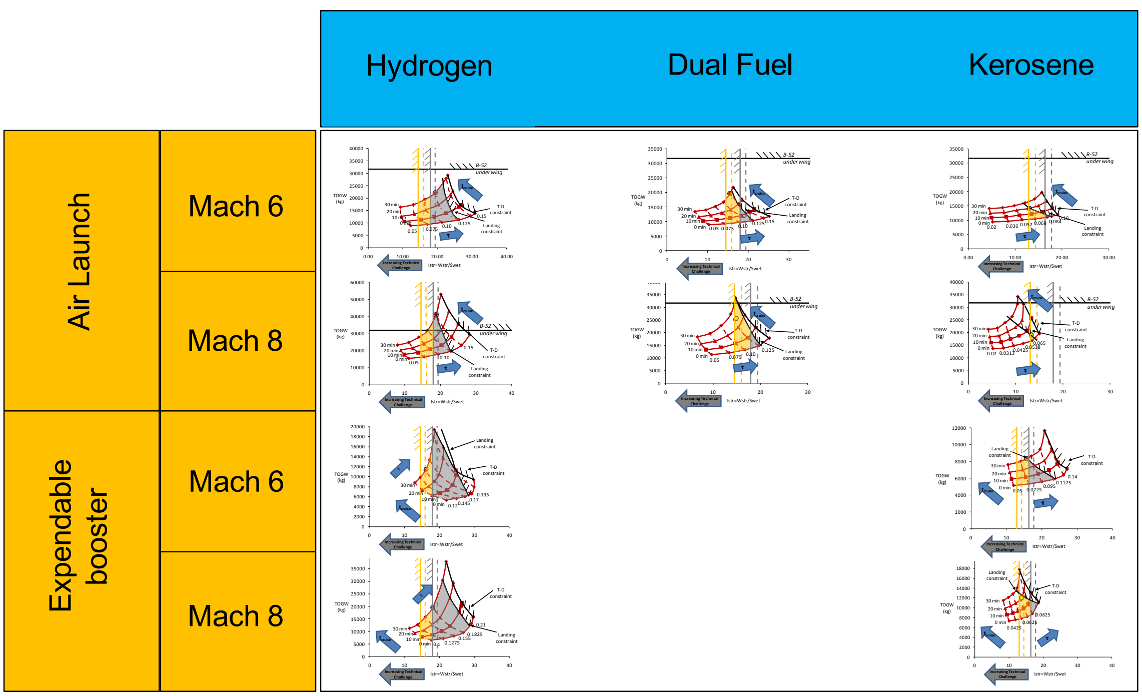


Figure 13. Relative comparison of solution spaces for each design trade explored.

Solution Space Comparison and Baseline Selection

Using the results of this study, two endurance hypersonic demonstrators have been identified as prospective baseline vehicles for research and development, concept formulation and definition, and system development efforts. It has been determined that the goal of first flight within the 10 to 20 year time span can be achieved with reasonable confidence using mostly existing industrial capability. Required technology development efforts would primarily focus on scramjet engine requirements for (a) a hydrogen-based, and/or (b) a kerosene-based operational infrastructure.

In summary, the current research undertaking has covered and delivered sensitivity trends for launch and staging options, accelerator motor selection, ramjet/scramjet fuel selection, material concept and configuration arrangement, all measured against the operational mission (i.e. cruise time, speed requirement). Considering the broadness of these engineering options evaluated, the value of parametric sizing (PS) on physical understanding and system-level decision-making has been demonstrated. Clearly, parametric sizing utilizes the first principles mindset and tools to answer how changes within the mission, operational scenario and overall research objectives influence the design 'hardware' requirements, thus the decision-making process. The recommendations and conclusions of the solution space trade analysis follow.

