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Solution-Space Screening of a Hypersonic Endurance Demonstrator

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October 2012

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FOREWORD

This report summarizes the results of the *Solution-Space Screening for a Hypersonic Endurance Demonstrator* study performed from 14 June 2010 through 31 August 2010 under the National Institute of Aerospace (NIA) contract NNL09AA00A, Task Order No. NIA Activity C10-2800-UTA for the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) by the Aerospace Vehicle Design (AVD) Laboratory at the Mechanical and Aerospace Department (MAE) at the The University of Texas at Arlington (UTA).

The study was funded by the Systems Analysis and Concepts Directorate (SACD), Vehicle Analysis Branch (VAB), with John J. Korte as study monitor and Lawrence L. Green as alternate study monitor.

Bernd Chudoba was the manager of the *Solution-Space Screening for a Hypersonic Endurance Demonstrator* project and Gary Coleman was the deputy manager. The study was conducted within the AVD Laboratory at UTA MAE under the direction of Bernd Chudoba.

The support of the following individuals is gratefully acknowledged: Ajay Kumar (NASA LaRC), John J. Korte (NASA LaRC), Charles P. Leonard (NASA LaRC), Lawrence L. Green (NASA LaRC), Jeffrey S. Robinson (NASA LaRC), Roger A. Lepsch (NASA LaRC), John G. Martin (NASA LaRC), Janet M. Ross (NASA LaRC), David E. Glass (NASA LaRC), John R. Olds (SpaceWorks Engineering, Inc.), William J.D. Escher (SpaceWorks Engineering, Inc.), Kevin G. Bowcutt (The Boeing Company), Heribert Kuczera (EADS Space Transportation), Dietrich E. Koelle (TCS-TransCostSystems), Peter W. Sacher (AeroSpace Consulting), Ivan Burdun (Intelonics, Inc.), and Georg Poschmann (Airbus Industrie).

The study deliverables consist of:

- Weekly teleconferences with supporting Microsoft PowerPoint files.
- Two-day UTA MAE AVD Laboratory workshop with supporting Microsoft PowerPoint file (14–15 September 2010).
- One-day NASA LaRC VAB VIP presentation with supporting Microsoft PowerPoint file (21 October 2010).
- AVD Laboratory final report in Adobe PDF format (01 November 2010).

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NOTATION

SYMBOLS

b	span
c	spatular width
c/s	spatula ratio, spatula width to outboard semispan
C_{D0}	zero-lift drag coefficient
C_{ev}	expansion component velocity coefficient
C_{ea}	expansion angularity coefficient
$(Cf/2\ A_w/A_3)_c$	dimensionless boundary-layer skin-friction quantity
$(Cf\ A_w/A_3)_b$	burner effective drag coefficient
$C_{L\alpha}$	lift curve slope
C_{Lmax}	maximum lift coefficient
C_{pe}	expansion specific heat
f	fuel-to-air ratio
h	vehicle height
h_c/l_c	ratio of external compression height to length
h_{iso}/l_{iso}	ratio of isolator height to length
h_{pr}	fuel heating value
I_{sp}	specific impulse
I_{str}	structural index, ratio of structural weight to wetted area
K_{str}	structural weight shape factor
l	vehicle length
L'	induced drag coefficient
L/D	Lift-to-Drag ratio
L_{comb}	length of combustor
l_c/l_w	ratio of external compression length to total vehicle length
N_{rkt}	number of rocket motors
S_{front}	frontal area
S_{pln}	planform area
S_{wet}	wetted area
t_{cruise}	cruise endurance time
T_{rkt}	total thrust from rocket motor
V_{fx}/V_3	ratio of fuel velocity to axial flow velocity
V_f/V_3	ratio of fuel velocity to total flow velocity
V_{ppl}	propellant volume
V_{prop}	propulsion system volume
V_{sys}	systems volume
V_{total}	total volume
V_{void}	void volume
W/S	wing loading
W_{margin}	design weight margin
W_{ppl}	propellant weight
W_{prop}	total propulsion system weight
W_{str}	structural weight
W_{sys}	systems weight

GREEK SYMBOLS

γ_c	compression system ratio of specific heats
γ_e	expansion system ratio of specific heats
η_1	adiabatic compression efficiency
η_b	burner efficiency
θ_{1n}	first nozzle angle
θ_{2n}	second nozzle angle
τ	Küchemann's slenderness parameter

ACRONYMS

AVD	Aerospace Vehicle Design Laboratory
CE	Configuration Evaluation
c.g.	center of gravity
CL	Configuration Layout
DB	Data-Base
DBS	Data-Base System
HL	Horizontal Landing
HTO	Horizontal Take Off
KB	Knowledge-Base
KBS	Knowledge-Base System
LaRC	Langley Research Center
Li-AL	Lithium-Aluminum alloy
M	Managerial
MLW	Maximum Landing Weight
MSTC	Multiple Stages To Cruise
OEW	Operating Empty Weight
OWE_w	Operating Weight Empty from weight budget
OWE_v	Operating Weight Empty from volume budget
PDE	Pulse Detonation Engine
PS	Parametric Sizing
RBCC	Rocket-Based Combined Cycle
RJ	Ramjet
RKT	Rocket
RSM	Response Surface Method
S	Synthesis
SiC/SiCMMC	Silicon Carbide/Silicon Carbide Metal Matrix Composite
SEP	Société Européenne de Propulsion
SERN	Single Expansion Ramp Nozzle
SJ	Scramjet
SSTC	Single Stage To Cruise
T	Technologies
TBCC	Turbine-Based Combined Cycle
T–D	Thrust minus Drag
TJ	Turbojet
TOGW	Take Off Gross Weight
TPS	Thermal Protection System

TSTC	Two Stage To Cruise
T/W	Thrust-to-Weight ratio
VAB	Vehicle Analysis Branch
VTO	Vertical Take Off

1 INTRODUCTION

The *Solution Space Screening for a Hypersonic Endurance Demonstrator* task has been a two and one-half month study with the aim:

- 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;
- to identify and visualize the solution space available for a hypersonic endurance demonstrator (20 to 30 minutes) that employs an air-breathing propulsion system;
- to propose prospective baseline vehicle(s) based on (1) available industry capability and (2) high-priority research (technology) required.
- to 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 AVD Laboratory at the University of Texas Arlington (UTA) with exploring the technical and operational solution space for a 20 minutes to 30 minutes 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 air-breathing hypersonic endurance flight vehicle to increase our existing understanding and knowledge-base regarding air-breathing propulsion, associated thermal proctection 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 minutes Mach 6 demonstrator (with 10 minutes 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.

2 OVERALL STUDY METHODOLOGY

The study has been organized into three distinct phases with the following individual work elements or tasks defined for each phase, see Figure 2-1:

Phase I	Preparatory Activities [DB/KB query, initial trade matrix] 3 weeks
Phase II	Configuration and Technology Identification [parametric solution space exploration] 6 weeks
Phase III	Recommendations [baseline flight vehicle(s) identification] 2 weeks

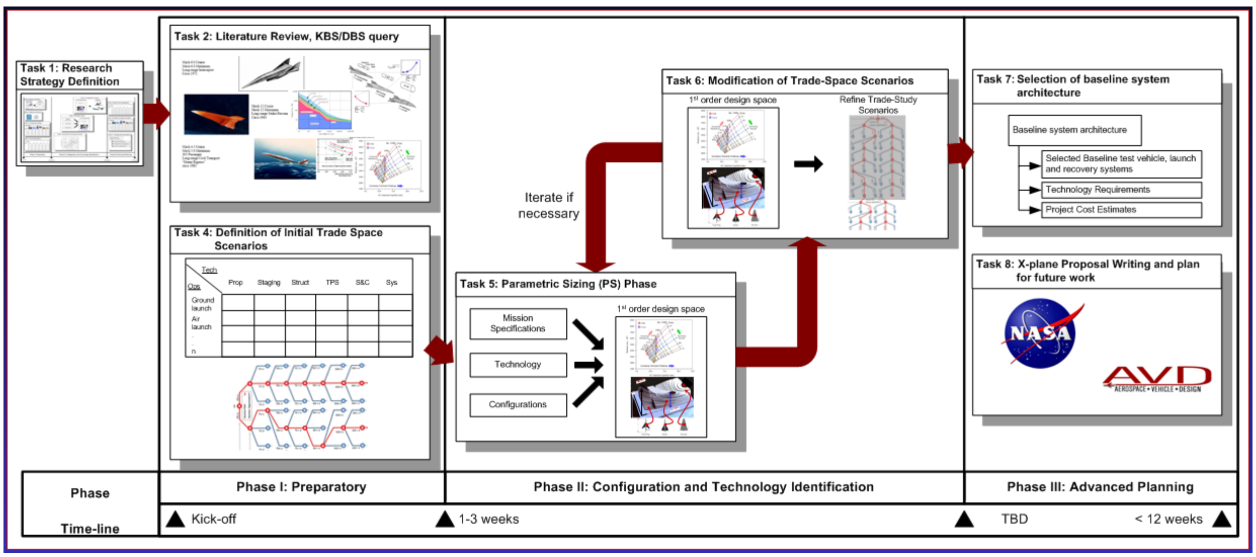


Fig. 2-1. Study approach to develop reusable hypersonic endurance test bed.

<u>Task 1: Research Strategy Definition</u>
The objective is to formulate, discuss, harmonize, and adopt research ground rules for the 11-week study. Bernd Chudoba and Gary Coleman traveled from 14 to 18 June 2010 to NASA LaRC to jointly define the research strategy with the VAB team members.

<u>Task 2: Literature Review, DB/KB Query</u>
A primary literature search is conducted to identify relevant past and present data and knowledge that are related to the planning of a hypersonic endurance demonstrator.

<u>Task 3: Reference Vehicle Definition</u>
The X-15 is selected as the appropriate reference aircraft or analog for the endurance demonstrator.

Task 4: Definition of Initial Trade Space Scenarios
The initially wide-open trade space for this study is refined successively and constrained to trades of immediate relevance for VAB.

Task 5: Parametric Sizing
The AVD Laboratory's parametric sizing (PS) methodology is executed. The conceptual design consists of three individual phases executed in sequence: (1) *Parametric Sizing* (PS), (2) *Configuration Layout* (CL), and (3) *Configuration Evaluation* (CE) (see Figure 2-2).

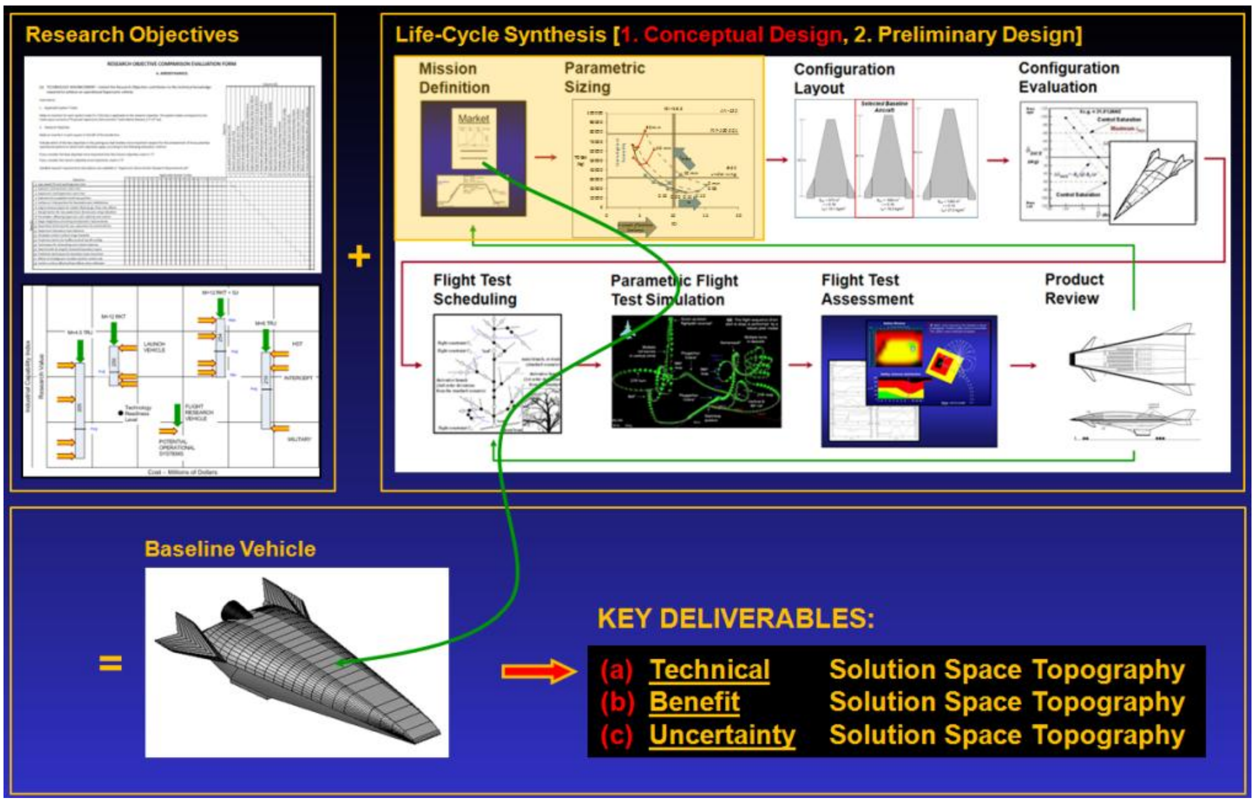


Fig. 2-2. AVD Laboratory integrated design life-cycle process.

Task 6: Modification of Trade Space Scenarios
The deliverables generated during the PS phase allow the AVD Laboratory and VAB researchers to review and modify the initial trade matrix. The PS phase is the key phase during which the researchers gain an initial physical understanding of the design problem and sensitivities at hand.

Task 7: Selection of Baseline Aircraft/System Architecture
After sufficiently exploring and visualizing the available solution space for the endurance demonstrator, the design team is in the position to select baseline flight vehicle parameters such as launch type, fuel type, size, and operational requirements.

Task 8: Research Aircraft Proposal Writing and Plan for Future Work

Once the technical solution-space topography for a hypersonic demonstrator has been established, a benefit and uncertainty requirement-topography must be imposed. Next, the flight demonstrator research objectives will be related to industry capability *available* and future technology *required*.

A central requirement for the AVD Laboratory team has been to work in partnership with the NASA VAB team via visits, weekly progress telecons, email communication, and presentation and report deliverables. Accepting the novelty of the design task, the aim of the AVD team is to generate deliverables emphasizing transparency, reproducibility, and physical correctness. This study approach, which is shown in Figure 2-3, details the three mindsets at work throughout the project life cycle: (a) *Managerial* (M), (b) *Synthesis* (S), and (c) *Technology* (T). This integration scheme maximizes the interaction between the VAB and the AVD Laboratory along the three principal mindsets at work.

Figure 2-3 further addresses the implications of the overall project time constraints. The actual trade matrix executed is limited to the study of the most important operational requirements and flight vehicle design parameters. Before a baseline vehicle selection can be reliably made, a comprehensive set of constraints & requirements representing the M, S, and T mindsets are explored via trade studies.

Please note the step called *Objectives Matching* shown in Figure 2-3. The following chapter will address its meaning.

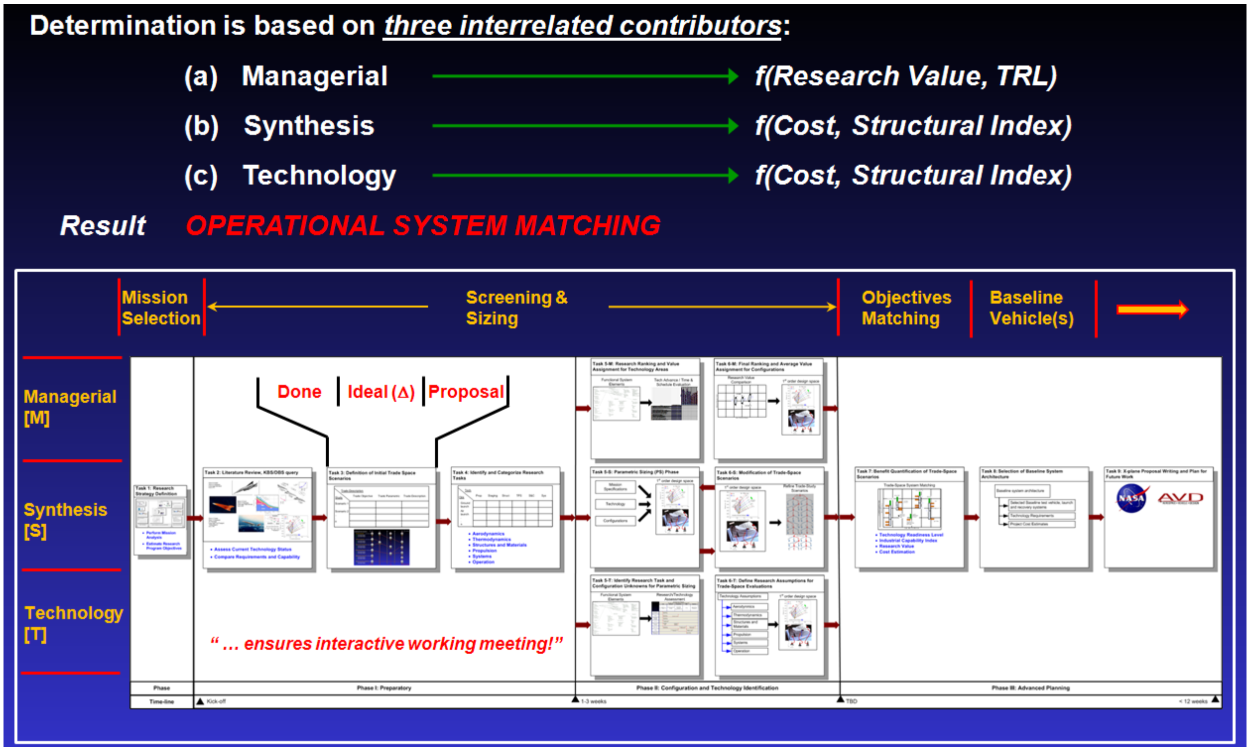


Fig. 2-3. AVD Laboratory integrated VAB-AVD team study approach.

3 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, see Figure 3-1.

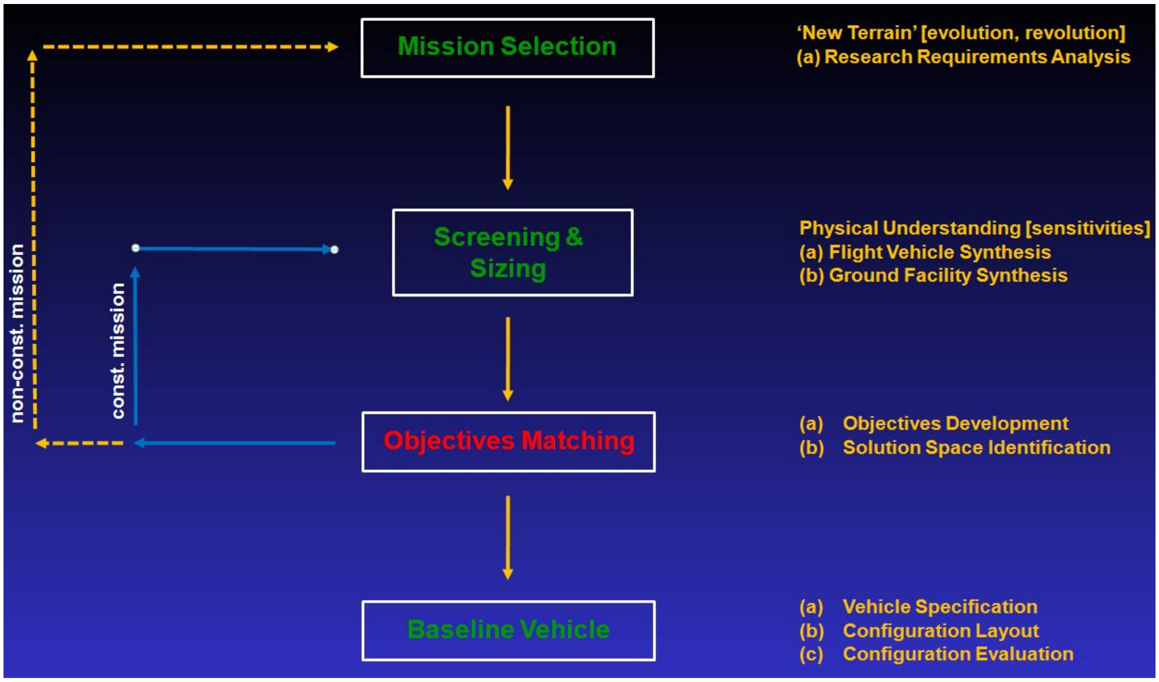


Fig. 3-1. Iterative nature of the mission & objectives & baseline vehicle(s) selection process.

Figure 3-1 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).

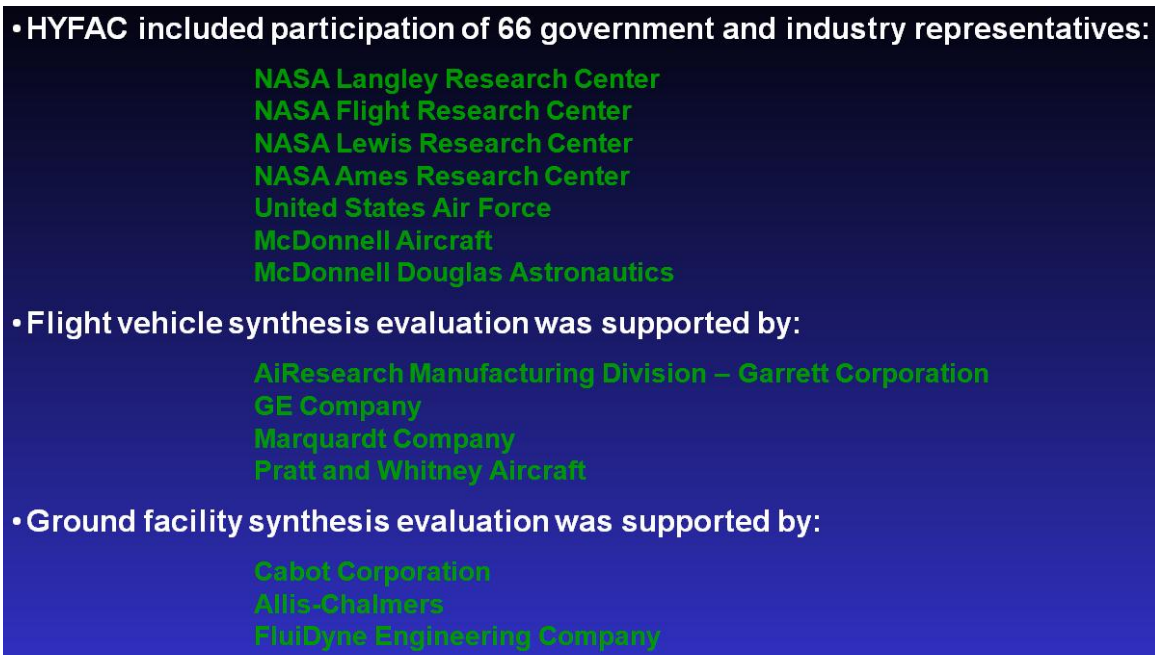


Fig. 3-2. HyFAC project research objectives identification and evaluation participants.

Between July 1969 and June 1970, the McDonnell Aircraft Company had been tasked by NASA (NASA Contract NAS2-5458) to conduct a comprehensive *Hypersonic Research Facilities Study* (HYFAC), see Reference 1. The objective of this study has been to assess research and development requirements for (a) *flight facilities* (demonstrator) and (b) *ground facilities* (e.g., wind tunnels) towards air-breathing operational hypersonic aircraft that satisfy multiple future operational missions. Overall, the study provides the required characteristics for flight-test research facilities and ground-test research facilities. In analogy to the present study, the McDonnell Aircraft Company make use of a dedicated sizing methodology as the primary means for the numerical design solution space identification. Noteworthy is the time and people effort invested by multiple participants to identify and evaluate the research objectives for future hypersonic missions and associated hardware, see Figure 3-2.

The McDonnell Aircraft Company *HyFAC* study highlights the significance of the objectives matching process, a process of significance for identifying and balancing the triangle relation between the (a) baseline mission, (b) research objectives, and (c) baseline vehicle(s). Due to project time constraints, the present research undertaking excludes the research objectives development and matching step. Figure 3-3 illustrates the finally implemented baseline vehicle development sequence for the present study by omitting the *objectives matching* step shown in Figure 3-1. 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.

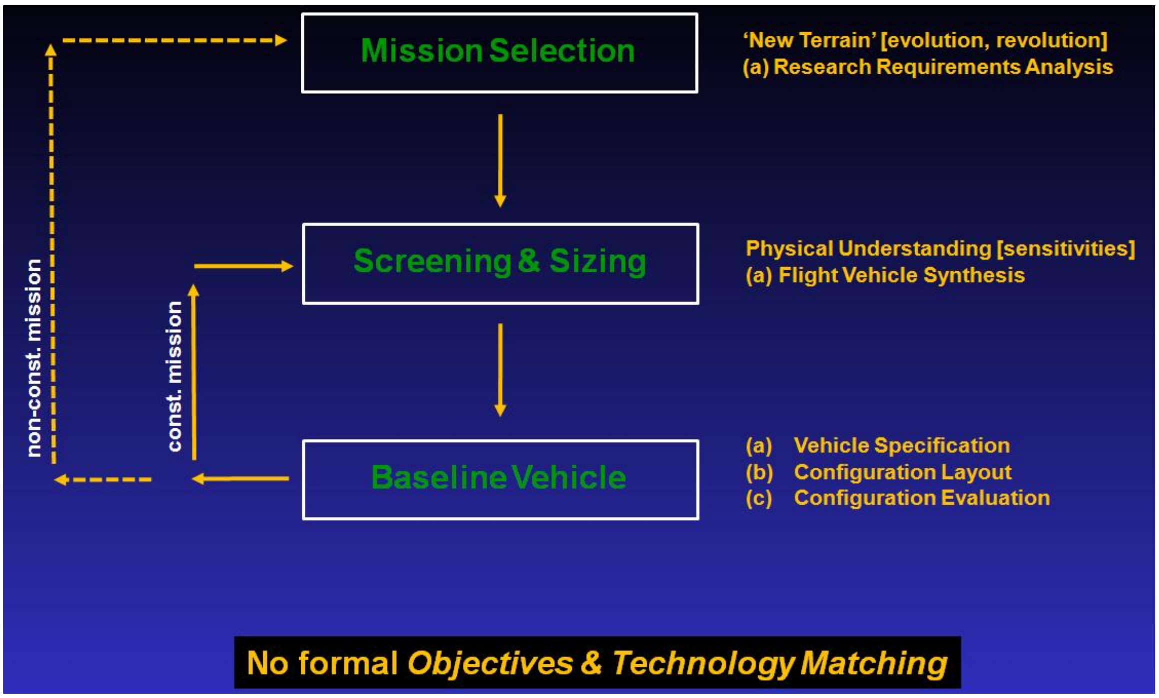


Fig. 3-3. VAB/AVD Laboratory baseline vehicle development sequence.

4 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 4-1 lists high-speed flight vehicles of direct relevance in the context of a future endurance testbed.

Table 4-1. 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

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.

4.1 HYPERSONIC FLIGHT VEHICLE DATA-BASE (DB)

The first step in efficiently utilizing existing high-speed aircraft design knowledge has been a systematic literature survey, which in itself has been an ongoing effort throughout the existence of the *AVD Laboratory* and of course during the current research period. Source for accessing normal and radical design data and knowledge have been (a) public domain literature, (b) institution and company internal sources, and (c) expert advice. For efficient handling of design related data and information, a dedicated computer-based aircraft conceptual design data-base (DB) has been set up, see Figure 4-1. Reference 2 presents the literature DB file-structure. This system handles disciplinary and inter-disciplinary literature relevant for conceptual design (methodologies, flight mechanics, aerodynamics, etc.), interview-protocols, flight vehicle case study information (descriptive-, historical-, numerical information on conventional and unconventional flight vehicle configurations), simulation and flight test information, etc. The overall requirement for the creation of the DB has been simplicity in construction, maintenance, and operation, to comply with the underlying time constraints.

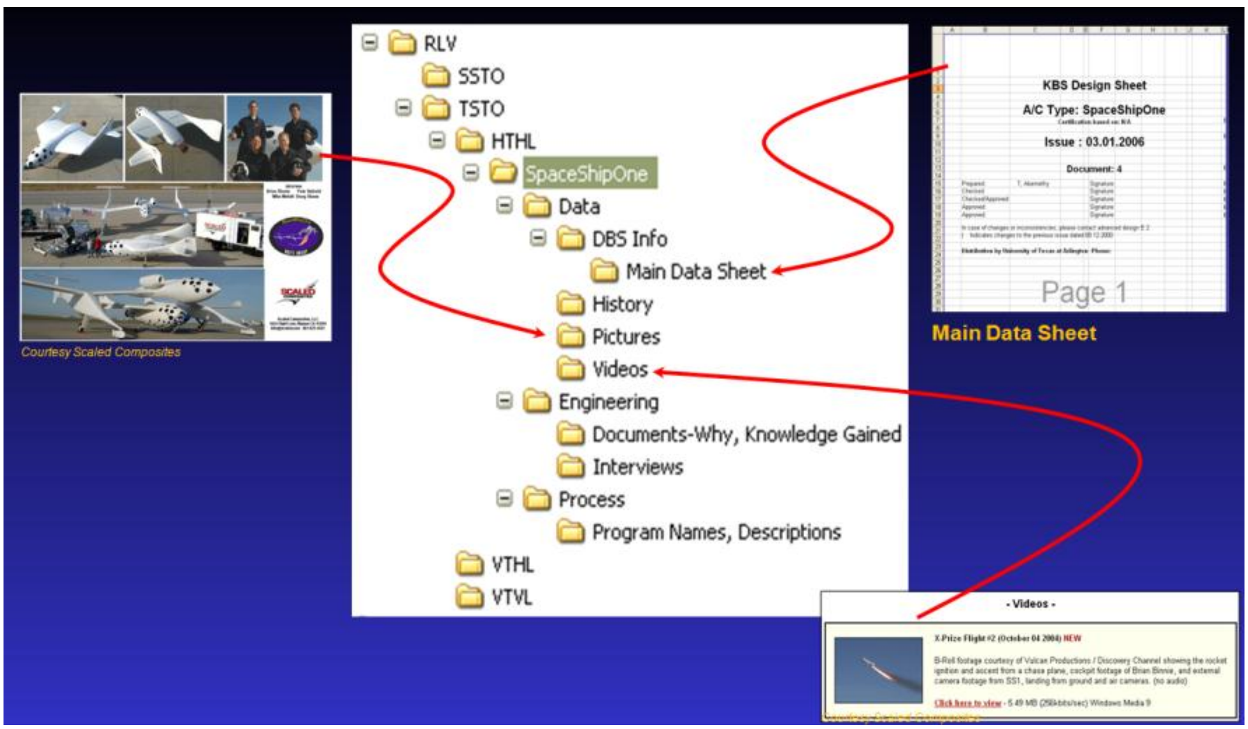


Fig. 4-1. Dedicated AVD Laboratory DB and organization scheme.

A detailed description of the DB is beyond the scope of the present discussion. The system has become a steadily growing, comprehensive, and effective working tool. Clearly, the quality of such system is only as good as the degree of completeness, actuality, and familiarity by the user. The DB has matured to be the central instrument for managing aircraft design data and information. However, the true potential of this system for utilizing design data and information has been opened up by proceeding as follows:

1. availability of a <u>*reference list*</u> containing meaningful entries; (*DB*)
2. availability of these references as a <u>*hardcopy*</u> on the table; (*DB*)
3. utilization of time to <u>*absorb*</u> the data & information; (*DB*)
4. <u>*review, select, classify, subtract, and document*</u> the data & information provided; (*DB*)
5. <u>*extraction, combination and utilization*</u> of data & information in a pre-defined manner. (*KB*)

The first four steps are handled within the DB. The DB has been put to use to provide in an intermediate step (step four) suitably selected, structured, and condensed flight vehicle conceptual design data and information. The research goal, to develop an air-breathing hypersonic demonstrator requires to account for as many design-related interactions as necessary, since the rationale for the evolution of aircraft is diverse as a quick browse through aviation history reveals. The aircraft design disciplines identified relevant and the representative case studies of design ingenuity selected, see Table 4-1, both elements need to be appreciated mutually, to efficiently serve the design understanding where innovation provided answers to otherwise troublesome problems. The updated DB embodies a technology-baseline attained, which is considered state-of-the-art for the current research undertaking.

Figure 4-2 summarizes four particular entries in the DB: (a) digital DB of past hypersonic demonstrator projects, (b) digital DB for rocket engines, (c) digital DB for carrier aircraft, and (c) digital DB for past hypersonic vehicle design solutions (visual/geometry evidence).

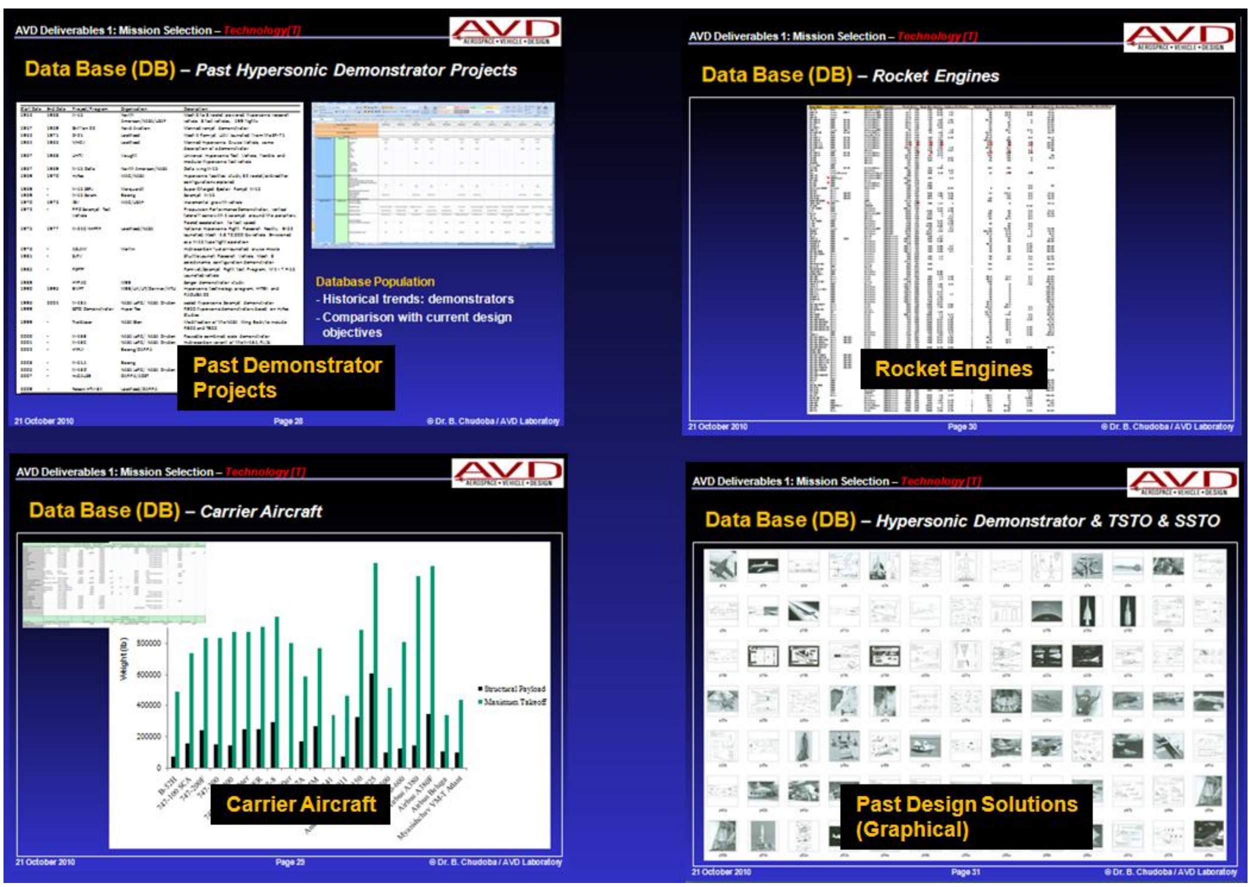


Fig. 4-2. Selected AVD Laboratory data-base (DB) entries.

Summarizing, all four DB development steps have been followed and completed to a satisfactory degree within the time span allocated. The knowledge-base (KB) step five has been organized outside the DB. Clearly, it is the process of knowledge extraction, knowledge compilation, and knowledge provision into an organized and concise format which finally makes relevant high-speed aircraft conceptual design knowledge available 'at the fingertips' for problem solving activities. For this purpose, a simplified knowledge-base (KB) has been constructed as detailed in the following sub-chapter.

4.2 HYPERSONIC FLIGHT VEHICLE KNOWLEDGE-BASE (KB)

The aircraft conceptual design knowledge-base (KB), as advanced and utilized for the present research undertaking, has to be considered an early development-version of a fully operational design knowledge-based system (KBS). Without reiterating the capability of exemplary KBSs, the KB system utilized here is a 'manual' system in contrast to the ideally automated KBS. However, independent on the degree of automation, both systems have in common that knowledge itself is the focus and that the knowledge acquisition activity is recognized as being one of the most problematic areas of KBS development. Clearly, it is the knowledge collecting, knowledge management and knowledge utilization activity, where the priorities for the present flight vehicle conceptual design KB have been laid due to time constraints imposed.

The primary objective of developing the dedicated hypersonic aircraft conceptual design KB has been, to make relevant normal and radical design knowledge effortlessly available. The particular strength of the system manifests, in that it enables the user to advance his/her understanding with respect to the variety of legacy high-speed aircraft and launch vehicle configurations by identifying aircraft configuration commonalties and peculiarities. This feature has been empowered by placing particular emphasis on consistently grouped flight vehicle configuration-specific design knowledge. As a result, design detail, for example longitudinal stability, can be compared between the range of aircraft configurations. This approach finally enables a reliable and trust-worthy generic aircraft configuration parameter identification process.

The hypersonic flight vehicle conceptual design KB for fixed-wing and lifting-body designs is subdivided into two main sections:

(a) *Longitudinal Motion*
(b) *Lateral/Directional Motion*

Each motion is subdivided into:

- *Flight Character* — *(Design Constraining Flight Conditions: trim, control, stability)*
- *Aerodynamic Character* — *(Stability and Control Derivatives:* u, u/t, w(α), w/t (α/t), *...)*
- *Flow Character* — *(Flow Phenomena: tuck, pitch-up, non-linearity, ...)*
- *Additional Grounds* — *(Landing gear location, geometry limitations, c.g. range, ...)*

Figure 4-3 overviews the lessons-learned section as described above. This section clearly emphasizes on physical understanding and design related decision-making of relevant aircraft case studies.

Figure 4-4 introduces the steps required to arrive at knowledge-derived numerical design guidelines. At first, intimate technical understanding of pertinent design case studies enables the identification of gross design-drivers and variables with significant impact on the overall design. Those gross design drivers then form the basis for the underlying sizing relations in the sizing methodology. The resulting numerical design guidelines represent a true continuum of the pertinent design characteristic in contrast to the narrow exposure of typical point-design characteristics.

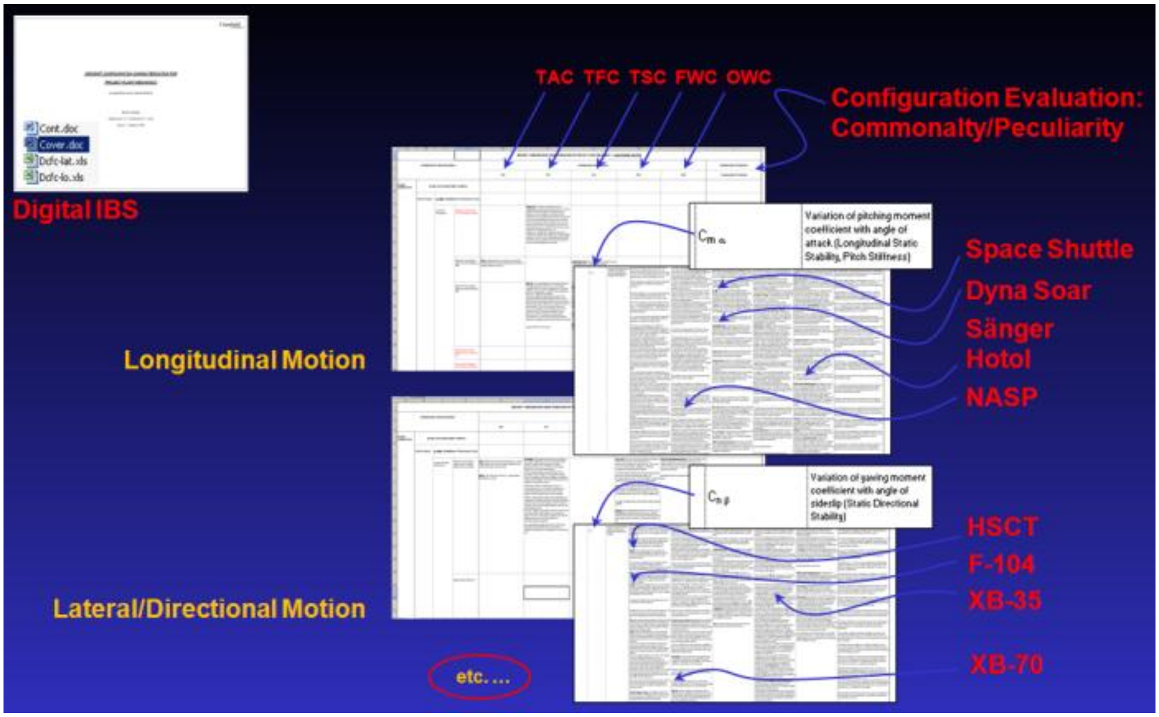


Fig. 4-3. Design lessons-learned of selected design case-studies.

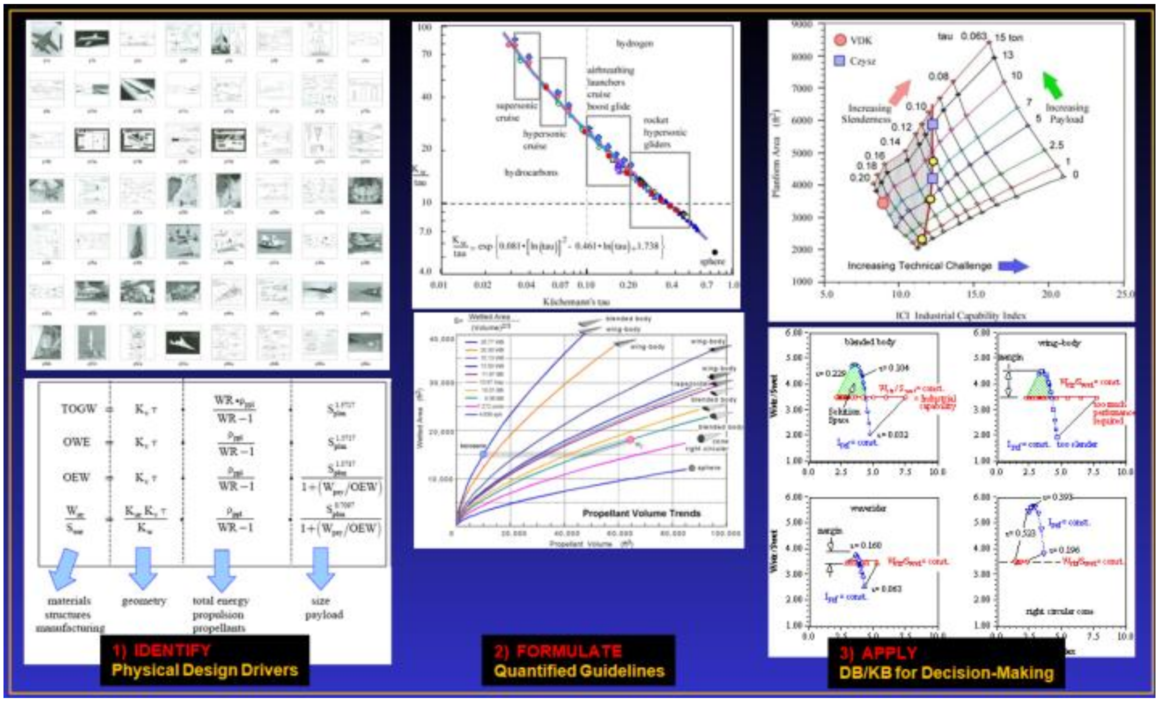


Fig. 4-4. KB development steps resulting in numerical design guidelines.