Solution Space Screening

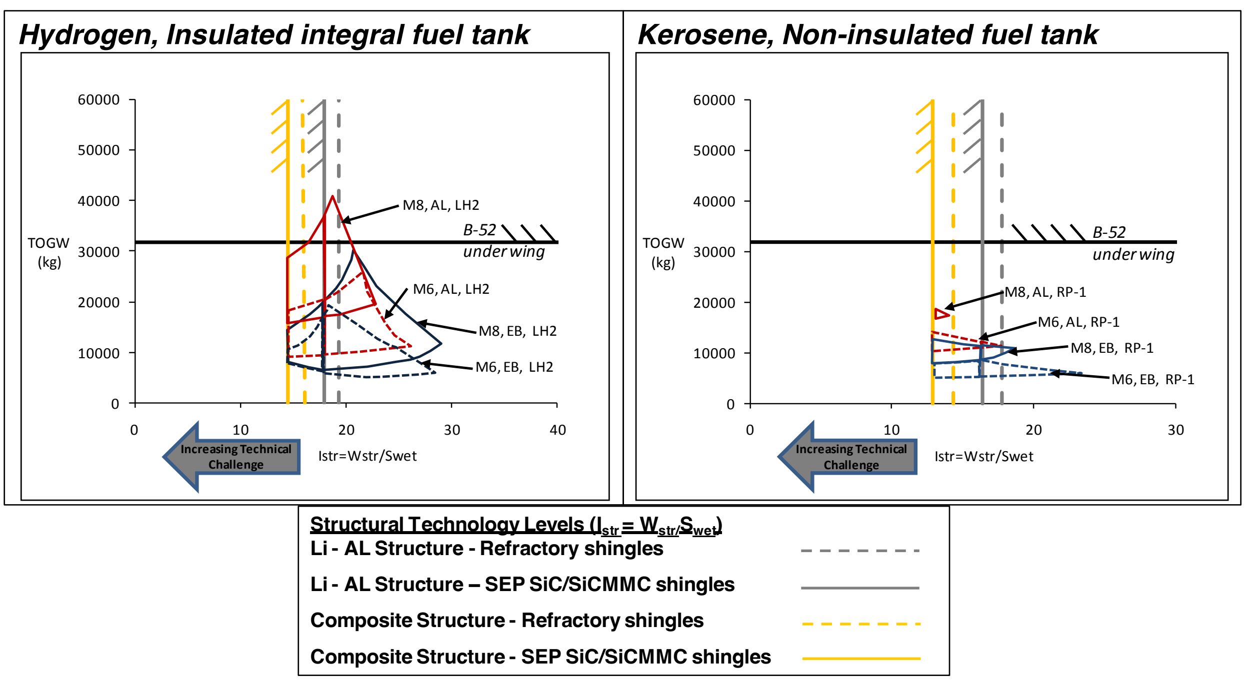


Figure 14. Hydrogen-fueled vehicles allow for a larger technical solution space compared to kerosene-fueled vehicles.

Proceedings of the 2013 ASEE Gulf-Southwest Annual Conference,
The University of Texas at Arlington, March 21 – 23, 2013.

A. Design-Level Summary
A direct comparison of the hydrogen and kerosene demonstrator trade space illustrates that hydrogen vehicles have a larger feasible design space relative to kerosene equivalents, see Figure 14. Comparing *kerosene vehicles relative to hydrogen vehicles*, the kerosene designs show larger sensitivity to landing constraints due to increased vehicle density (which increases wing loading) and the requirement for a lighter structure to compensate for reduced fuel I_{sp} values. Comparing *hydrogen vehicles relative to kerosene vehicles*, the trade-off between fuel weight density and energy density characteristics yields a higher total system benefit for hydrogen.

B. Mission-Level Summary
In order to explore the hypersonic design relationships at mission level, Figure 14 superimposes the outer contours of the hydrogen and kerosene solution spaces. Both design spaces, with decreasing maximum *TOGW*, include (a) M=8 Air-Launch, (b) M=6 Air-Launch, (c) M=8 Expendable Booster, and (d) M=6 Expendable Booster. This discussion centers on the cruise time constraint equal to 30 min (positive curve at the top of the trade space). For the hydrogen-based demonstrators, the individual solution spaces offer a vehicle point-design each that meets the operational limit while having the largest structural technology margin compared to kerosene equivalents. The M=8 Air-Launch option could be considered the higher risk solution for the 30 minutes cruise mission. For the kerosene-based demonstrators, only the M=6 Expendable Booster trade offers a feasible 30 minutes endurance solution. The remaining trades do not present feasible solutions for the 30 minutes demonstrator due to structural constraints. This shows that overall vehicle feasibility is dependent on not-yet-available structural industry capability, thus requiring future structures technology developments.