The ‘living-character’ of the DB and KB is ensured by permitting unconstrained data & knowledge entries as gained during the iterative design life-cycle, see Figure 3-3.

In summary, the dedicated hypersonic vehicle DB and KB have both matured towards fully integrated design support domains. The AVD Laboratory is routinely utilizing the project-specific DB and KB in concert with the process domain (sizing methodology), see Figure 4-5.

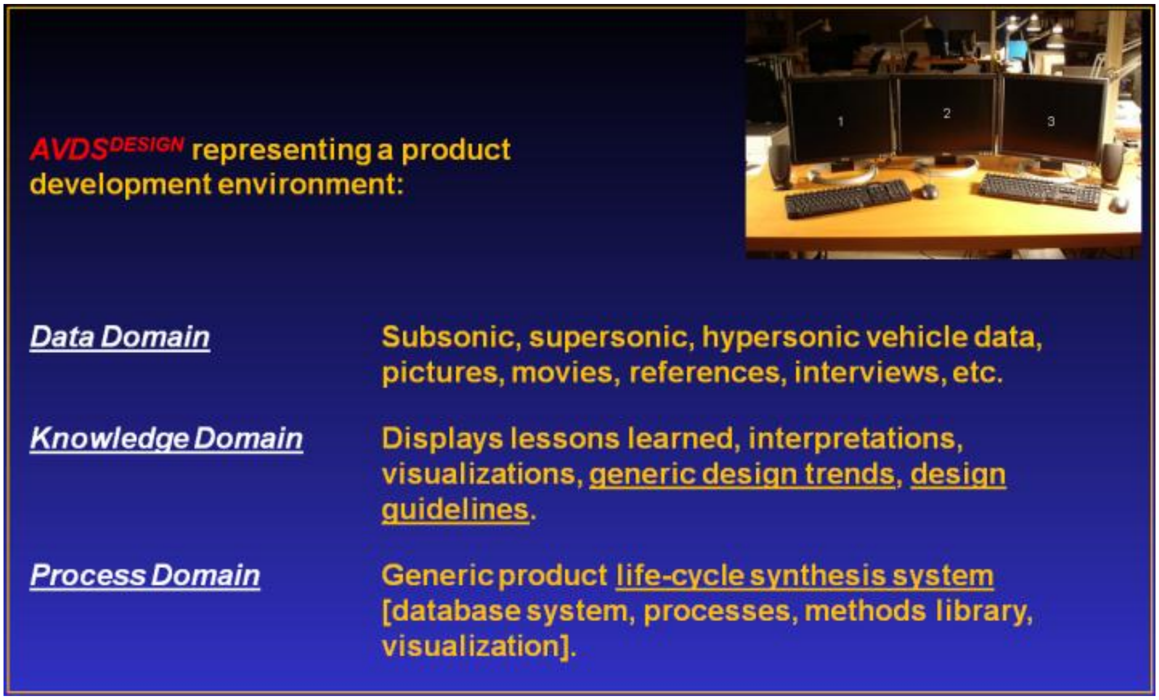


Fig. 4-5. Integration scheme of data domain, knowledge domain, and process domain.

5 OVERALL TRADE-SPACE 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.

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 5-1 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 5-1 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.

Table 5-1. 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

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 5-2 and Figure 5-1.

Table 5-2. 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	

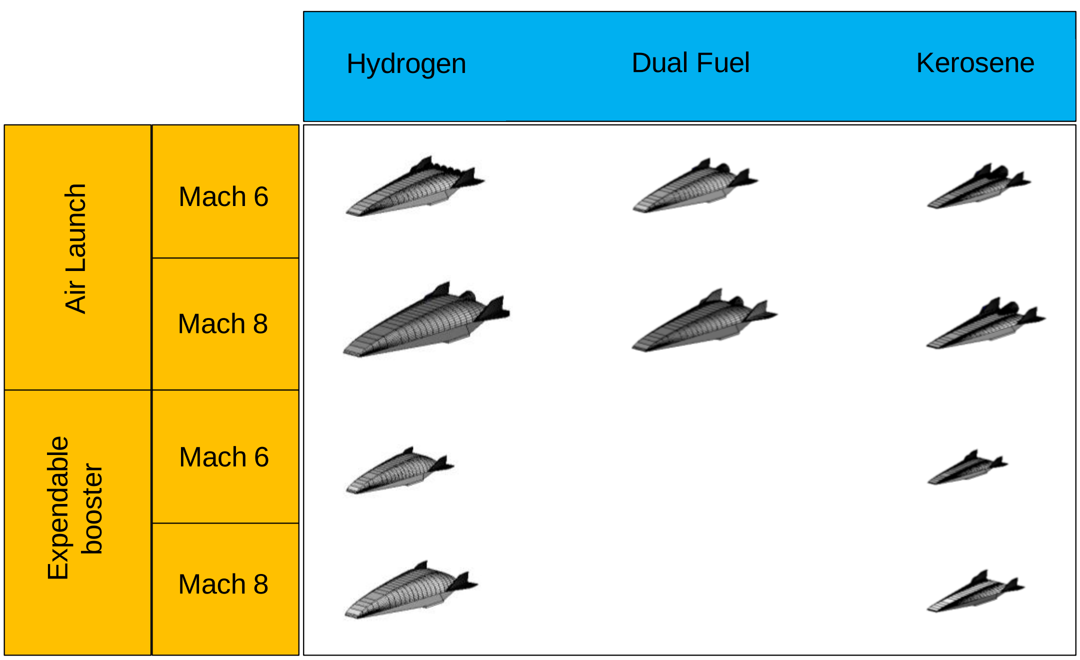


Fig. 5-1. Reduced trade-space explored.

6 PARAMETRIC SIZING AND SOLUTIONS SPACE SCREENING

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.

6.1 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 6-1 visualizes the top level sizing process implemented.

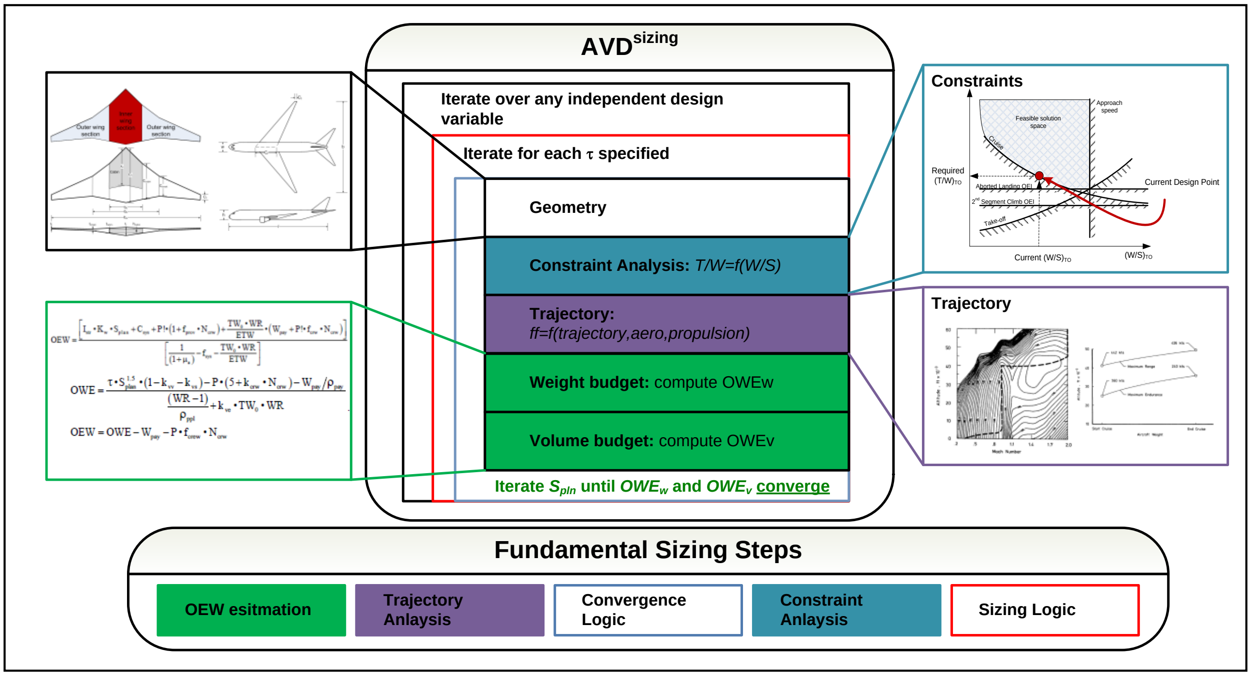


Fig. 6-1. AVD^{sizing} methodology visualized via Nassi-Schneidermann structogram.

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.

6.2 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 6-1 summarizes the disciplinary methods used for this study. Selected methods are further documented in Appendix A.

Table 6-1. 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

6.3 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 6-2.

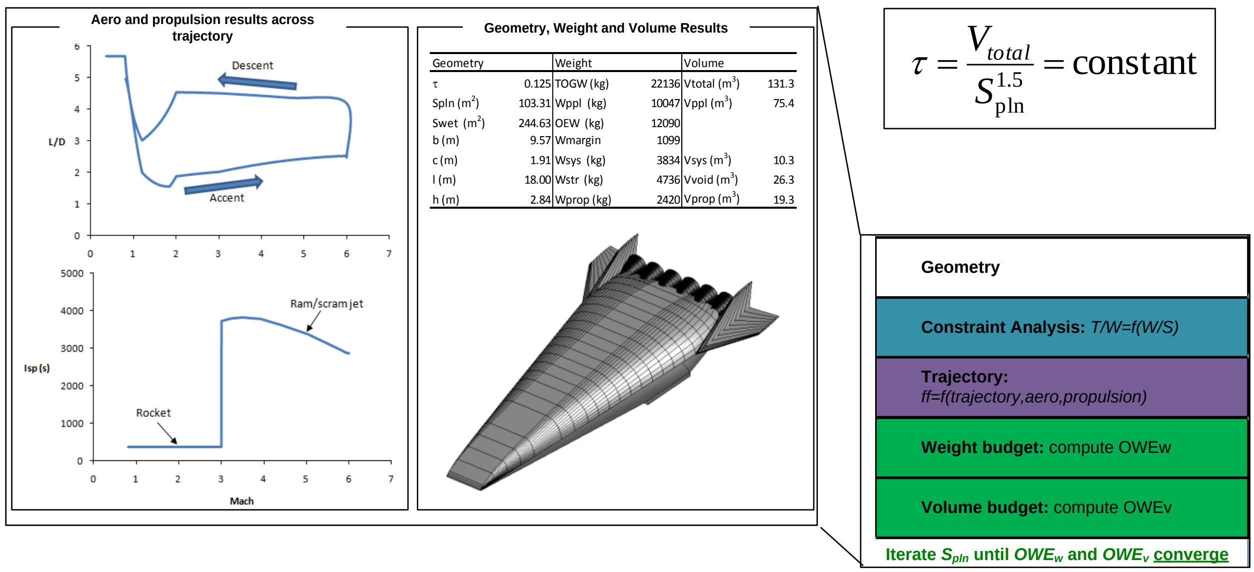


Fig. 6-2. Each design point represents a converged complete hypersonic vehicle (Example: Mach-6, 30 minutes, cruiser configuration).

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 6-3. 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.

<u>Solution Space Constraint Description:</u> 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 6-4.

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 6-4.

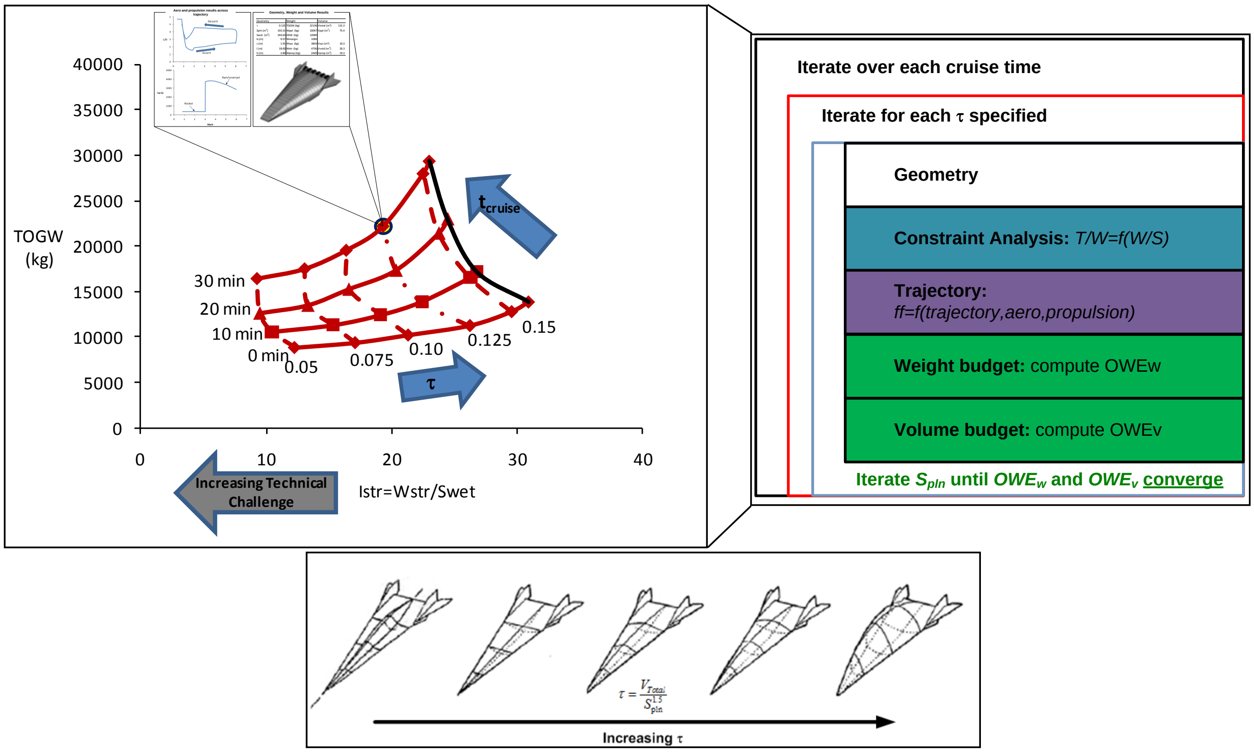


Fig. 6-3. Solution space carpet plot of *TOGW* and I_{str} for varying vehicle slenderness (τ) and cruise time.

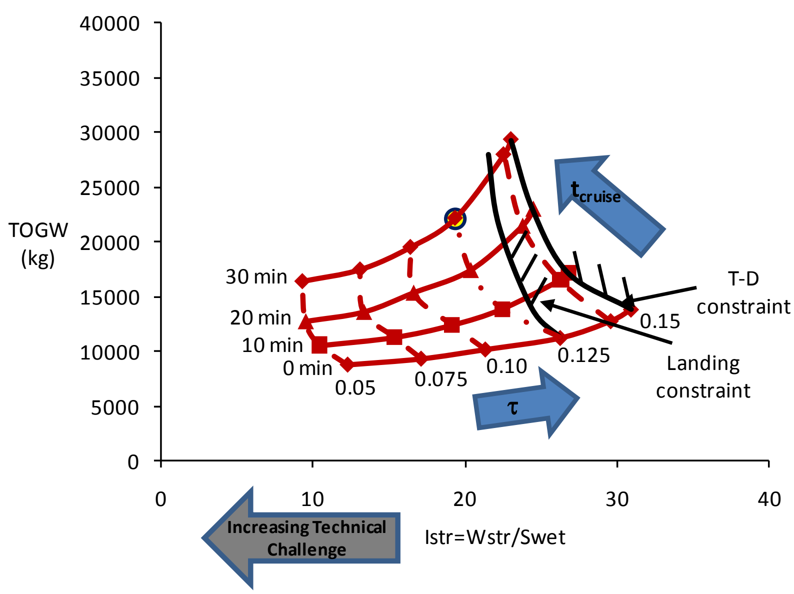


Fig. 6-4. Landing and *T-D* constraints imposed on the solution space. For the Mach 6 demonstrator, the landing constraint is more constraining than *T-D*.

Figure 6-4 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 6-5. Figure 6-6 documents the structural indices utilized to derive the technology solution space boundaries pertinent to the flight mission.

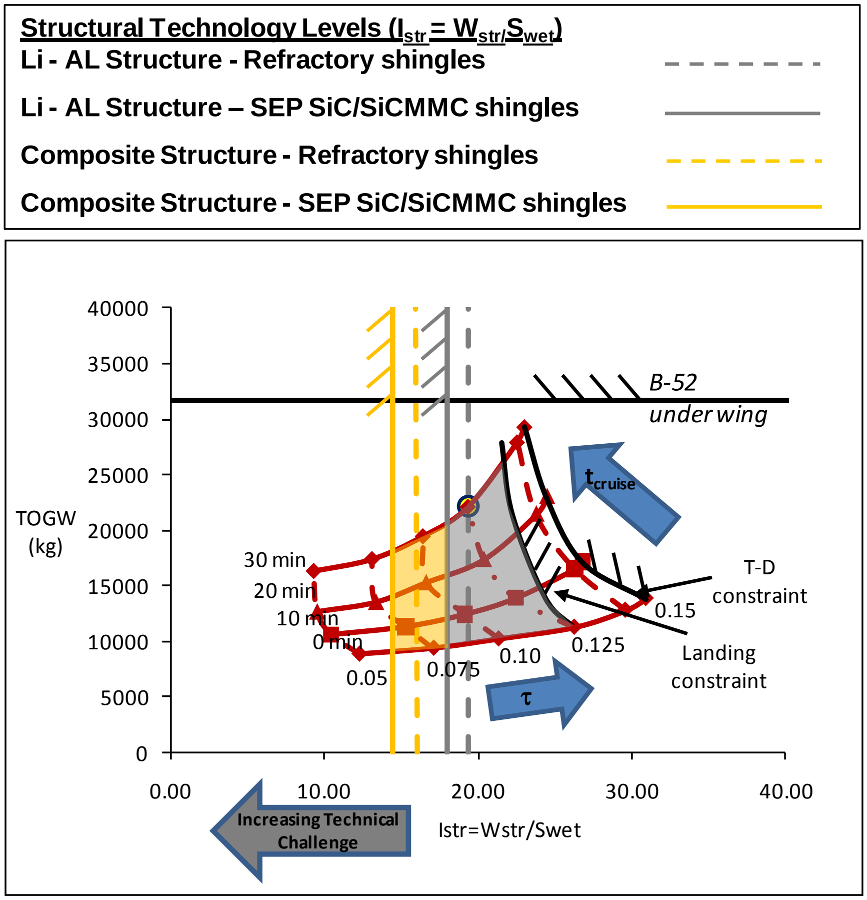
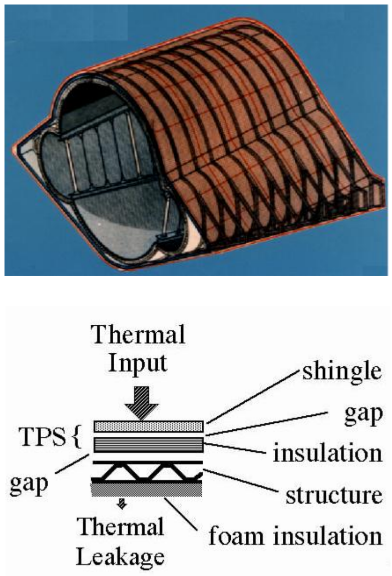


Fig. 6-5. Superposition of structural indices provides the final constraint to determine the technical solution space.

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 6-7. 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 6-8.