Design Point Comparison

The following discussion reviews the converged baseline vehicle design points selected from the hypersonic flight vehicle design solution space screening activity. For more information regarding the demonstrator selection for individual hydrogen- and kerosene-fuel trades, please refer to the earlier sections. Figure 15 presents the short-list overview of prospective baseline vehicle configuration-, speed- and fuel combinations. Table 5 and Table 6 are summarizing the general ‘parametric’ design characteristics for the feasible baseline vehicle options utilizing either hydrogen or kerosene fuel.

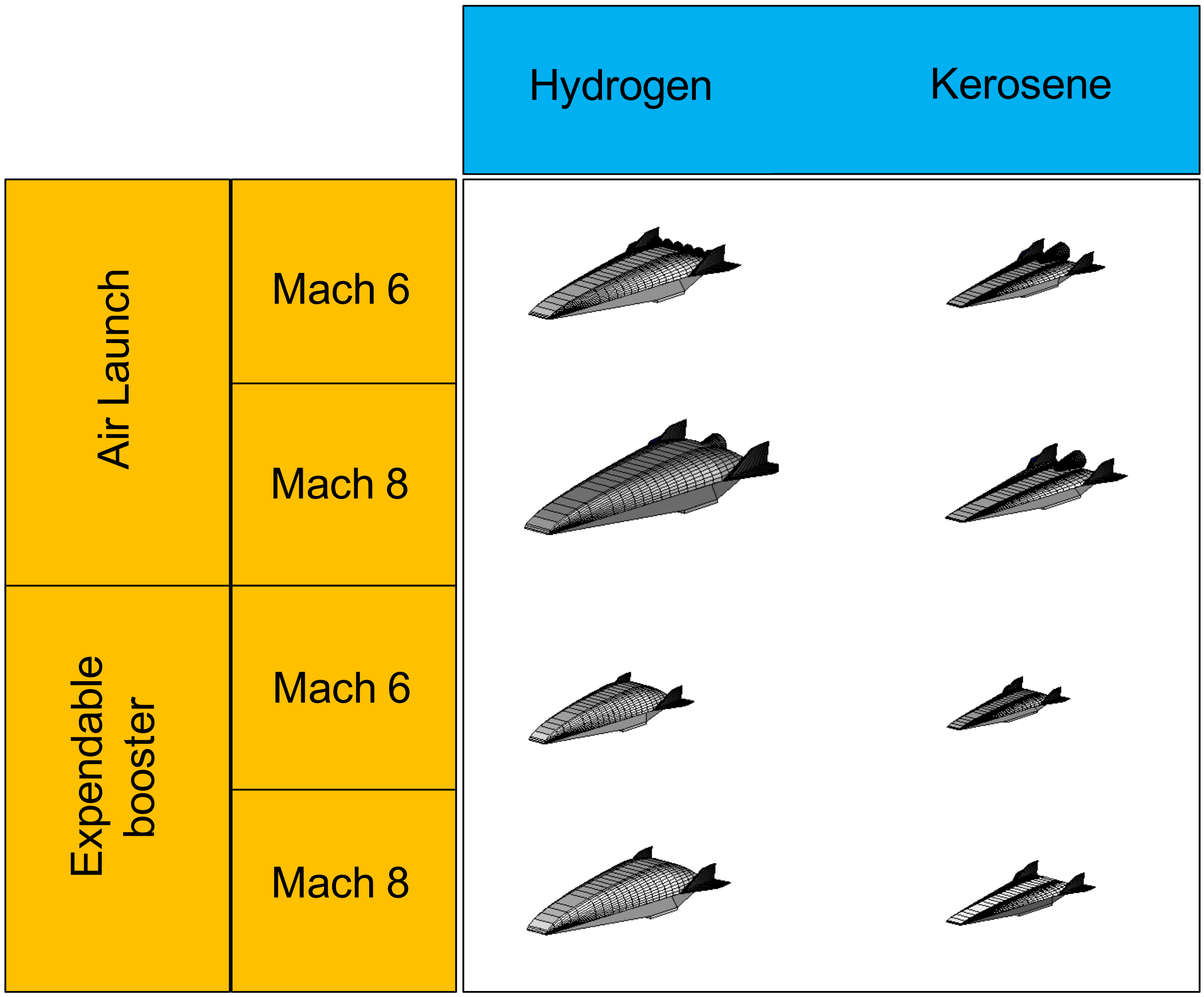


Figure 15. Configuration geometry of proposed hydrogen and kerosene hypersonic baseline vehicle designs.

Table 5. Design Characteristics for Hydrogen-Based Suggested Vehicle Selection

	Mach 6, Air-Launch, LH_2		Mach 8, Air-Launch, LH_2		Mach 6, Expendable Booster, LH_2		Mach 8, Expendable Booster, LH_2	
t_{cruise}	30 min		30 min		30 min		30 min	
Down range	4060 km	2190 nm	6300 km	3402 nm	4120 km	2224 nm	6000 km	3239 nm
TOGW	22136 kg	48802 lbs	40900 kg	90170 lbs	25635 kg	25364 lbs	19577 kg	43160 lbs
W_{ppl}	10047 kg	22149 lbs	20821 kg	45903 lbs	3757 kg	8283 lbs	7423 kg	16365 lbs
OEW	12090 kg	26653 lbs	20079 kg	44267 lbs	7709 kg	16995 lbs	12153 kg	26793 lbs