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***

Fig. 6-6. Definition of structural capability indices used for this study. (Ref 6)

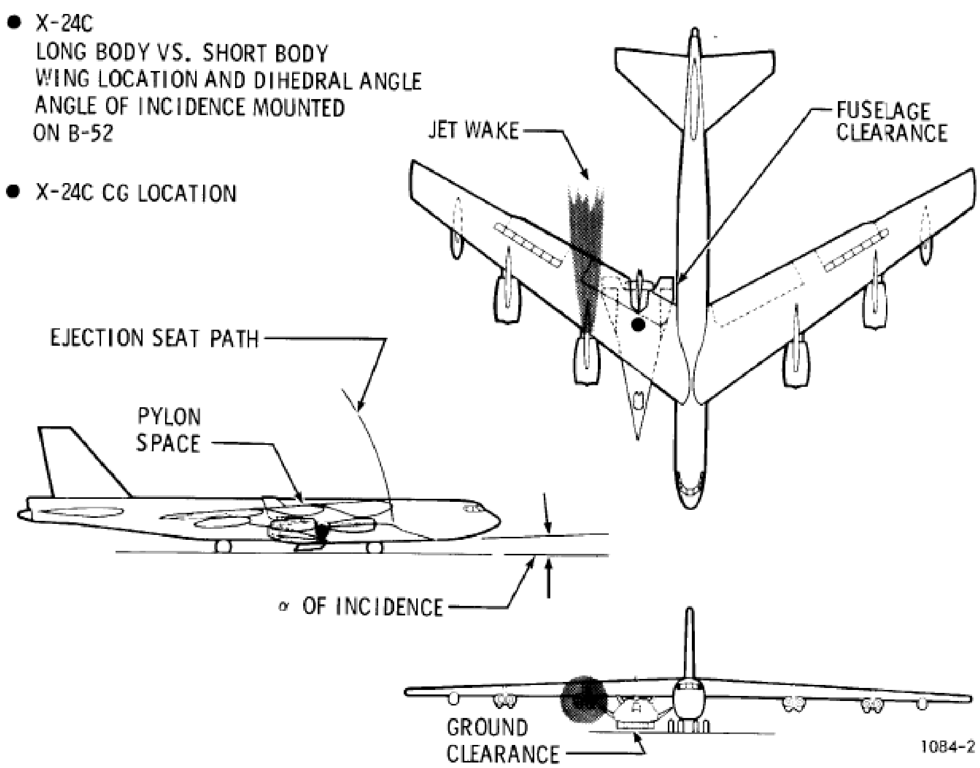


Fig. 6-7. B-52H under-wing mount geometric constraints. (Ref 15)

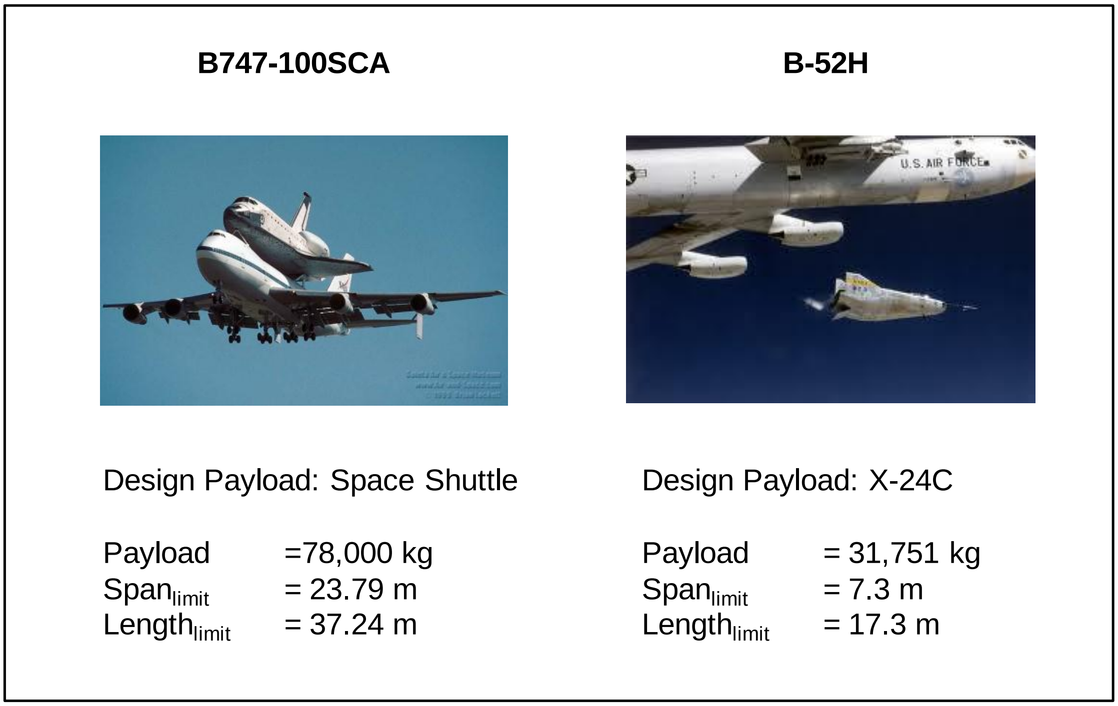


Fig. 6-8. Summary of B747-SCA and B-52H constraints for the hypersonic demonstrator study. (Ref 15,16)

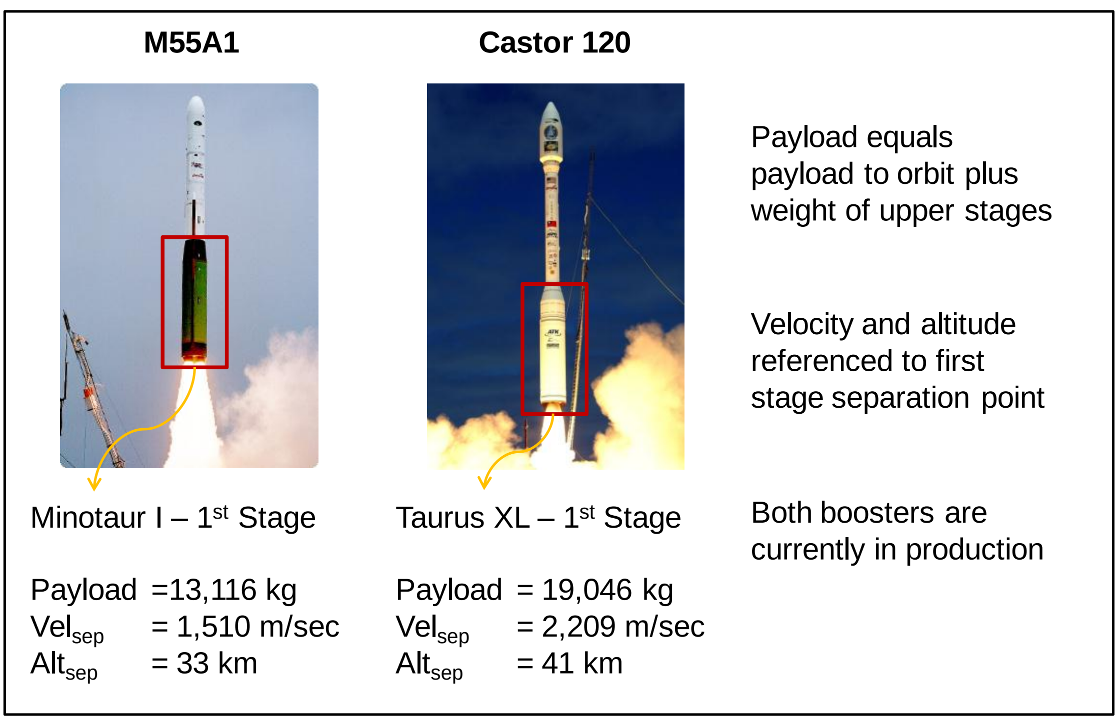


Fig. 6-9. Summary of Minotaur I and Taurus XL 1st stage constraints for the hypersonic demonstrator study. (Ref 17)

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 6-9. 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.

6.4 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 6-10. 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 6-10 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.

The remainder of this chapter is structured to address each specific trade-study in terms of: (1) trade-summary, (2) mission summary, (3) solutions space visualization, (4) carrier vehicle constraints, (5) additional sub-trades explored during the study, and (6) selected vehicle baseline design point.

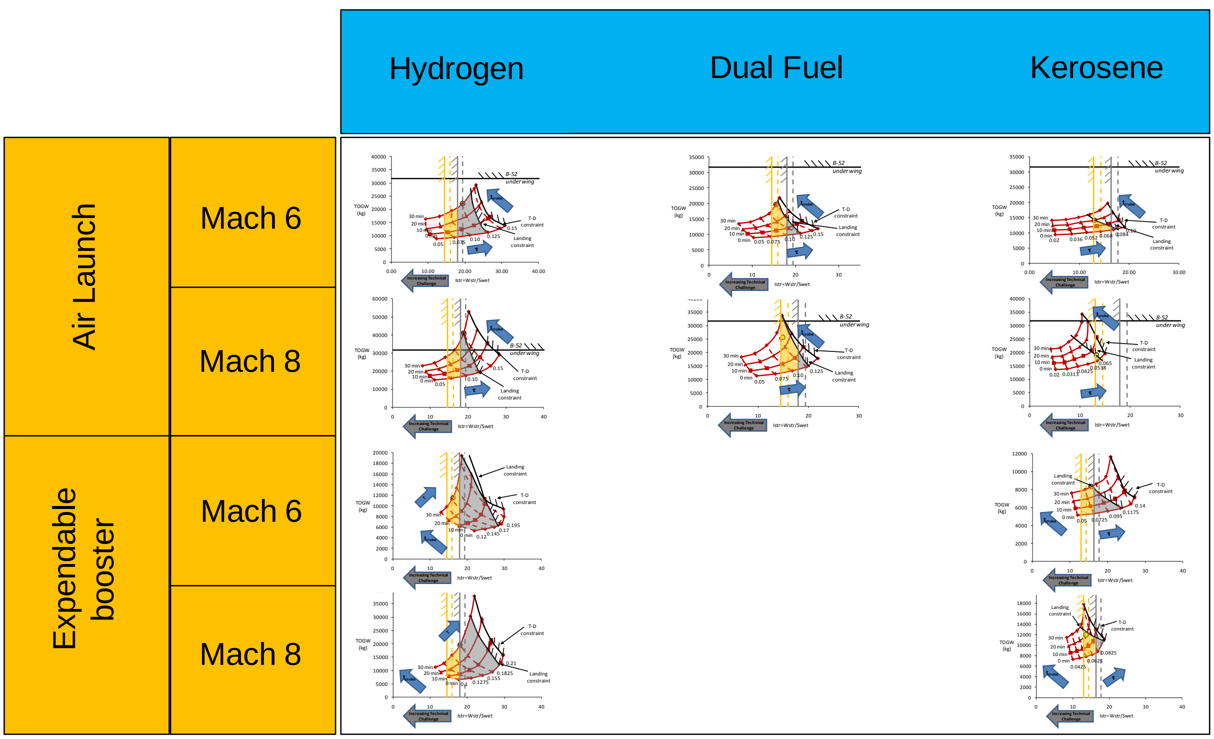


Fig. 6-10. Relative comparison of solution spaces for each design trade explored.

6.4.1 AIR-LAUNCHED, MACH 6, HYDROGEN FUEL

Trade Summary: This trade explores the Mach 6 cruise mission with varying endurance time. The vehicle is air-launched at 36,000 ft, 0.8M via carrier aircraft and rocket accelerated to ramjet start at 3.0M. Hydrogen fuel is utilized for the rocket and ramjet/scramjet. This trade determines that (a) the mission is feasible with current industrial capability, (b) the vehicle can be air-launched from the B747-100SCA, and (c) the RL-10-5A liquid hydrogen rocket is an appropriate accelerator motor.

Mission Summary: Table 6-2 summarizes the mission and operational constraints for the air-launched, Mach 6, hydrogen trade study.

Table 6-2. Air-Launch, Mach-6, Hydrogen Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	LH, LOX
Fuel density	74.63kg/m^3 (4.65 lbs/ft^3)
Oxidizer density	1,287 kg/m^3 (803.34 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-11 presents the solution space for the hydrogen fueled, Mach 6, air-launch trade. The solution space is bounded by the landing constraint, composite and aluminum structural constraints, and the 0 to 30 minutes cruise requirements. This trade is feasible with either structural or TPS material. The design point selected has an endurance of 30 minutes. It is composed of an aluminum structure and refractory metal TPS. This design point yields the largest design margin from the structural, landing and *T-D* constraints.

Carrier Constraints: While the B-52H could handle the weight of the demonstrator vehicle, it cannot accommodate the planform under the wing (constrained by the distance between the fuselage and the inboard engine). Figure 6-12 shows the B-52H's span and length constraints compared to the constant τ-contour ($\tau = 0.125$) of varying cruise time. From this comparison it becomes clear that only the 10 minutes cruise vehicle can be accommodated under the B-52H wing.

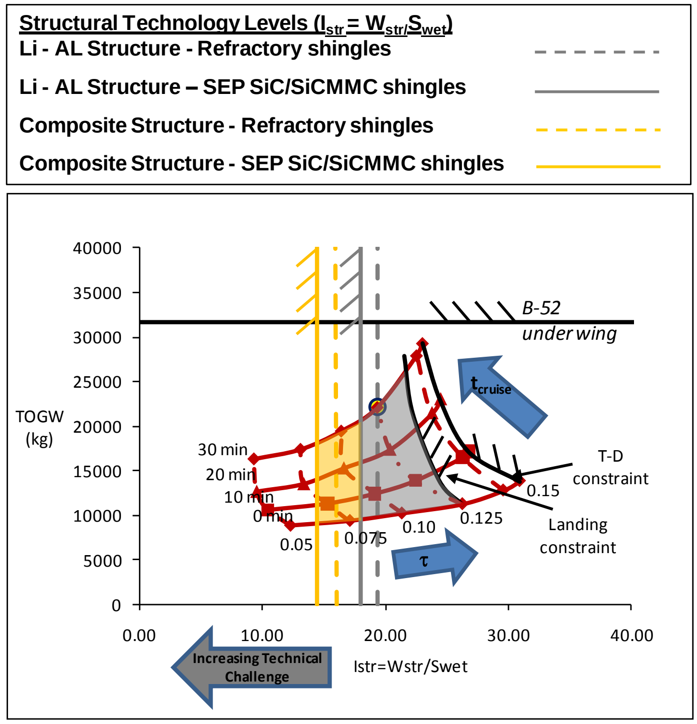


Fig. 6-11. Air-launched Mach 6 hydrogen-fueled trade solution space.

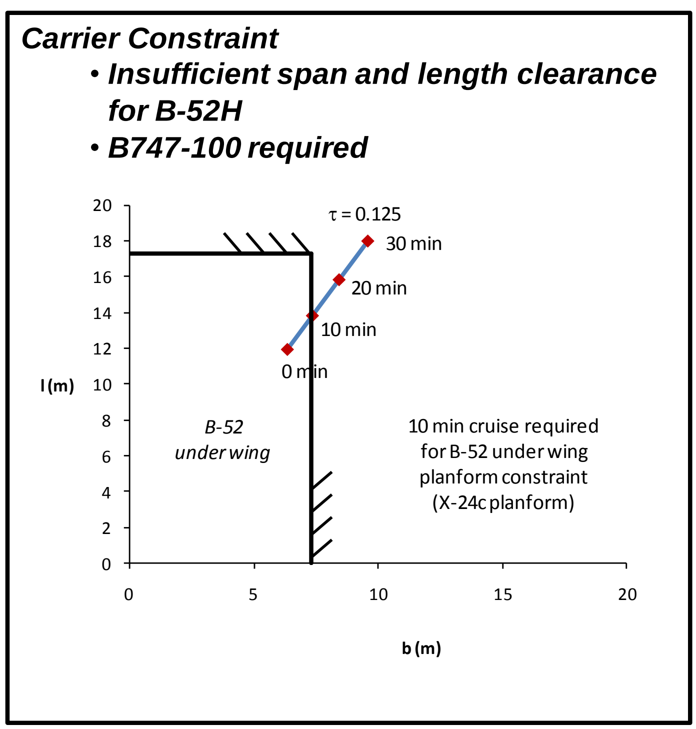


Fig. 6-12. B-52H planform area constraint and suggested design point, Mach 6, hydrogen-fuel trade.

Additional Trade Studies and Sensitivity Analysis: In addition, this trade study explores utilizing the RL-10A-5 (Reference 18) and Vulcain (Reference 17) rocket motors as well as varying the spatular ratio (*c/s*) of the lifting body. From this analysis it is determined that the RL-10 provides sufficient thrust for this vehicle, resulting in a lighter engine and *TOGW* vehicle relative to the Vulcain accelerated variant. A spatular ratio (*c/s*) of 0.5 provides the best balance between scramjet capture area and drag due to wetted area. As long as the spatular ratio is contained between 0.25 and 0.75, the parameter has a second order effect on vehicle size. Later studies can determine an optimum *c/s* ratio.

Suggested Design Point Summary: The selected design point has a cruise endurance of 30 minutes, seven (7) RL-10A-5 rocket motors, it is composed of aluminum structure, refractory metal TPS and is air-launched from the B747-100SCA. This design point provides adequate margin from the structural, landing and *T-D* constraints. The vehicle is summarized in Figure 6-13.

Design Summary				
t_{cruise}	30	min		
Down range	4,060	km	2,190	nm
TOGW	22,136	kg	48,802	lbs
W_{ppl}	10,047	kg	22,149	lbs
OEW	12,090	kg	26,653	lbs
τ	0.125			
S_{pln}	103.3	m^2	1,112	ft^2
B	9.57	m	31	ft
L	18.00	m	59	ft
L/D cruise	2.46			
Isp cruise(s)	2,613	s		
Trkt	453	kN	102	klbs
Nrkt (64.7 kN each)	7			

Suggested Design Point
- ***30 min cruise***
- ***τ = 0.125***
- ***B747-100 Launch Vehicle***
- ***RL-10 Rocket motor***
- ***Li-Al structure***
- ***SiC or Refractory TPS***

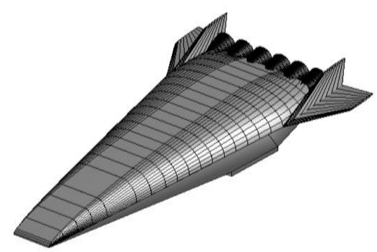


Fig. 6-13. Summary of suggested design point for the air-launched, Mach 6 hydrogen-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 6 cruise mission is feasible with LH_2 fuel, aluminum structure and metal TPS.
- The RL-10A-5 is a satisfactory of-the-shelf rocket for this mission.
- A *c/s* of 0.5 provides a good balance between engine capture area and wetted area. Spatular ratio has a 2^{nd} order effect on vehicle size and is therefore fixed at *c/s* = 0.5 for the remaining trade-studies.
- The B-52H could accommodate the vehicle from a load perspective, but the vehicle would not fit between the fuselage and inboard engine. Therefore, the B747-100SCA is the preferred launch vehicle.

6.4.2 AIR-LAUNCHED, MACH 8, HYDROGEN FUEL

Trade Summary: This trade explores the Mach 8 cruise mission with varying cruise endurance. The vehicle is air-launched at 36,000 ft, 0.8M via carrier aircraft and rocket accelerated to ramjet start at 3.0M. Hydrogen fuel is utilized for the rocket and ramjet/scramjet. This trade determines that (a) the mission is feasible with current industrial capability, (b) the vehicle can be air-launched from the B747-100SCA, and (c) the Vulcain liquid hydrogen rocket is an appropriate accelerator motor.

Mission Summary: Table 6-3 summarizes the mission and operational constraints for the air-launched, Mach 8, hydrogen trade study.

Table 6-3. Air-Launch, Mach 8, Hydrogen-Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	LH, LOX
Fuel density	74.63kg/m^3 (4.65 lbs/ft^3)
Oxidizer density	1,287 kg/m^3 (803.34 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-14 shows the solution space for the hydrogen fueled, Mach 8, air-launch trade. The solution space is constrained by the landing constraint, the composite and aluminum structural constraints and the 0 to 30 minutes cruise requirement. This trade demonstrates that the vehicle is feasible with either composite or aluminum structure from a cruise time of 0.0 minutes to 30 minutes. The design point is selected at the intersection of the landing constraint and the 30 minutes solution curve, providing a design margin for the structural (I_{str}) and propulsion (T-D) constraints.

Note that the slope of the 30 minutes cruise curve increases from $\tau = 0.125$ to 0.15. This increase in slope indicates that the vehicle size is increasingly sensitivity to changes in structural weight. The aluminum structure is selected to provide a conservative weight estimate; however, a composite structure vehicle will be easier to converge in future studies.

Carrier Constraints: The B-52H can support the weight of the demonstrator vehicle for 0 to 20 minutes cruise vehicles. However, it cannot accommodate the vehicle under its wing, see Figure 6-15. Plotting the span and vehicle length of a constant slenderness parameter ($\tau = 0.15$) with varying cruise time, it becomes clear that even the 0 minutes cruise time vehicle violates the planform requirement. Thus, the B747-100SCA must be utilized for the Mach-8 mission.

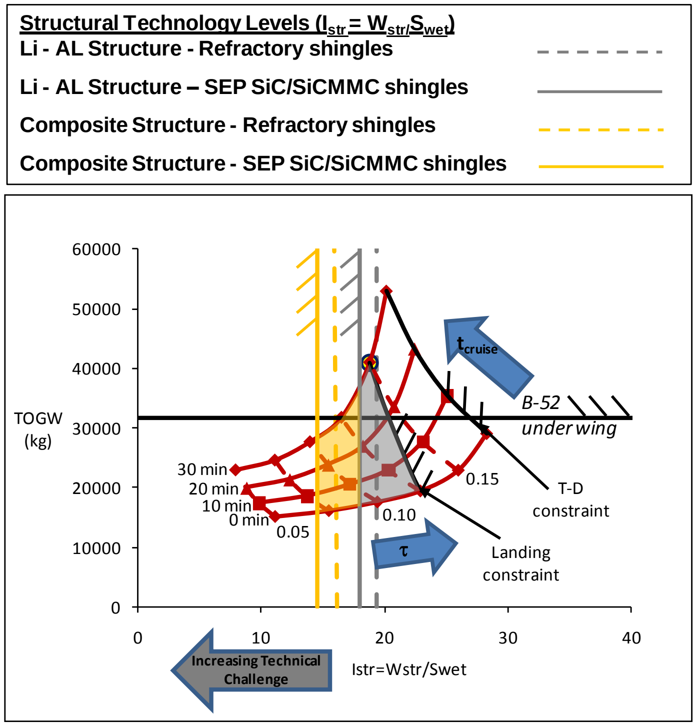


Fig. 6-14. Hydrogen-fuel, Mach 8 air-launch trade solution space.

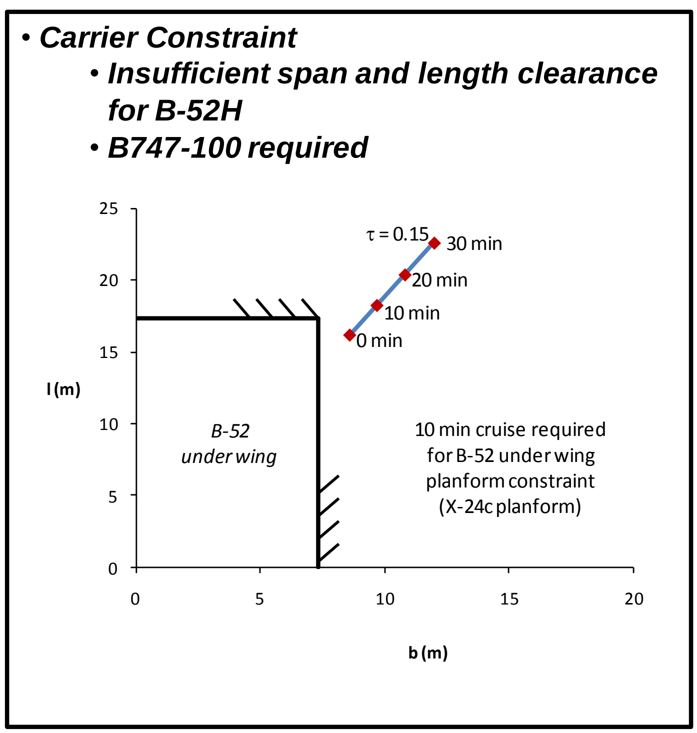


Fig. 6-15. B-52H planform area constraint and suggested design point, Mach 8, hydrogen-fuel trade.

Additional Trade Studies and Sensitivity Analysis: For this cruise mission, the RL-10A-5 and Vulcain rocket motors are explored. From this analysis it has been determined that the RL-10A-5 would require an excessive number of engines to provide sufficient thrust for the 30 minutes vehicle, requiring twelve (12) rocket motors. Therefore, the Vulcain engine is preferred even though it possesses more thrust then required for the design.

Suggested Design Point Summary: The selected design point has an endurance of 30 minutes, one (1) Vulcain rocket motor, aluminum structure, refractory metal TPS, and it is air-launched from the B747-100SCA. This design point provides adequate margin from the structural and *T-D* constraints. The vehicle is summarized with Figure 6-16.