τ	0.125		0.15		0.175		0.1825	
S_{pln}	103.3 m^2	1112 ft^2	161.2 m^2	1735 ft^2	63.5 m^2	683.5 ft^2	95.67 m^2	1230 ft^2
B	9.57 m	31 ft	11.95 m	39 ft	7.5 m	25 ft	9.2 m	30 ft
L	18 m	59 ft	22.48 m	74 ft	14.1 m	46 ft	17.32 m	57 ft
L/D cruise	2.46		2.31		1.88		1.98	
***Isp cruise* (s)**	2613 s		2246 s		2600 s		2248 s	
Trkt	453 kN	102 klbs	1015 kN	228 klbs				
Nrkt	7 at 64.7kN each		1 at 1015 kN each					

Table 6. Design Characteristics for Kerosene-Based Suggested Vehicle Selection

	Mach 6, Air-Launch, RP-1		Mach 8, Air-Launch, RP-1		Mach 6, Expendable Booster, RP-1		Mach 8, Expendable Booster, RP-1	
t_{cruise}	20 min		4.5 min		30 min		20 min	
Down range	3480 km	1880 nm	3270 km	1770 nm	4523 km	2442 nm	5640 km	3045 nm
TOGW	14191 kg	31287 lbs	19013 kg	41917 lbs	8345 kg	18398 lbs	12027 kg	26515 lbs
W_{ppl}	7715 kg	17009 lbs	10627 kg	23429 lbs	3536 kg	7796 lbs	6074 kg	13391 lbs
OEW	6476 kg	14277 lbs	8386 kg	18488 lbs	4809 kg	10602 lbs	5953 kg	13124 lbs
τ	0.07		0.0675		0.085		0.075	
S_{pln}	58.4 m^2	628 ft^2	76.7 m^2	826 ft^2	34.75 m^2	374 ft^2	51.28 m^2	552 ft^2
b	7.19 m	24 ft	8.24 m	27 ft	5.55 m	18 ft	6.74 m	22 ft
l	13.53 m	44 ft	15.51 m	51 ft	10.44 m	34 ft	12.68 m	42 ft
L/D cruise	3.79		3.39		4.08		3.92	
***Isp cruise* (s)**	943 s		753 s		970 s		732 s	
Trkt	512 kN	115 klbs	512 kN	115 klbs				
Nrkt	1 at 512 kN each		1 at 512 kN each					