Design Summary				
t_{cruise}	30	min		
Down range	6,300	km	3,402	nm
TOGW	40,900	kg	90,170	lbs
W_{ppl}	20,821	kg	45,903	lbs
OEW	20,079	kg	44,267	lbs
τ	0.15			
S_{pln}	161.2	m^2	1,735	ft^2
b	11.95	m	39	ft
l	22.48	m	74	ft
L/D cruise	2.31			
Isp cruise(s)	2,246	s		
Trkt	1,015	kN	228	klbs
Nrkt (1015 kN each)	1			

- ***Suggested Design Point***
  - ***30 min cruise***
  - ***τ = 0.15***
  - ***B747-100 Launch Vehicle***
  - ***Vulcain Rocket***
  - ***Li-Al structure***
  - ***SiC/SiCMMC TPS***

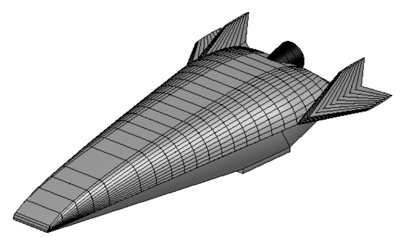


Fig. 6-16. Summary of suggested design point for the air-launched, Mach 8 hydrogen-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 8 cruise mission is feasible with LH_2 fuel, aluminum structure and refractory metal TPS.
- The Vulcain rocket is a satisfactory of-the-shelf rocket for this mission; however, a LH_2 rocket between the RL-10A-5 and Vulcain thrust classes is preferred.
- The B-52H cannot support the 30 minutes Mach 8 vehicle nor geometrically accommodate the vehicle under the wing. Therefore, the B747-100SCA is the preferred air-launch vehicle.

6.4.3 AIR-LAUNCHED, MACH 6, KEROSENE FUEL

Trade Summary: This trade explores the Mach 6 cruise mission with varying endurance time. The vehicle is air-launched at 36,000 ft, 0.8M via carrier aircraft and rocket accelerated to ramjet start at 3.0M. Kerosene fuel is utilized for the rocket and ramjet/scramjet. It is determined that the 30 minutes mission is not feasible with current industrial capability. The 20 minutes cruise represents the endurance limit bounded by the intersection of the landing constraint and composite structure constraint. This flight vehicle can be air-launched from the B-52H, it utilizes the Merlin kerosene rocket for acceleration to ramjet start. However, an off-the-shelf rocket may present an integration problem due to the high slenderness of kerosene vehicles, reducing the upper surface height.

Mission Summary: Table 6-4 summarizes the mission and operational constraints for the air-launched, Mach 6, kerosene trade study.

Table 6-4. Air-Launch, Mach 6, Kerosene-Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	LH, LOX
Fuel density	820.0 kg/m^3 (51.2 lbs/ft^3)
Oxidizer density	1,287 kg/m^3 (803.34 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-17 shows the solution space for the kerosene-fueled, Mach 6, air-launched trade. The solution space is constrained by the landing constraint, the composite structural constraint, and the 0 to 20 minutes cruise requirement. This trade demonstrates that the kerosene vehicle is more severely constrained via the landing field length compared to the hydrogen vehicle due to the increased fuel density, which translates into higher wing loadings. In case the landing constraint is relaxed, a 30 minutes composite vehicle is technically feasible. The selected design point is at the intersection of the landing constraint, composite structure constraint, and 20 minutes cruise solution curve. This design point represents a maximum endurance vehicle while still allowing for: (a) the aborted landing condition, (b) a reasonable propulsion margin (distance from *T-D*), and (c) a limited structural margin. In order to increase the structural design margin, the cruise time must be reduced to 10 minutes.

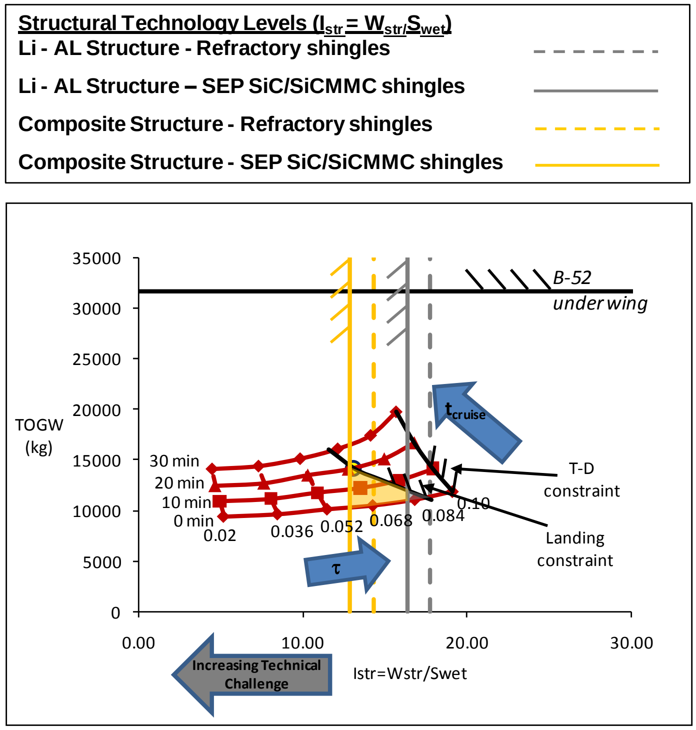


Fig. 6-17. Kerosene-fuel Mach-6 air-launched trade solution space.

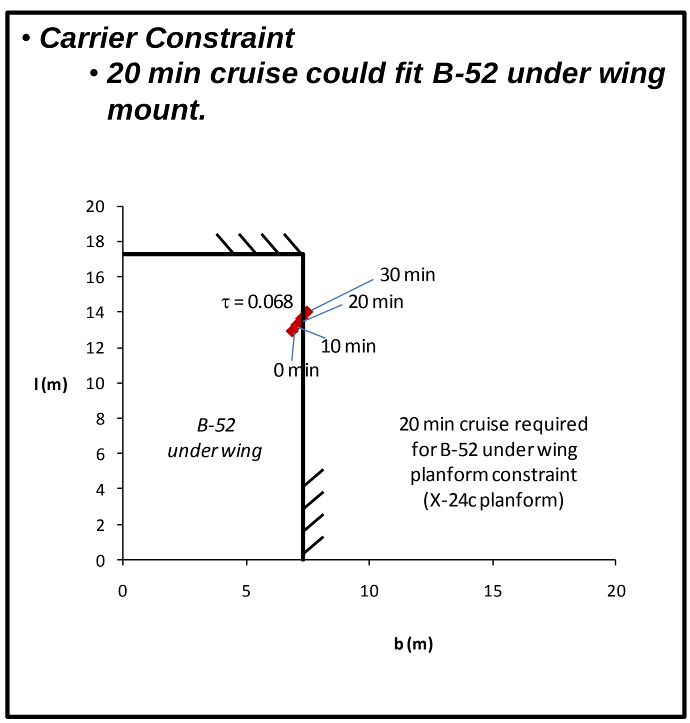


Fig. 6-18. B-52 planform area constraint and suggested design point, Mach 6, kerosene-fuel trade.

Carrier Constraints: The B-52H can support the weight of all vehicles converged in Figure 6-17. The 20 minutes cruise vehicle complies with the planform constraints for the B-52H wing mount, see Figure 6-18. Therefore, the B-52H is selected as the launch vehicle for this trade.

Additional Trade Studies and Sensitivity Analysis: None; the Merlin engine is representative of the thrust class required.

Suggested Design Point Summary: The selected design point for this trade consists of air-launch from the B-52H and acceleration to ramjet start with the Merlin rocket motor. However, due to the slenderness required for the vehicle, the rocket accelerator integration will not geometrically fit into the upper surface of the vehicle. This integration will require further design studies if a kerosene Mach 6, air-launched demonstrator is selected. The vehicle is summarized in Figure 6-19.

Design Summary				
t_{cruise}	20	min		
Down range	3,480	km	1,880	nm
TOGW	14,191	kg	31,287	lbs
W_{ppl}	7,715	kg	17,009	lbs
OEW	6,476	kg	14,277	lbs
τ	0.07			
S_{pln}	58.4	m^2	628	ft^2
b	7.19	m	24	ft
l	13.53	m	44	ft
L/D cruise	3.79			
Isp cruise(s)	943	s		
Trkt	512	kN	115	klbs
Nrkt (512 kN each)	1			

- ***Suggested Design Point***
  - ***20 min cruise***
  - ***τ = 0.07***
  - ***B-52 Launch Vehicle***
  - ***Merlin Rocket motor***
  - ***Composite structure***
  - ***Si/SiCMMCTPS***

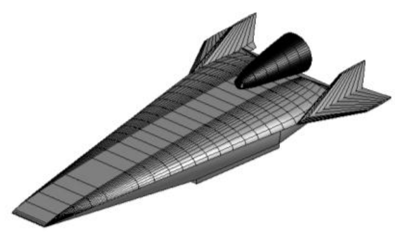


Fig. 6-19. Summary of suggested design point for the air-launched, Mach 6 kerosene-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 6 kerosene mission is feasible for 20 minutes cruise endurance with a composite structure. If the landing constraint is relaxed, the endurance can be increased to 30 minutes or the 20 minutes vehicle could be constructed of aluminum.
- The Merlin rocket has satisfactory thrust performance; however, an off-the-shelf rocket will present integration problems due to the required slenderness of the kerosene endurance vehicle.
- The B-52H could support the selected 20 minutes Mach 6 vehicle.

6.4.4 AIR-LAUNCHED, MACH 8, KEROSENE FUEL

Trade Summary: This trade explores the air-launched, Mach 8 kerosene cruise mission with varying cruise endurance. The vehicle is air-launched at 36,000 ft, 0.8M via carrier aircraft and rocket accelerated to ramjet start at 3.0M. Kerosene fuel is utilized for the rocket and ramjet/scramjet. It is determined that the 30 minutes mission is not feasible with the current industrial capability. The 4.5 minutes cruise represents the endurance limit bounded by the intersection of the landing constraint and composite structure constraint. The 4.5 minutes cruise vehicle can be air-launched from the B-52H; it utilizes the Merlin kerosene rocket for acceleration to ramjet start. However, an off-the-shelf rocket may present an integration problem due to the required low slenderness of kerosene vehicles.

Mission Summary: Table 6-5 summarizes the mission and operational constraints for the air-launched, Mach 8, kerosene trade study.

Table 6-5. Air-Launch, Mach 8, Kerosene-Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	RP-1, LOX
Fuel density	820.0 kg/m^3 (51.2 lbs/ft^3)
Oxidizer density	1,287 kg/m^3 (803.34 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-20 shows the solution space for the kerosene-fueled, Mach 8, air-launched trade. The solution space is bounded by the landing constraint, composite structural constraint, and 0 to 30 minutes cruise contour. This demonstrates that the kerosene vehicle is more severely constrained by the landing field length relative to hydrogen due to the increased fuel density which translates into higher wing loadings. The increase in cruise Mach number from 6 to 8 shifts the solution space up and to the left, leaving only a small feasible region with a maximum endurance of 4.5 minutes. In case the landing constraint is relaxed, a 10 minutes cruise composite vehicle is technically feasible. However, such a vehicle will be dangerously close to the thrust minus drag (T-D) constraint.

The selected design point is at the intersection of the landing and composite structure constraint, representing the maximum endurance based on the current industry capability available.

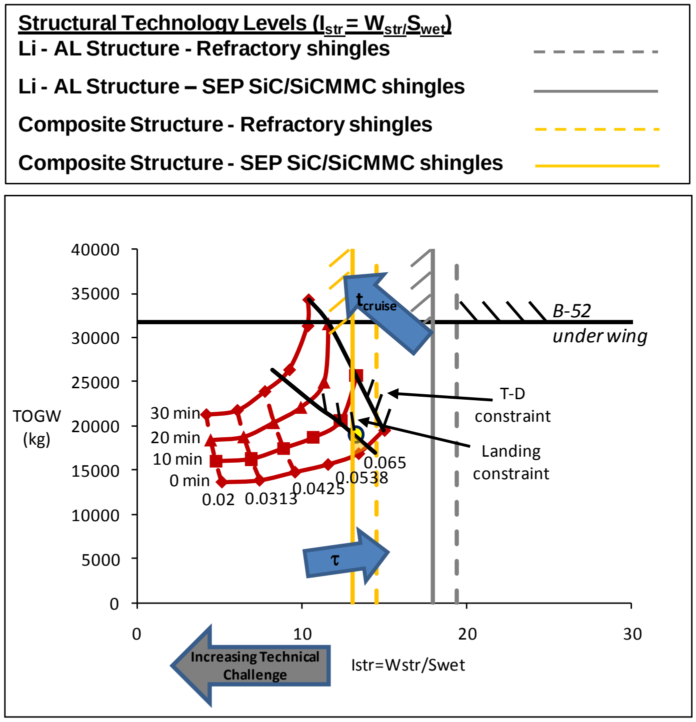


Fig. 6-20. Kerosene-fuel Mach 8 air-launched trade solution space.

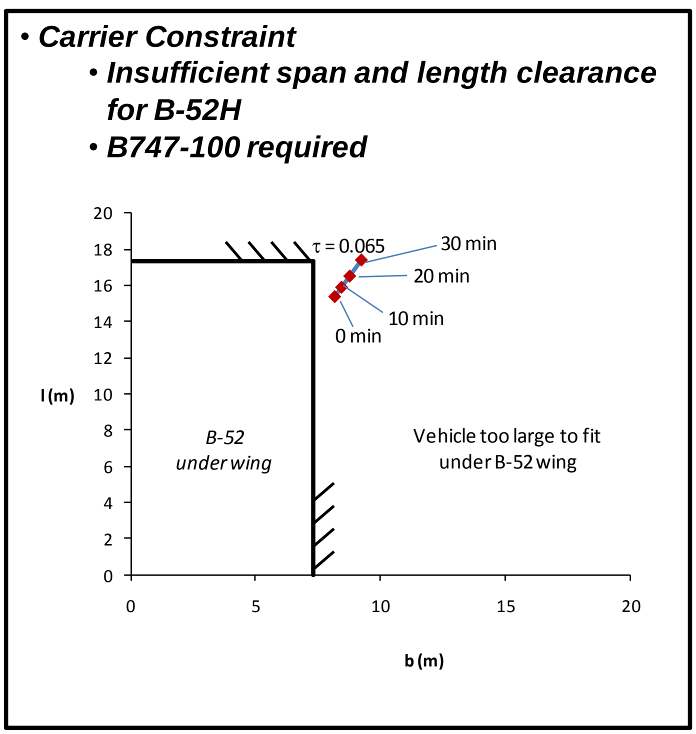


Fig. 6-21. B-52H planform area constraint and suggested design point, Mach 8, kerosene-fuel trade.

Carrier Constraints: As with the Mach 8 hydrogen vehicle, none of the vehicles will fit geometrically under the B-52 wing. Therefore, the B747-100SCA is the required carrier aircraft, see Figure 6-21.

Additional Trade Studies and Sensitivity Analysis: None; the Merlin engine is representative of the thrust class required.

Suggested Design Point Summary: The selected design point for this mission will consist of an air-launch from the B747-100SCA, and acceleration to ramjet start with the Merlin rocket motor. However, due to slenderness requirements, the rocket accelerator integration will geometrically not fit into the upper surface of the vehicle. The integration will require further research if a kerosene Mach 8, air-launched demonstrator is selected. The vehicle is summarized in Figure 6-22.

Design Summary				
t_{cruise}	4.5	min		
Down range	3,270	km	1,770	nm
TOGW	19,013	kg	41,917	lbs
W_{ppl}	10,627	kg	23,429	lbs
OEW	8,386	kg	18,488	lbs
τ	0.0675			
S_{pln}	76.7	m^2	826	ft^2
b	8.24	m	27	ft
l	15.51	m	51	ft
L/D cruise	3.39			
Isp cruise(s)	753	s		
Trkt	512	kN	115	klbs
Nrkt (512 kN each)	1			

- ***Suggested Design Point***
  - ***20 min cruise***
  - ***τ = 0.07***
  - ***B-52 Launch Vehicle***
  - ***Merlin Rocket motor***
  - ***Composite structure***
  - ***Si/SiCMMCTPS***

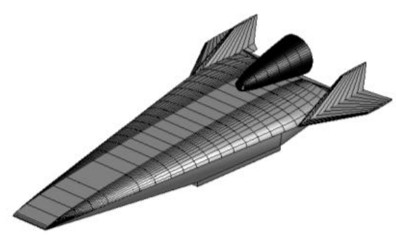


Fig. 6-22. Summary of suggested design point for the air-launched, Mach 8 kerosene-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 8 cruise mission is feasible with kerosene for a maximum endurance of 4.5 minutes. If the landing constraint is relaxed, the endurance can be increased to 10 minutes. This represents the smallest solution space of all trades explored.
- The Merlin rocket has satisfactory thrust performance; however, an off-the-shelf rocket will present integration problems due to the required slenderness of the kerosene endurance vehicles.
- The B747-100SCA is required for air-launch.

6.4.5 AIR-LAUNCHED, MACH 6, DUAL-FUEL

Trade Summary: The Mach 8 hydrogen fueled demonstrator shows that the 1,000 kN thrust class Vulcain rocket is feasible; however, only a 600 kN rocket is required. Given that the Merlin rocket is in the 500 kN thrust class and the X-24C utilized a kerosene rocket and hydrogen scramjet (Reference 15), it has been decided to add a dual-fuel option to the air-launch studies.

This trade explores the Mach 6 cruise mission with varying endurance time. The vehicle is air-launched at 36,000 ft, 0.8M via carrier aircraft and rocket accelerated to ramjet start at 3.0M. Kerosene is utilized for the rocket and hydrogen for the ramjet/scramjet. This trade determines that (a) the mission is feasible with the current industrial capability, (b) the vehicle can be air-launched from the B747-100SCA, and (c) the Merlin kerosene rocket is an appropriate accelerator motor.

Mission Summary: Table 6-6 summarizes the mission and operational constraints for the air-launched, Mach 6, dual-fuel trade study.

Table 6-6. Air-Launch, Mach 6, Dual-Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	RP-1, LH, LOX
Kerosene fuel density	820.0 kg/m^3 (51.2 lbs/ft^3)
Hydrogen fuel density	74.63kg/m^3 (4.65 lbs/ft^3)
Oxidizer density	1,287 kg/m^3 (803.34 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-23 shows the solution space for the dual-fueled, Mach 6, air-launched trade. The solution space is constrained by the landing constraint, the composite and aluminum structural constraints, and the 0 to 30 minutes cruise requirements. This vehicle is feasible with composite structure and either TPS. The design point selected has an endurance of 30 minutes at Mach 6 and is composed of a composite structure and refractory metal TPS. This design point provides the required endurance with some margin for both structural (I_{str}) and propulsion (*T-D*) technology constraints. While the dual-fuel variant is technically feasible, it requires a lighter structure compared to the equivalent hydrogen vehicle due to the reduced I_{sp} of the kerosene rocket.

Carrier Constraints: Similar to the Mach 6 hydrogen vehicle, the B-52H can support the weight of the vehicle but not the geometry, see Figure 6-24.

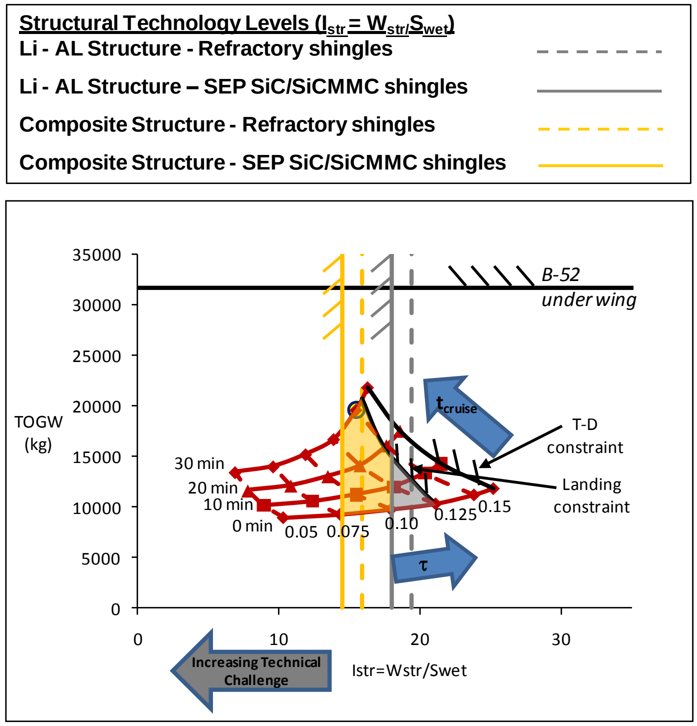


Fig. 6-23. Dual-fuel Mach 6 air-launched trade solution space.

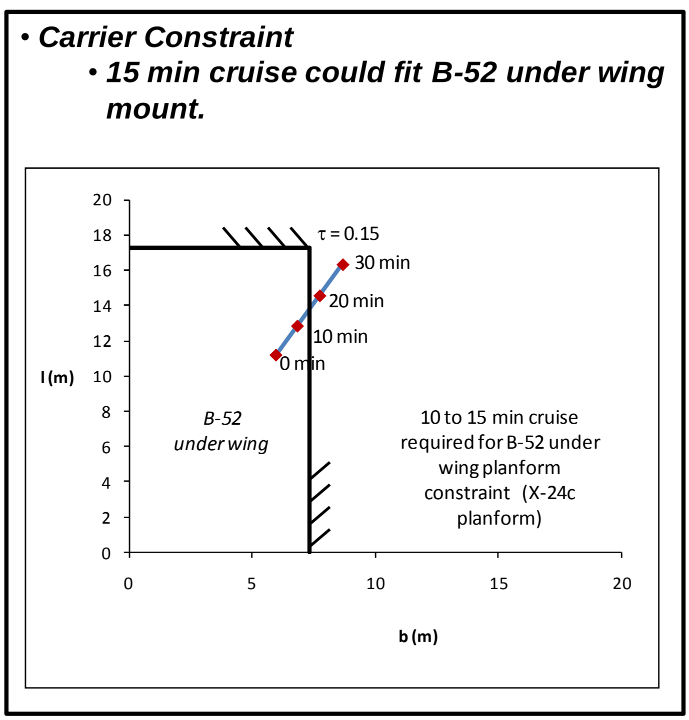


Fig. 6-24. B-52H planform area constraint and suggested design point, Mach 6, dual-fuel trade.

Additional Trade Studies and Sensitivity Analysis: None; the Merlin engine is representative for the thrust class required.

Suggested Design Point Summary: The selected design point for this mission will consist of air-launch from the B747-100SCA and acceleration to ramjet start with the Merlin rocket motor. This vehicle will require composite structure to compensate for the reduced I_{sp} of kerosene. The vehicle is summarized in Figure 6-25.

Design Summary				
t_{cruise}	30	min		
Down range	4,226	km	2,282	nm
TOGW	19,606	kg	43,224	lbs
W_{ppl}	10,126	kg	22,324	lbs
OEW	9,480	kg	20,900	lbs
τ	0.15			
S_{pln}	84.7	m^2	912	ft^2
B	8.66	m	28	ft
L	16.30	m	53	ft
L/D cruise	2.03			
Isp cruise(s)	2,619	s		
Trkt	512	kN	115	klbs
Nrkt (512 kN each)	1			

- ***Suggested Design Point***
  - ***30 min cruise***
  - ***τ = 0.15***
  - ***B747-100 Launch Vehicle***
  - ***Merlin Rocket motor***
  - ***Composite structure***
  - ***SiC or refractory metal TPS***

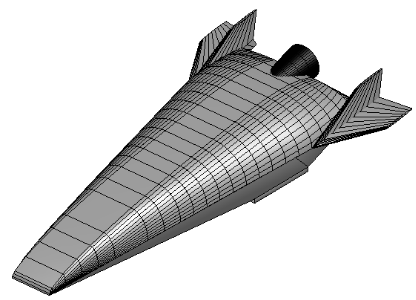


Fig. 6-25. Summary of suggested design point for the air-launched, Mach 6 dual-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 6 cruise mission is feasible with the dual-fuel option for 30 minutes endurance. However, a composite structure is required to compensate for the reduced I_{sp} and heavier kerosene rocket fuel.
- The Merlin rocket has satisfactory performance as an off-the-shelf rocket. The dual-fuel option will not have the same integration issues as the kerosene-only vehicles due to the decrease in slenderness.
- The 30 minutes vehicle requires the B-747-100SCA for air launch.

6.4.6 AIR-LAUNCHED, MACH 8, DUAL-FUEL

Trade Summary: The Mach 8 hydrogen fueled demonstrator, using the 1,000 kN thrust class Vulcain rocket, shows feasibility. However, only a 600 kN rocket is required. Given that the Merlin rocket is in the 500 kN thrust class and the X-24C has been utilizing a kerosene rocket and hydrogen scramjet (Reference 15), it has been decided to add a dual-fuel option to the air-launch studies.

This trade explores the Mach 8 cruise mission with varying endurance time. The vehicle is air-launched at 36,000 ft, 0.8M via carrier aircraft and rocket accelerated to ramjet start at 3.0M. Kerosene is utilized for the rocket and hydrogen for the ramjet/scramjet. This trade determines that (a) the mission is feasible with the current industrial capability, (b) the vehicle can be air-launched from the B747-100SCA, and (c) the Merlin rocket is an appropriate thrust class accelerator motor.

Mission Summary: Table 6-7 summarizes the mission and operational constraints for the air-launched, Mach 6, dual-fuel trade study.

Table 6-7. Air-Launch, Mach 8, Dual-Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	RP-1, LH, LOX
Kerosene fuel density	820.0 kg/m^3 (51.2 lbs/ft^3)
Hydrogen fuel density	74.63kg/m^3 (4.65 lbs/ft^3)
Oxidizer density	1,287 kg/m^3 (803.34 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-26 shows the solution space for the dual-fuel, Mach 8, air-launched trade. The solution space is constrained by the landing constraint, composite structure, and the 0 to 30 minutes solution requirements. Interestingly, the thrust minus drag (*T-D*), landing and composite structure constraints all coalesce at a single point on the 30 minutes solution curve, representing a zero margin design point. To allow for a propulsion margin, a 25 minutes cruise time design point is selected. In the case of the dual-fuel Mach 8 vehicle, the increased weight of kerosene and reduced I_{sp} results in reduced cruise endurance compared to the all-hydrogen vehicle alternative.

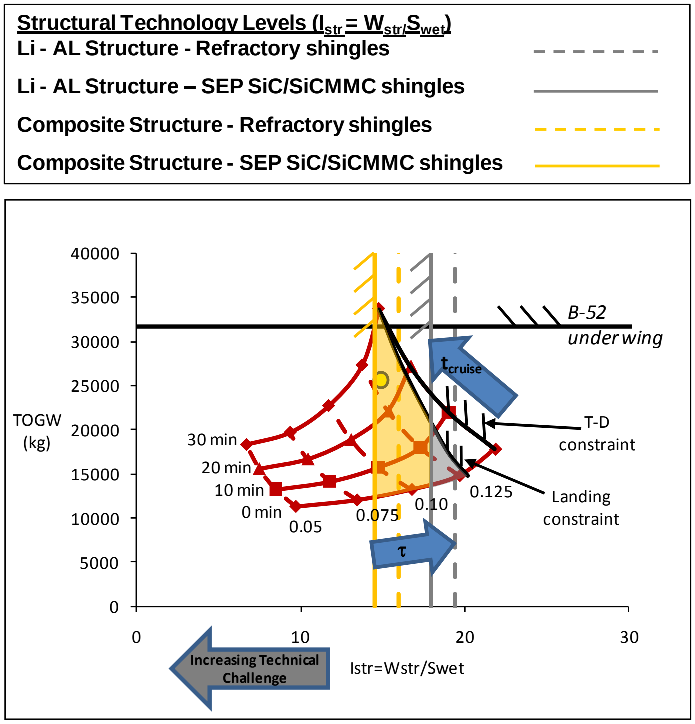


Fig. 6-26. Dual-fuel, Mach-8 air-launched trade solution space.

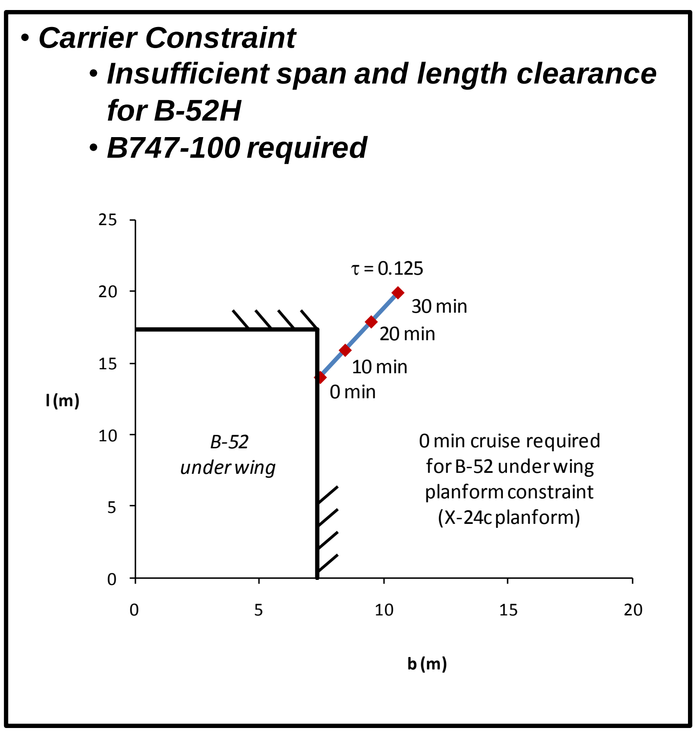


Fig. 6-27. B-52H planform area constraint and suggested design point, Mach 8, dual-fuel trade.

Carrier Constraints: While the B-52H could support the weight of the vehicle, however, its planform size is too large for all cruise endurance points at Mach 8, see Figure 6-27.

Additional Trade Studies and Sensitivity Analysis: None; the Merlin engine is representative for the thrust classes required.

Suggested Design Point Summary: The selected design point for this mission consists of air-launch from the B747-100SCA and acceleration to ramjet start with the Merlin rocket motor. Due to the increase in fuel density (increasing wing loading) and the reduced I_{sp} of the kerosene rocket, the cruise time must be reduced to 25 minutes to provide some propulsion margin. The vehicle is summarized in Figure 6-28.

Design Summary				
t_{cruise}	25	min		
Down range	5,560	km	3,000	nm
TOGW	25,635	kg	56,516	lbs
W_{ppl}	13,667	kg	30,130	lbs
OEW	11,968	kg	26,385	lbs
τ	0.13			
S_{pln}	114.4	m^2	1,231	ft^2
B	10.06	m	33	ft
L	18.94	m	62	ft
L/D cruise	2.28			
Isp cruise(s)	2,246	s		
Trkt	512	kN	115	klbs
Nrkt (512 kN each)	1			

- ***Suggested Design Point***
  - ***25 min cruise***
  - ***τ = 0.13***
  - ***B747-100 Launch Vehicle***
  - ***Merlin Rocket***
  - ***Composite structure***
  - ***SiC/SiCMMC TPS***

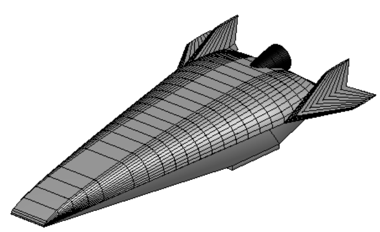


Fig. 6-28. Summary of suggested design point for the air-launched, Mach 8 dual-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 8 cruise mission is feasible with the dual-fuel option for 30 minutes endurance; however, the 30 minutes option represents a zero margin design point. Therefore the cruise endurance is reduced to 25 minutes.
- The Merlin rocket has satisfactory performance for an off-the-shelf rocket. The dual-fuel option will not have the same integration issues as the kerosene-only vehicles due to the decrease in slenderness.
- All cruise times violate the B-52 under wing geometry constraint, requiring the B-747-100SCA carrier aircraft for air launch.

6.4.7 EXPENDABLE BOOSTER, MACH 6, HYDROGEN FUEL

Trade Summary: This trade explores the Mach 6 cruise mission with varying cruise endurance. The vehicle is vertically launched on top of an expendable booster and accelerated to ramjet start at 3.0M. Hydrogen fuel is used for the ramjet/scramjet. The trade study determines that this mission is feasible with the current industrial capability available. The vehicle is within the weight, separation velocity, and separation altitude constraints for the Castor 120 expendable booster.

Mission Summary: Table 6-8 summarizes the mission and operational constraints for the expendable booster, Mach 6, hydrogen-fuel trade study.

Table 6-8. Expendable Booster, Mach 6, Hydrogen Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	17,260 m (56,630 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	LH
Hydrogen fuel density	74.63kg/m^3 (4.65 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-29 shows the solution space for the hydrogen-fueled, Mach 6, expendable booster trade. The solution space is constrained by the landing constraint, composite structure constraint and 0 to 30 minutes cruise requirement. The landing and thrust minus drag (*T-D*) constraints cross at the 10 minutes cruise solution, meaning that for cruise times below 10 minutes the landing constraint is dominant, whereby above 10 minutes the *T-D* constraint dominates. This switch in dominant constraints is due the increase fuel weight of the 20 to 30 minutes endurance vehicles, leading to increased thrust requirements.

Expendable Booster Constraints: All Mach 6 hydrogen vehicles meet the weight, separation velocity, and separation altitude constraints of the M55A1 and Castor 120 expendable boosters, see Figure 6-30.

Additional Trade Studies and Sensitivity Analysis: None.

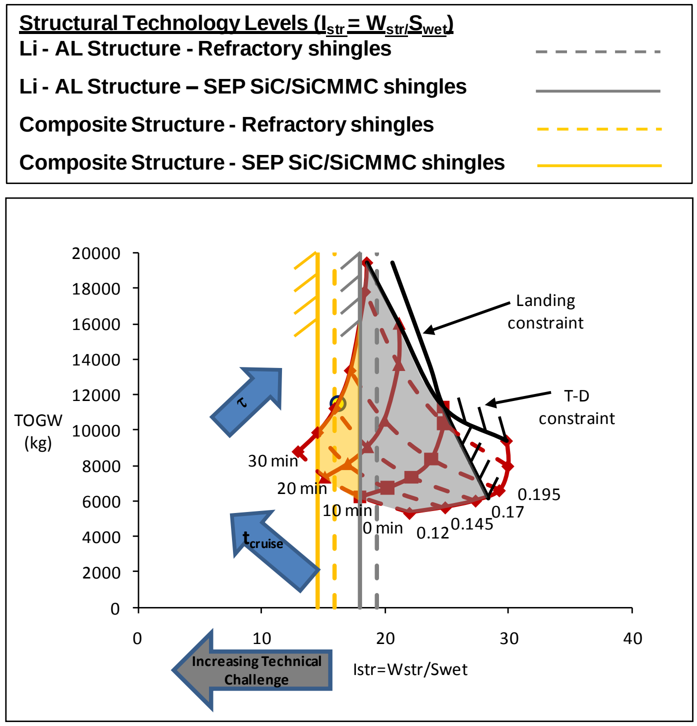


Fig. 6-29. Hydrogen-fuel, Mach 6 expendable booster trade solution space.

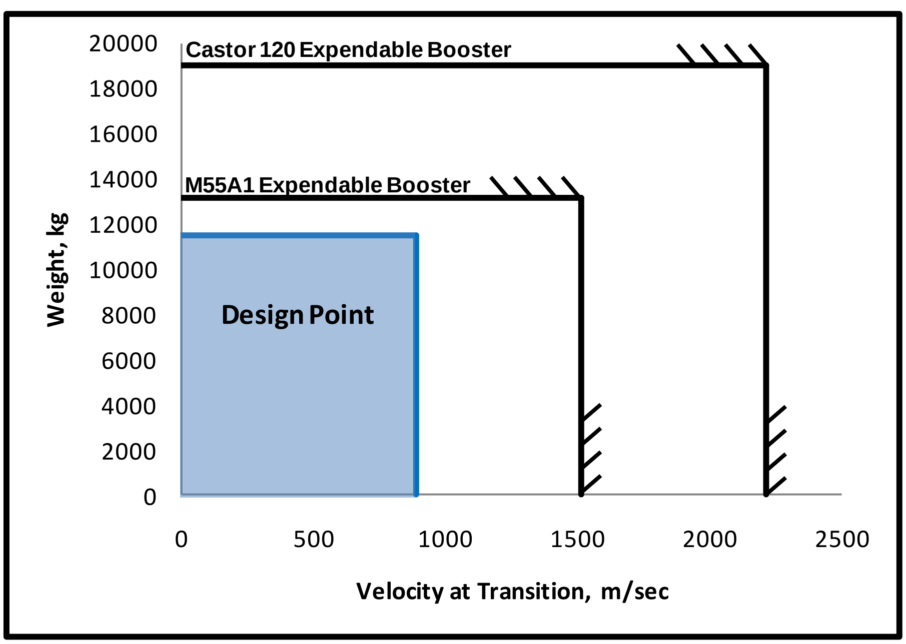


Fig. 6-30. Expendable booster constraints and suggested design point, Mach 6, hydrogen- fuel trade.

Suggested Design Point Summary: The selected design point for this mission consists of vertical launch using the M55A1 expendable booster for acceleration to ramjet start at Mach 3. A composite structure has been chosen for the design point, although aluminum is technically possible. This choice has been made in order to increase the propulsion margin relative to the thrust minus drag (*T-D*) constraint. The vehicle is summarized in Figure 6-31.

Design Summary				
t_{cruise}	30	min		
Down range	4,120	km	2,224	nm
TOGW	25,635	kg	25,364	lbs
W_{ppl}	3,757	kg	8,283	lbs
OEW	7,709	kg	16,995	lbs
τ	0.175			
S_{pln}	63.5	m^2	683.5	ft^2
B	7.50	m	25	ft
L	14.1	m	46	ft
L/D cruise	1.88			
Isp cruise(s)	2,600	s		

- ***Suggested Design Point***
  - ***30 min cruise***
  - ***τ = 0.175***
  - ***M55A1 Expendable Booster***
  - ***Composite structure***
  - ***SiC/SiCMMC or Refractory TPS***

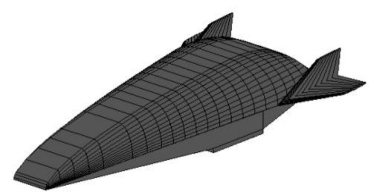


Fig. 6-31. Summary of suggested design point for the expendable booster, Mach 6 hydrogen- fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade:

- The Mach 6 cruise mission is feasible with the hydrogen fuel option for 30 minutes endurance.
- The M55A1 expendable booster meets the requirements for the Mach 6 mission.
- For increasing cruise durations, the thrust minus drag (*T-D*) becomes more constraining relative to the aborted landing constraint.

6.4.8 EXPENDABLE BOOSTER, MACH 8, HYDROGEN FUEL

Trade Summary: This trade explores the Mach 8 cruise mission with varying endurance time. The vehicle is vertically launched on top of an expendable booster and accelerated to ramjet start at 3.0M. Hydrogen fuel is used for the ramjet/scramjet. It is determined that this mission is feasible with the current industrial capability. The vehicle is within the weight, separation velocity, and separation altitude constraints for the Castor 120 expendable booster.

Mission Summary: Table 6-9 summarizes the mission and operational constraints for the expendable booster, Mach 8, hydrogen fuel trade study.

Table 6-9. Expendable Booster, Mach 8, Hydrogen Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	17,260 m (56,630 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	LH
Hydrogen fuel density	74.63kg/m^3 (4.65 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-32 shows the solution space for the hydrogen fueled, Mach 8, expendable booster trade. The solution space is constrained by the landing constraint, composite structure constraint and 0 to 30 minutes solution curves. The demonstrator vehicle is feasible with either composite or aluminum structure for cruise times from 0.0 to 30 minutes. The design point is selected at the intersection of the landing constraint and aluminum structure constraint. This has been done to provide sufficient design margin for the structural and propulsion (*T-D*) constraints.

Expendable Booster Constraints: The selected design point meets the weight, separation velocity, and separation altitude constraints of the Castor 120 expendable booster. However, a more powerful booster is required if *TOGW* is expected to increase, see Figure 6-33.

Additional Trade Studies and Sensitivity Analysis: None.

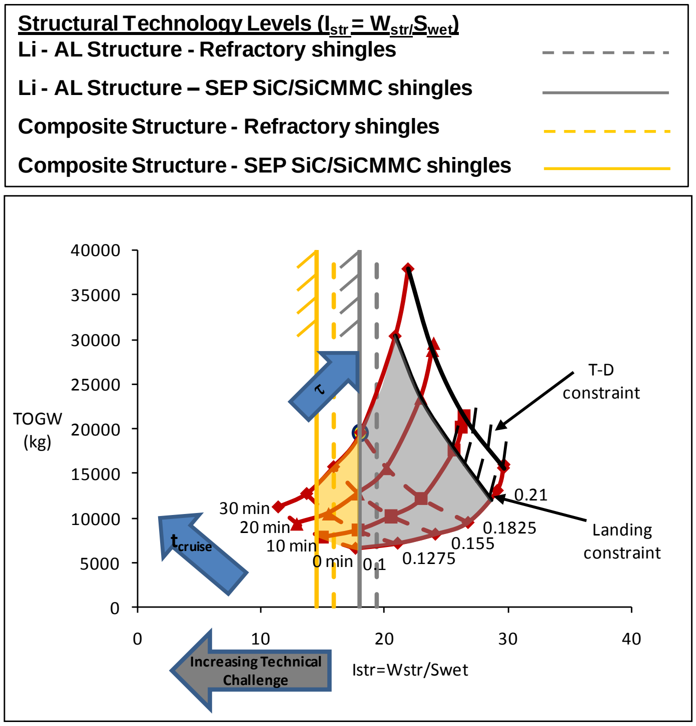


Fig. 6-32. Hydrogen-fuel, Mach 8 expendable booster trade solution space.

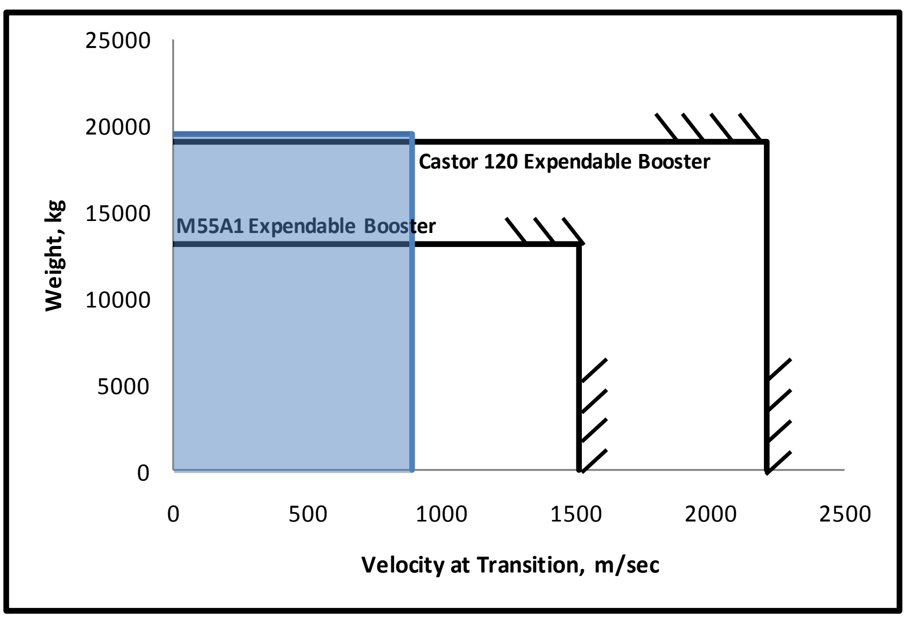


Fig. 6-33. Expendable booster constraints and suggested design point, Mach 8, hydrogen-fuel trade.

Suggested Design Point Summary: The selected design point for this mission consists of vertical launch using the Castor 120 expendable booster for acceleration to ramjet start at Mach 3. The design point is selected at the intersection of the landing constraint and aluminum structure constraint. Note that for slenderness parameters greater than the design point, the gradient of *TOGW* with respect to the structural index is increasing almost asymptotically. Note that a small increase in material weight will spiral into a large increase in vehicles size. The vehicle is summarized in Figure 6-34.