Baseline Vehicle Description

While feasible options for both, the hydrogen-fueled and kerosene-fueled vehicles, exist, the selection of the fuel type alone is not a sufficient indicator for demonstrator feasibility. The selection criteria for the fuel type are primarily determined by the required operational vehicle characteristics, in this case being a robust air-breathing propulsion system flying test bed. Clearly, additional criteria are needed to measure the risk and benefit merits of this demonstrator vehicle. At this point we ask the simple question: *"If a hydrogen fueled scramjet is required, what demonstrator is recommended?"* and *"If a kerosene-fueled scramjet is required, what demonstrator is recommended?"*

- ***Selection Criteria***
  - ***Versatility***
    (largest flexibility in operation)
    - ***Mach 8, air-launch, 30 min***
  - ***Growth capability in concept***
    (sensitivity to increase in scale)
    - ***Mach 6, air-launch, 30 min***
  - ***Design confidence***
    (largest technology margins)
    - ***Mach 6, air-launch, 30 min***
  - ***Limitations***
    (Hydrogen demonstrator)
    - ***B747-100 carrier required for air-launch***
    - ***Operational limitation of Hydrogen (relative to Kerosene)***

- ***Selection***
  - ***Mach 6, 30 min cruise, air launch with Mach 8, 10 min cruise capability (<u>the solutions spaces overlap</u>)***
  - ***B747-100 air-launch (planform constrained on the B-52)***
  - ***RL-10 rocket accelerator***
  - ***Li-Al structure***

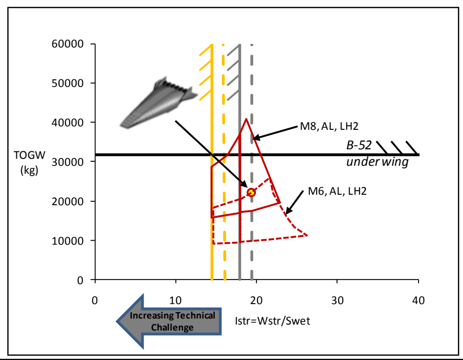


Figure 16. The Mach 8 air-launched case represents the largest operational flexibility while Mach 6 air-launched has larger growth capability and design confidence. Since M6 30 min and M8 10 min solution curves overlay, it appears that the M6 30 min vehicle could perform the Mach 8 mission for 10 minutes.

For each fuel requirement, trade-studies will have to address the following four qualitative metrics:

1. *Versatility* Which vehicle represents the largest flexibility of its operational capability?
2. *Growth Capability* Which vehicle is the least sensitive to scale? In other words, which vehicle is least sensitive to changes in structural capability which are assumed for this study?

3. *Design Confidence* Which vehicle has the largest technology margins and allows for a design point which has sufficient margin in terms of structural technology, *T-D* and landing distance?
4. *Limitations* Which vehicle has any perceived limitations that would hinder development?

If *hydrogen scramjet testing* is required, assessment results are presented with Figure 16:

Observing that the Mach 6, 30 minutes vehicle can perform the Mach 8 mission for 10 minutes, this scenario provides a compromise which will allow for both, the endurance and speed requirements to be accomplished at a lower risk option compared to the Mach 8, 30 minutes vehicle. Consequently, the selection of this particular baseline design provides a superior design margin and a concept less sensitive to structural and propulsion technology requirements.