Design Summary				
t_{cruise}	30	min		
Down range	6,000	km	3,239	nm
TOGW	19,577	kg	43,160	lbs
W_{ppl}	7,423	kg	16,365	lbs
OEW	12,153	kg	26,793	lbs
τ	0.1825			
S_{pln}	95.67	m^2	1,230	ft^2
b	9.20	m	30	ft
l	17.32	m	57	ft
L/D cruise	1.98			
Isp cruise(s)	2,248	s		

- ***Suggested Design Point***
  - ***30 min cruise***
  - ***τ= 0.1825***
  - ***Castor 120 Expendable Booster***
  - ***Li-Al structure***
  - ***SiC/SiCMMC or Refactory TPS***

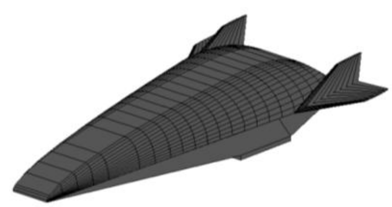


Fig. 6-34. Summary of suggested design point for the expendable booster, Mach 8, hydrogen-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 8 cruise mission is feasible with the hydrogen fuel option for 30 minutes endurance.
- The Castor 120 expendable booster meets the requirements for the Mach 8 mission design point although any increase in TOGW will require the use of a more powerful expendable booster.
- The large gradients in the hydrogen solution curves lead to large changes in TOGW with small changes in material weight.

6.4.9 EXPENDABLE BOOSTER, MACH 6, KEROSENE FUEL

Trade Summary: This trade explores the Mach 6 cruise mission with varying endurance time. The vehicle is vertically launched on top of an expendable booster and accelerated to ramjet start at Mach 3. Kerosene fuel is used for the ramjet/scramjet. It is determined that this mission is feasible with current industrial capability. The vehicle is within the weight, separation velocity, and separation altitude constraints for the Castor 120 expendable booster.

Mission Summary: Table 6-10 summarizes the mission and operational constraints for the expendable booster, Mach 6, kerosene-fuel trade study.

Table 6-10. Expendable Booster, Mach 6, Kerosene-Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	17,260 m (56,630 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	RP-1
Kerosene-fuel density	820.0 kg/m^3 (51.2 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-35 shows the solution space for the kerosene-fueled, Mach 6, expendable booster trade. The solution space is constrained by the landing constraint, composite structure constraint, and the 0 to 30 minutes solution curves. The solution space demonstrates that the vehicle is feasible with either composite or aluminum structure for cruise times between 0 to 30 minutes. The design point is selected at the intersection of the landing constraint and aluminum structure constraint. This selection provides a healthy design margin from the structural and propulsion (*T-D*) constraints.

Expendable Booster Constraints: All Mach 6 kerosene vehicles meet the weight, separation velocity, and separation altitude constraints of the M55A1 and Castor 120 expendable boosters, see Figure 6-36.

Additional Trade Studies and Sensitivity Analysis: None.

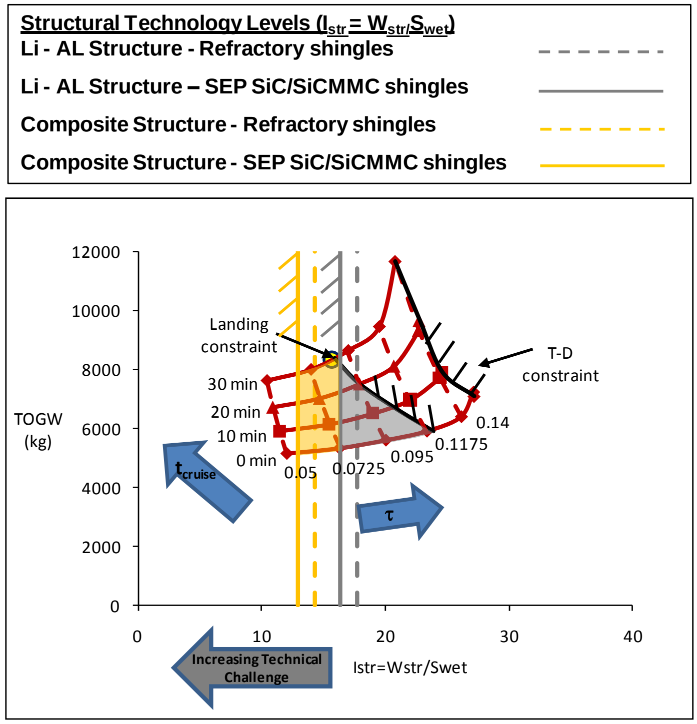


Fig. 6-35. Kerosene-fuel, Mach 6 expendable booster trade solution space.

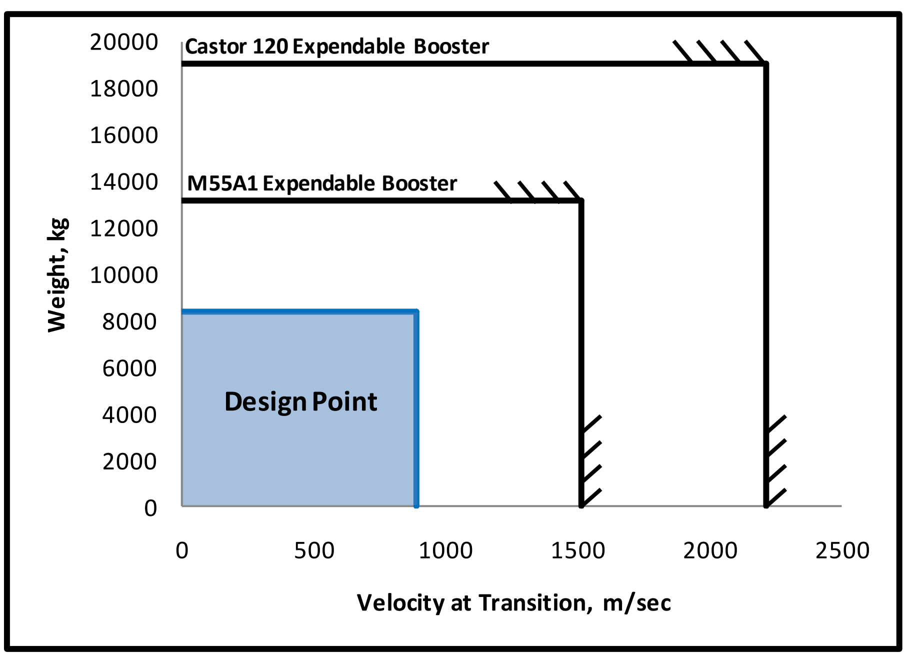


Fig. 6.36. Expendable booster constraints and suggested design point, Mach 6, kerosene-fuel trade.

Suggested Design Point Summary: The selected design point for this mission consists of vertical launch using the M55A1 expendable booster for acceleration to ramjet start at Mach 3. The design point is selected at the intersection of the landing constraint and aluminum structure constraint. The vehicle is summarized in Figure 6-37.

Design Summary

t_{cruise}	30	min		
Down range	4,523	km	2,442	nm
TOGW	8,345	kg	18,398	lbs
W_{ppl}	3,536	kg	7,796	lbs
OEW	4,809	kg	10,602	lbs
τ	0.085			
S_{pln}	34.75	m^2	374	ft^2
B	5.55	m	18	ft
L	10.44	m	34	ft
L/D cruise	4.08			
Isp cruise(s)	970	s		

- ***Suggested Design Point***
  - ***30 min cruise***
  - ***τ = 0.085***
  - ***M55A1 Expendable Booster***
  - ***Composite structure***
  - ***SiC/SiCMMC TPS***

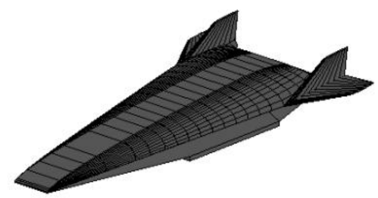


Fig. 6.37. Summary of suggested design point for the expendable booster, Mach 6 kerosene-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 6 cruise mission is feasible with the kerosene-fuel option for 30 minutes endurance.
- The N55A1 expendable booster meets the requirements for the Mach 6 mission.

6.4.10 EXPENDABLE BOOSTER, MACH 8, KEROSENE FUEL

Trade Summary: This trade explores the Mach 8 cruise mission with varying endurance time. The vehicle is vertically launched on top of an expendable booster and accelerated to ramjet start at 3.0M. Kerosene fuel is used for the ramjet/scramjet. It is determined that the mission is feasible with current industrial capability, though with a reduction in cruise time to 20 minutes. The vehicle is within the weight, separation velocity, and separation altitude constraints for the Castor 120 expendable booster.

Mission Summary: Table 6-11 summarizes the mission and operational constraints for the expendable booster, Mach 8, kerosene-fuel trade study.

Table 6-11. Expendable Booster, Mach 8, Kerosene-Fuel Mission Summary

Mission Requirements	
Endurance	0, 10, 20 and 30 min
Payload	0 kg (0 lbs)
Launch altitude	17,260 m (56,630 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	RP-1
Kerosene fuel density	820.0 kg/m^3 (51.2 lbs/ft^3)
Operational Constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Solution Space Visualization: Figure 6-38 shows the solution space for the kerosene-fueled, Mach 8, expendable booster trade. The solution space is constrained by the landing constraint, composite structure constraint and the 0 to 30 minutes solution curve. The solution space is severely constrained by the aborted landing constraint. This is due to the increased fuel density translating into higher vehicle wing loadings. In case the landing constraint is relaxed, a 30 minutes composite vehicle is technically feasible. This point is at the intersection of the structural capability and the thrust minus drag (*T-D*) constraints, resulting in a zero design margin for the structural weight and thrust available. Consequently, the design point selected is reduced to 20 minutes endurance.

Expendable Booster Constraints: All Mach 8 kerosene vehicles meet the weight, separation velocity, and separation altitude constraints of the M55A1 and Castor 120 expendable boosters, see Figure 6-39.

Additional Trade Studies and Sensitivity Analysis: None.

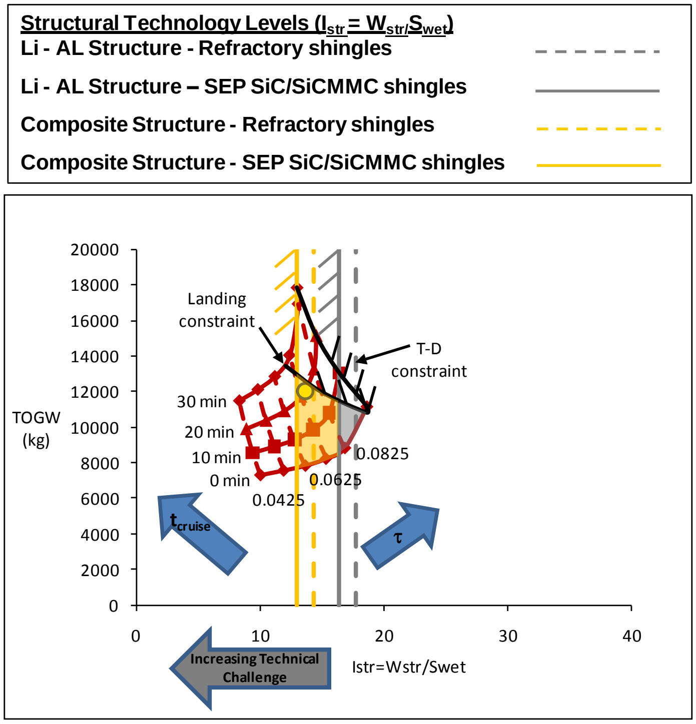


Fig. 6-38. Kerosene-fuel, Mach 8, expendable booster trade solution space.

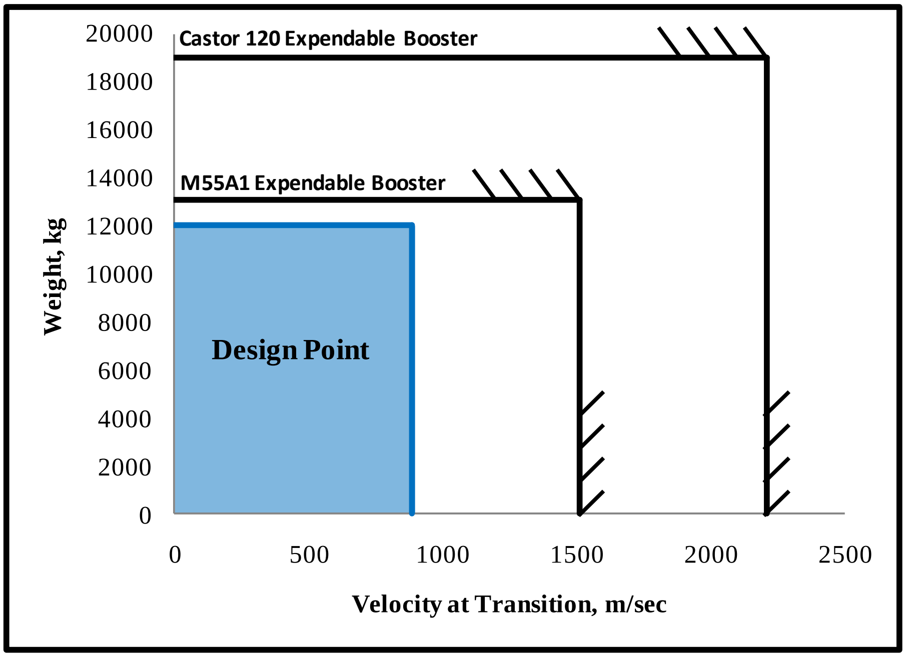


Fig. 6-39. Expendable booster constraints and suggested design point, Mach 8, kerosene-fuel trade.

Suggested Design Point Summary: The selected design point for this mission consists of vertical launch using the M55A1 expendable booster for acceleration to ramjet start at Mach 3. The design point is selected at the intersection of the 20 minutes solution curve and the composite structure constraint. In case the aborted landing constraint is relaxed, the thrust minus drag constraint for the 30 minutes cruise vehicle is feasible with a minimal thrust margin. Reducing the endurance to 20 minutes allows for a sufficient propulsion margin that meets the aborted launch constraint. The vehicle is summarized in Figure 6-40.

Design Summary

t_{cruise}	20	min		
Down range	5,640	km	3,045	nm
TOGW	12,027	kg	26,515	lbs
W_{ppl}	6,074	kg	13,391	lbs
OEW	5,953	kg	13,124	lbs
τ	0.075			
S_{pln}	51.28	m^2	552	ft^2
b	6.74	m	22	ft
l	12.68	m	42	ft
L/D cruise	3.92			
Isp cruise(s)	732	s		

- ***Suggested Design Point***
  - ***20 min cruise***
  - ***τ= 0.075***
  - ***M55A1 Expendable Booster***
  - ***Composite structure***
  - ***SiC/SiCMMC TPS***

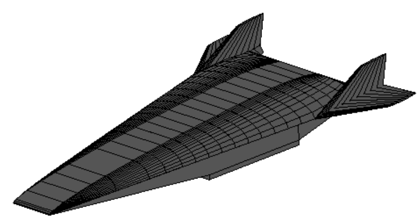


Fig. 6-40. Summary of suggested design point for the expendable booster, Mach 8, kerosene-fuel trade.

Summary of Conclusions and Key Points: Below are the primary conclusions from this trade.

- The Mach 8 cruise mission is infeasible with the kerosene-fuel option for 30 minutes endurance; however, the 20 minutes option can be accomplished.
- The M55A1 expendable booster meets the requirements for the Mach 8 mission.

7 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.

7.1 SOLUTION SPACE COMPARISON

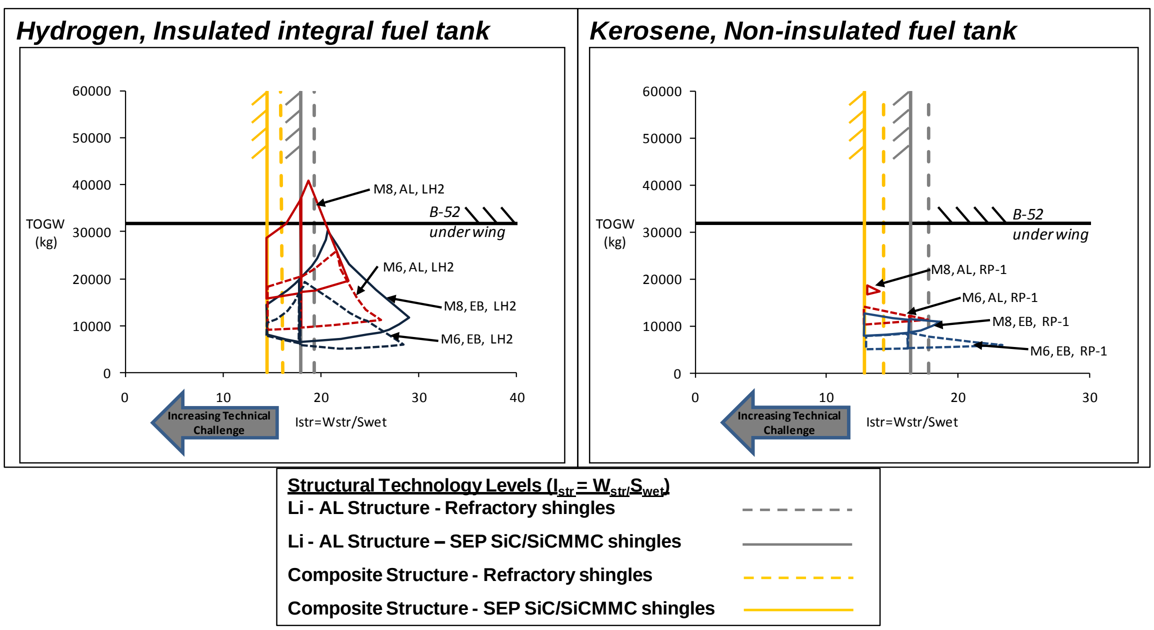


Fig. 7-1. Hydrogen-fueled vehicles allow for a larger technical solution space compared to kerosene-fueled vehicles.

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 7-1. 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 7-1 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.

7.2 Design Point Comparison

The following discussion reviews the converged baseline vehicle design points selected from the hypersonic flight vehicle design solution space screening activity presented in Chapter 6. For more information regarding the demonstrator selection for individual hydrogen- and kerosene-fuel trades, please refer to the earlier sections. Figure 7-2 presents the short-list overview of prospective baseline vehicle configuration-, speed- and fuel combinations. Table 7-1 and Table 7-2 are summarizing the general 'parametric' design characteristics for the feasible baseline vehicle options utilizing either hydrogen or kerosene fuel.

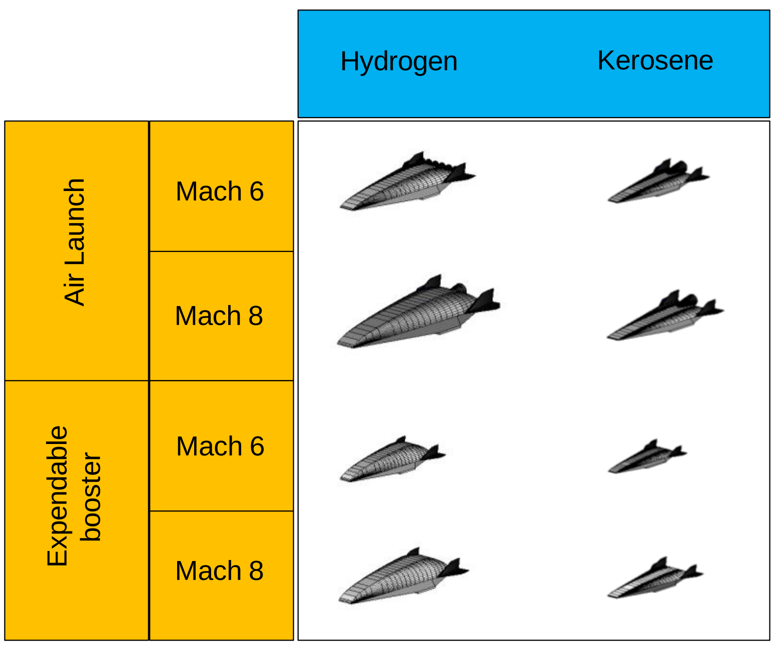


Fig. 7-2. Configuration geometry of proposed hydrogen and kerosene hypersonic baseline vehicle designs.

Table 7-1. 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 7-2. 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					

7.3 BASELINE VEHICLE SELECTION

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?"*

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 <u>*hydrogen scramjet testing*</u> is required, assessment results are presented with Figure 7-3:

- ***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***

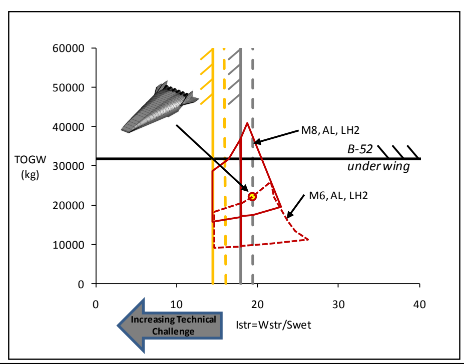


Fig. 7-3. The Mach 8 air-launched case represents the largest operational flexibility while Mach 6 air-launched has larger growth capability and design confidence. Since M6 30 min and M8 10 min solution curves overlay, it appears that the M6 30 min vehicle could perform the Mach 8 mission for 10 minutes.

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.

If *kerosene scramjet testing* is required, assessment results are presented with Figure 7-4:

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.

- ***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***

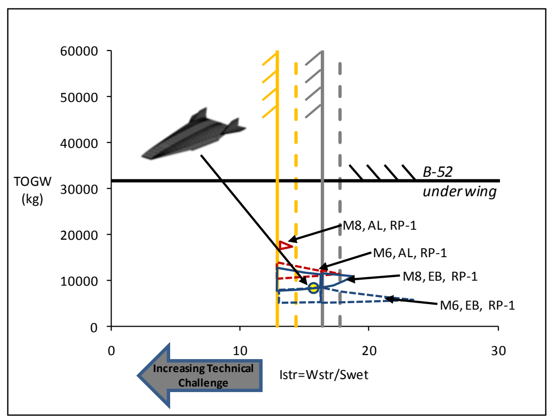


Fig. 7-4. The Mach 6 kerosene-fuel expendable booster trade is the only trade-study which allows for 30 minutes cruise endurance.

Both research demonstrators represent attractive options, each offering the capability to explore advanced propulsion design concepts.

8 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

This report documents a parametric sizing (PS) study performed to develop a program strategy for (a) research and development (R&D), and (b) procurement of a feasible next-generation hypersonic air-breathing endurance demonstrator. Overall project focus has been on complementing technical and managerial decision-making during the earliest conceptual design phase towards minimization of operational, technical, and managerial risks.