- ***Selection Criteria***
  - ***Versatility (largest flexibility in operation)***
    - ***Mach 6, expendable, 30 min***
  - ***Growth capability in concept (sensitivity to increase in scale)***
    - ***Mach 6, expendable, 30 min***
  - ***Design confidence (largest technology margins)***
    - ***Mach 6, expendable, 30 min***
  - ***Limitations (Kerosene demonstrator)***
    - ***High level of structural technology required***
    - ***Operation of Kerosene at high temperatures***

- ***Selection***
  - ***Mach 6, 30 min cruise***
  - ***Composite structure (possible aluminum)***
  - ***M55A1 Expendable Booster***

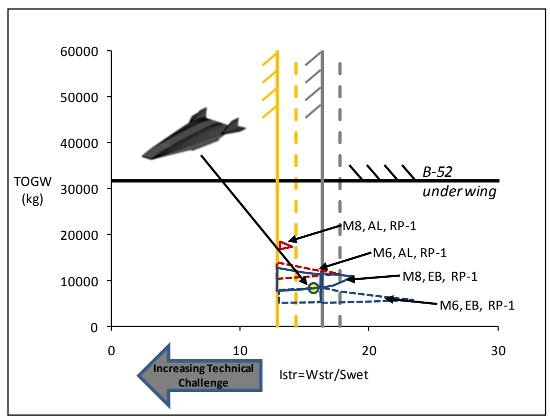


Figure 17. The Mach 6 kerosene-fuel expendable booster trade is the only trade-study which allows for 30 minutes cruise endurance.

If *kerosene scramjet testing* is required, assessment results are presented with Figure 17:

Given the increased density of kerosene (which increases *W/S* and causes the landing constraint to increase) accompanied with a reduced energy density, the required structural technology must increase to compensate. This leaves the Mach 6, 30 minutes vehicle as the only viable technical option for kerosene scramjets. Furthermore, it is important to note that the Mach 6, 30 minutes solution overlays with the Mach 8, 0 minutes cruise time solution. Consequently, the Mach 6, 30 minutes research vehicle can accelerate to Mach 8, but it will not have sufficient fuel for 30 minutes but 10 minutes cruise endurance.

Summary and Conclusions

This report documents a parametric sizing study performed to develop a program strategy for (1) research and development (R&D) and (2) procurement of a next-generation hypersonic air-breathing endurance demonstrator. In the context of the present research undertaking, the AVD Lab team has utilized the *parametric sizing* (PS) tool to measure sensitivities and classical figures-of-merit for the manager [M], synthesis specialist [S], and technologist [T]. The systematic approach applied (**screening & sizing**) is utilized to iteratively harmonize the relationships amongst: (a) mission selection, (b) research objectives definition, and (c) baseline vehicle(s) characterization. The above outlined process arrives at a justification package able to characterize the suggested baseline hypersonic vehicle design.

Design Lessons Learned

Beyond the two primary recommendations communicated in Section VI, several design lessons have been learned through the course of this project which are worthy of note.

- *LH_2 fuel* allows for a larger technical solution space relative to the kerosene option.
- *Air-launch* from the B-52 is limited due to under-wing geometry (planform) constraints rather then under-wing load limitations.
- *Selection of scramjet fuel* is not driven by technical feasibility of the demonstrator test-bed but requirements specified by the operational aircraft.
- *Air-launch and expendable booster launch* are both viable options with LH_2.
- *Launch arrangement* should be based on flight rate requirement and associated operating cost.
- *Off-the-shelf accelerator rocket motors* are available, thereby reducing overall development program costs and initial program risks.
- *Landing constraints*, driven by the abort mission, tend to constrain the solution space.
- *Dual fuel option* marginally decreases size of vehicle, relative to the 30 min LH_2 variant.
- A *reduced cruise time* Mach 8 mission could represent an off-design point for the Mach 6 demonstrator (Merlin thrust class rocket is no longer required).

It is felt that each of the lessons learned require attention before a selection of confidence can be made for a baseline vehicle and moving forward with the design.

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Amit Oza
Mr. Oza currently serves as a graduate research assistant at the University of Texas at Arlington

Gary Coleman
Dr. Coleman currently serves as a Mechanical Engineer at RSG AeroDesign

Lex Gonzalez
Mr. Gonzalez currently serves as a graduate research assistant at the University of Texas at Arlington

Bernd Chudoba
Dr. Chudoba currently serves as an Assistant Professor of Aerospace Engineering at the University of Texas at Arlington

Paul Czsyz
Mr. Czysz currently serves as a consultant through Hypertech Concepts LLC