The first segment in the course of the conceptual design phase is *parametric sizing* (PS), the second segment performs *configuration layout* (CL), and the third segment is the *configuration evaluation* (CE) stage. The early, thus critical, PS segment requires a systematic approach, enabling the generation of physically correct understanding and knowledge of the solution space available before the subsequent CD stages (CL and CE) are locking in on a baseline system in this very solution space.

In the context of the present research undertaking, the AVD Laboratory team has utilized a dedicated *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 iteratively harmonizing the relationships amongst: (a) mission selection, (b) research & technology objectives definition, and (c) baseline vehicle(s) characterization. The above outlined process arrives at a justification package able to characterize and defend the suggested baseline hypersonic vehicle design selected.

8.1 DESIGN LESSONS LEARNED

In addition to the primary flight vehicle system recommendations communicated in Chapter 7.3, several design lessons have been learned through the course of this project which are worthy of note.

- *Increasing cruise time* from 0 to 30 minutes increases vehicle size and technology requirements (30 minutes cruise hypersonic demonstrator appears possible).
- *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 than under-wing load limitations.
- *Selection of scramjet fuel* is not driven by technical feasibility of the demonstrator test-bed, but by requirements specified for the operational aircraft (range and payload requirements, infrastructure).
- *Air-launch and expendable booster launch* are both viable options with LH_2.
- *Launch arrangement* should be based on flight rate requirement and associated operational 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 minutes 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).

- A 30 minutes *turning cruise flight* has minimum effect on vehicle size due to operation at higher *L/D* at large turning radius and low load factor.

The study results generated within the available time frame conclude with the recommendations outlined in Chapter 8.2. It is felt that the recommendations require attention *before* a selection of confidence can be made for a baseline vehicle and the resulting moving forward with the design.

8.2 RECOMMENDATIONS

The parametric sizing results clearly indicate that the design of a hypersonic endurance demonstrator is far from trivial. Although the parametric sizing (PS) phase is considered not complete at this point, the results generated allow the decision-makers (manager, synthesis specialist, and technologist) to plan ahead and proceed with some degree of confidence. Clearly, more research is required for selecting a baseline hypersonic demonstrator concept.

Remaining Top-Level Questions

The remaining top-level questions at (a) synthesis level, (b) managerial level, and (c) technology level are:

A. Synthesis Level

- What future scenarios and operational systems warrant hydrogen and/or kerosene scramjet research?

- Is the flight vehicle capability targeted satisfying the program objectives in terms of time and resources available?

- What is the required demonstrator capability able to accommodate a wide range of test conditions contributing to *general* hypersonic research?

- What is the required demonstrator capability able to accommodate a wide range of test conditions contributing to *specific* hypersonic research?

B. Managerial Level

- What is the sensitivity characterizing expendable booster cost and air-launch cost?

- Does a hydrogen, Mach 8 and 30 minutes demonstrator warrant the increased technology & cost requirement relative to the Mach 6 and 30 minutes, Mach 8 and 10 minutes vehicle?

- What effect will a RBCC, such as an ejector ramjet, have on the vehicle and its technology requirements?

- What are the maximum allowable down-range and cross-range requirements?

C. Technology Level

- Are primary disciplinary and multi-disciplinary technology parameters sufficiently represented throughout the design life-cycle?

- Can operational vehicle and demonstrator vehicle (a) technology, (b) operational mission & flight test program, and (c) vehicle utilization be predicted?

- What technology breakthroughs are necessary or desirable for each of the final baseline demonstrator vehicle types?

Recommendations for Future Work

With these questions in mind, the following steps are necessary to complete the conceptual design study:

A. Complete requirements and objectives research

- Expand requirements & objectives definition activity for proposed operational hypersonic applications; particular interest should be given to refining endurance and fuel selection.

- Expand survey of hypersonic technologies (ground & in-flight) which support *near-term* experimental validation and verification towards an operational system.

- Expand survey of hypersonic technologies (ground & in-flight) which require *longer-term* experimental validation and verification towards an operational system.

B. Expand demonstrator parametric sizing (PS) study

- Expand kerosene trades with wing-body combinations with various abort, emergency, or failure scenarios.

- Expand fuel trades to include natural gas as a middle ground between the performance of hydrogen and available infrastructure of kerosene.

- Explore impact of RBCC and/or TBCC demonstration capability to support future launch and point-to-point vehicle programs.

- Compare demonstrator vehicle solution spaces based on development and operational cost metrics.

- Explore the solution space of operational vehicle concepts (vehicles with payload) while the technology demonstrator will be designed to validate a suite of technologies to directly satisfy those operational missions.

C. Complete conceptual design: configuration layout (CL) and configuration evaluation (CE) stages

- CL and CE will validate and refine the initial operational and technical assumptions made during parametric sizing step.

- Development of baseline demonstrator vehicle (conceptual design & safety assessment).

- Identification of associated operational vehicle(s) (conceptual design & safety assessment).

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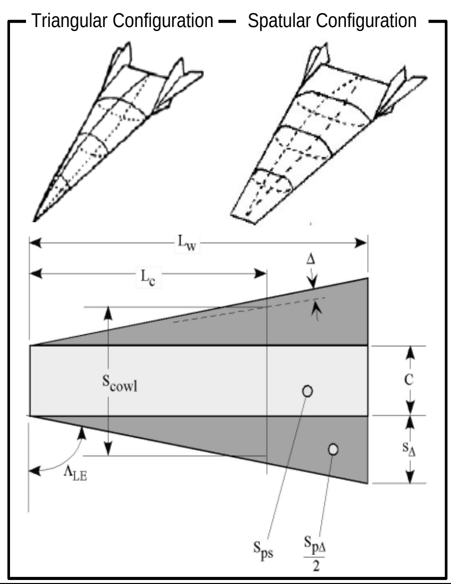
Appendices

Appendix A. Disciplinary Methods Library

1. Geometry

Table A-1. Hypersonic Cruiser Planform Description Method

<table>
<tr><td colspan="6">Method overview</td></tr>
<tr><td>Discipline
Geometry</td><td>Design phase
Sizing</td><td colspan="2">Method title
Hypersonic cruiser planform description</td><td>Categorization
Semi-empirical</td><td>Author
Czysz/Coleman</td></tr>
<tr><td colspan="6">Reference: (Modified from) Czysz, P.A., “Hypersonic Convergences,” Volume 1, Air Force Research Laboratory, Wright-Patterson Air Force Base, AFRL-VA-WP-TR-2004-3114, 2004.</td></tr>
<tr><td colspan="6">Brief description
Planform description of hypersonic cruisers with delta-wing planform with a given spatular ratio (c/s).</td></tr>
<tr><td colspan="3">Assumptions
Simplified geometry</td><td colspan="3">Applicability
General glider and air breather configuration</td></tr>
<tr><td colspan="6">Execution of method</td></tr>
<tr><td colspan="6">Input: Spln, c/s, Λ_{LE}</td></tr>
<tr><td colspan="3">Analysis description
$l = \sqrt{\frac{S_{pln} \tan \Lambda_{LE}}{1 + c/s}}$
$s_\Delta = l / \tan \Lambda_{LE}$
$c = c/s \cdot s_\Delta$
$b = 2 s_\Delta + c$</td><td colspan="3">
</td></tr>
<tr><td colspan="6">Output: l, s, c, b</td></tr>
<tr><td colspan="6">Experience</td></tr>
</table>

Accuracy	**General comments**
Dependent on assumed values	Use the figure provided for guidance for K_0

Table A-2. Hypersonic Air-Breather Volume and Wetted Area Estimation

Method overview				
Discipline	**Design phase**	**Method title**	**Categorization**	**Author**
Geometry	Sizing	Hypersonic air-breather volume and wetted area	Semi-empirical	Czysz/Coleman
Reference: (Modified from) Czysz, P.A., *"Hypersonic Convergences,"* Volume 1, Air Force Research Laboratory, Wright Patterson Air Force Base, AFRL-VA-WP-TR-2004-3114, 2004.				
Brief description Volume and wetted area are computed based on planform parameters, vehicle slenderness (τ) ,and engine design cowl location.				
Assumptions Simplified geometry		**Applicability** General glider and air breather configuration		
Execution of method				
Input: *Spln, t, c/s*, L_w, Λ_{LE}, Δ, s_Δ ,L_c/L_w, h_c/L_c, θ_1, h_t/L_{iso}, L_{comb}				

Analysis description

Compute underside geometry:

$h_c = h_c/L_c \cdot L_c$

$L_c = L_c/L_w \cdot L_w$

$\Lambda_{\text{cowl}} =\cdot \Lambda_{LE} - \Delta$

$s_{out} =\cdot L_c/\tan(\Lambda_{\text{cowl}})$

$s_{\text{cowl}} = c + 2\, s_{\text{out}}$

Iterate h_t until L_{iso} convergence:

$L_{\text{iso}} =\cdot h_t/(h_t/L_{iso})$

$L_{\text{noz}} =\cdot L_w - L_c - L_{iso} - L_{\text{comb}}$

Call one-dimensional stream thrust analysis at cruise condition to compute contraction ratios:

$$h_{t\ \text{new}} = \frac{h_c/L_c}{\frac{A3}{A4}\cdot\frac{A0}{A3}\cdot\frac{Ac}{A0}\cdot\frac{2s_{\text{cowl}}}{s_{\text{cowl}}+c}+1}$$

$L_{\text{iso new}} =\cdot h_{t\ \text{new}}/(h_t/L_{\text{iso}})$

Compute minimum τ (flat top):

$$\tau_{\min} = \frac{(h_c - h_t)\left(c + \frac{2}{3}s_{\text{out}}\right)\left(\frac{1}{3}L_c + L_{\text{iso}} + L_{\text{comb}} + \frac{1}{3}L_{\text{noz}}\right)}{S_{\text{pln}}^{1.5}}$$

Compute height of upper surface (flat top)

$$h_{\text{top}} = \frac{(\tau - \tau_{\min})S_{\text{pln}}^{1.5}}{\pi L_c\left(c + \frac{2}{3}s_{\text{out}}\right)}$$

Compute wetted area per planform area:

$$k_w = \frac{S_{\text{wet}}}{S_{\text{pln}}} = \frac{k_{ws}\cdot s_\Delta \cdot L_w + k_{wc}\cdot c \cdot L_w}{S_{\text{pln}}}$$

$$k_{ws} = -62.214\tau_0^3 + 29.904\tau_0^2 - 1.581\tau_0 + 2.469$$

$$\tau_0 = 2/3 \cdot h_{\text{top}}/\sqrt{L_w \cdot s_\Delta}$$

$$k_{wc} = \frac{2\sqrt{h_{\text{top}}^2 + L_w^2}}{L_w}$$

Estimate frontal area and capture area:

$$S_{\text{front}} = \pi s_\Delta h_{\text{top}} + h_{\text{top}} h_c c$$

$$A_c = \frac{1}{2}(s_{\text{cowl}} + c)(h_c - h_t) + h_t s_{\text{cowl}}$$

Output: A_c, S_{front}, k_w, h_{top}, h_t, h_c, L_c, L_{iso}, L_{noz}, s_{cowl}

Experience	
Accuracy	**General comments**
Dependent on assumed values	Wetted are based on MAC pointed-nose configuration, expanded by spatula.

Further description:
The parameterization of the volume (Figure A-1) and wetted area (Figure A-2) for a hypersonic air-breather follows.

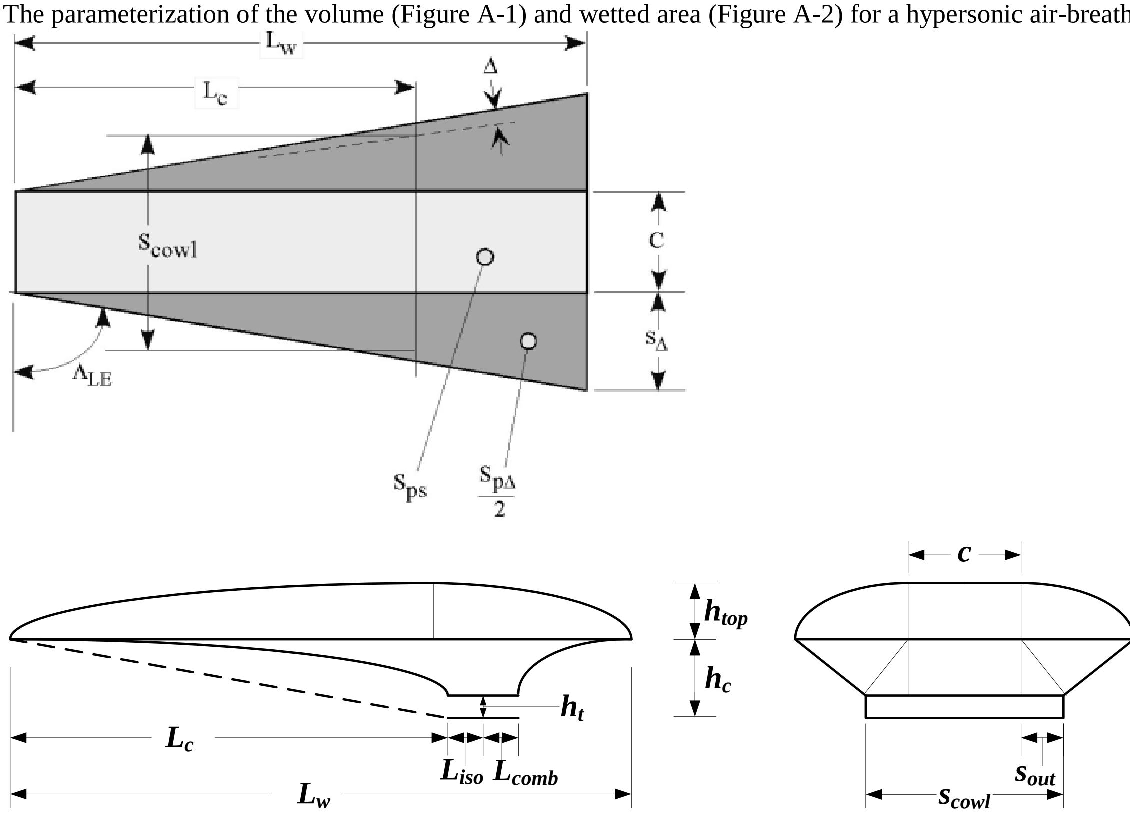
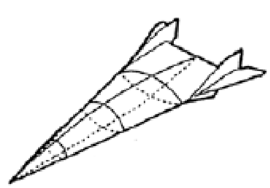


Fig. A-1. Volume parameterization of a hypersonic air-breather.



$$K_w = -62.217 \cdot \tau^3 + 29.904 \cdot \tau^2 - 1.581 \cdot \tau + 2.469$$

Blended Body, McDonnell Douglas circa 1965

Fig. A-2. Wetted area description of a hypersonic air-breather.

2. Performance

Trajectory thrust requirement and fuel requirement

Table A-3. Hypersonic Cruiser Trajectory Determination Method

<table>
<tr><th colspan="5">Method overview</th></tr>
<tr><td>Discipline
Propulsion</td><td>Design phase
Sizing</td><td>Method title
Hypersonic cruiser trajectory</td><td>Categorization
Numerical</td><td>Author
HYFAC</td></tr>
<tr><td colspan="5">Reference: Czysz, P.A., "Hypersonic Convergence," Air Force Research Laboratory, Wright Patterson Air Force Base, AFRL-VA-WP-TR-2004-3114, 2004.</td></tr>
<tr><td colspan="5">Brief description
From an assumed segmented trajectory, an energy integration is performed to compute the required fuel weight. From the computed drag and propulsion-system performance data, the thrust that is required at sea level is computed at each step. The largest thrust requirement is utilized for the acceleration.</td></tr>
<tr><td colspan="3">Assumptions
Step climb up to transonic acceleration.
Constant altitude transonic acceleration.
Constant dynamic pressure climb to cruise altitude.
Cruise-climb (constant C_L) and max L/D descent.</td><td colspan="2">Applicability
Air-breathing hypersonic or supersonic cruisers or first-stage launchers.</td></tr>
<tr><th colspan="5">Execution of method</th></tr>
<tr><td colspan="5">Input
Trajectory, $C_{D0,} L', T/Tsl$, $n_{\max}$, I_{sp} at each step</td></tr>
<tr><td colspan="5">Analysis description
At each point, the following equation is utilized to compute the total fuel burn and thrust requirement (see the additional information following this table in the further description section).
Each segment is then integrated based on constant, altitude, velocity, or dynamic pressure.
The total fuel fraction is then summed for weight and volume convergence.
The largest thrust-to-weight ratio is used for engine weight estimation.</td></tr>
<tr><td colspan="5">Output: $WR, (T/W)_{TO}$</td></tr>
<tr><th colspan="5">Experience</th></tr>
<tr><td colspan="2">Accuracy
Depends on aero and propulsion system accuracy</td><td colspan="3">General comments
This type of trajectory tends to yield the lowest thrust requirement because of the constant altitude transonic acceleration. Transonic acceleration is typically what sets the thrust requirement for the vehicle.</td></tr>
</table>

Further description:

Assumed trajectory:

(1) Climb to 10,000 ft, (2) constant altitude acceleration to 0.8 M, (3) constant Mach climb to 12,000 ft, (4) constant altitude acceleration through the transonic region to maximum dynamic pressure, (5) constant dynamic pressure climb to cruise altitude, (6) cruise-climb to altitude, (7) maximum *L/D* descent, and (8) landing (see Figure A-3 below).

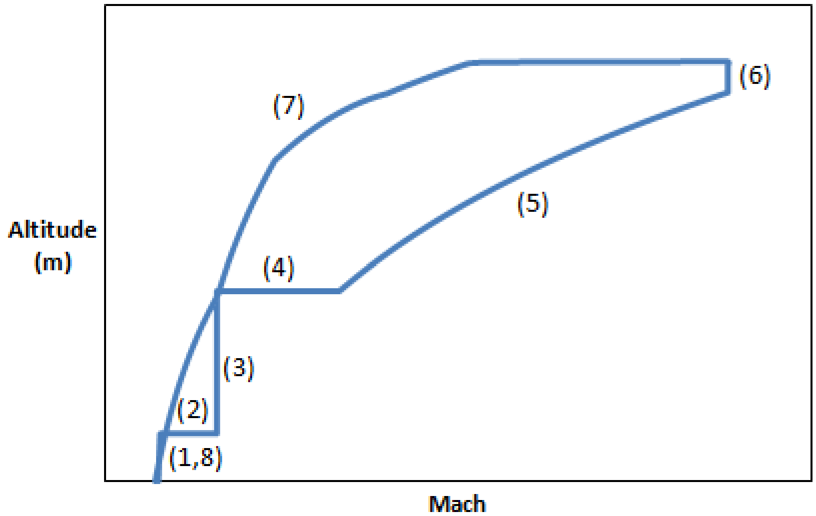


Fig. A-3. Assumed trajectory of the hypersonic cruiser.

At each integration step (ι) (each segment of the trajectory is broken down by predefined step size), compute the following:

Gravity relief:

$$\frac{L}{W} = 1 - \frac{V^2}{g(R_e + h)}$$

Aerodynamic efficiency:

$$C_L = \frac{L}{W} \frac{W_i}{TOGW} \frac{(W/S)_{TO}}{\bar{q}}$$

$$\frac{L}{D} = \frac{C_L}{C_{D0} + L' C_L^2}$$

Acceleration available:

$$n_{\text{avail}} = \left(\frac{T}{W}\right)_i - \frac{1}{L/D}$$

Energy at step *i:*

$$E_i = \frac{h_i R_e}{h_i + R_e} + \frac{V_i^2}{2g}$$

Derivatives:

$$\dot{E}_i = V_i \cdot n_{\max}$$

$$\Delta t = \frac{E_i - E_{i-1}}{\dot{E}_i}$$

$$\Delta R = V_i \cdot \Delta t$$

$$\frac{\Delta W_i}{TOGW} = -\Delta T \frac{T/W}{I_{SP}}$$

Then,

$$t_{i+1} = t_i + \Delta t$$

$$R_{i+1} = R_i + \Delta R$$

$$\frac{W_{i+1}}{TOGW} = \frac{W_i}{TOGW} + \frac{\Delta W_i}{TOGW}$$

3. Weight and Balance

Empty Weight and Volume Formulation

Table A-4. Convergence Empty Weight Estimation Method

<table>
<tr><th colspan="5">Method overview</th></tr>
<tr><td>Discipline
Weight estimation</td><td>Design phase
Parametric sizing</td><td>Method title
Convergence empty-weight estimation</td><td>Categorization
Empirical</td><td>Author
Coleman/
Czysz</td></tr>
<tr><td colspan="5">Reference: Dissertation</td></tr>
<tr><td colspan="5">Brief description
A modification of the hypersonic convergence method for estimating the converged empty weight based on volume and mass. This method has been modified to allow for the incorporation of additional methods for structural, propulsion, systems, and operational item weights beyond what are presented in hypersonic convergence.</td></tr>
<tr><td colspan="2">Assumptions
Wing area is not constant</td><td colspan="3">Applicability
Any aircraft or launcher configuration. Applicability depends on the methods used for the structural, propulsion, and systems weight.</td></tr>
<tr><th colspan="5">Execution of method</th></tr>
<tr><td colspan="5">Input: WR, T/W, W_{pay}, W_{crew}, V_{pay}, V_{crew}</td></tr>
<tr><td colspan="5">Analysis description
Solve the following system for S_{pln} and OWE:
Weight budget: $OWE = \dfrac{W_{str} + C_{sys} + W_{oper} + (T/W)_{max} WR/E_{TW}(W_{pay} + W_{crw})}{\frac{1}{1+\mu_a} - f_{sys} - (T/W)_{max} WR/E_{TW}} + W_{pay}$
Volume budget: $OWE = \dfrac{\tau \cdot S_{pln}^{1.5}(1 - k_{vv} - k_{vs}) - V_{fix} - V_{pay} - V_{crew}}{\frac{WR-1}{\rho_{fuel}} + k_{ve}(T/W)_{max} WR}$
Use the additional methods for W_{str}, W_{sys},, f_{sys}, W_{oper} and E_{TW}</td></tr>
<tr><td colspan="5">Output: OEW, TOGW, OWE, S_{pln}</td></tr>
<tr><th colspan="5">Experience</th></tr>
</table>

Accuracy	Time to calculate	General comments
Depends upon additional methods	Depends on structural weight estimation	Works well for any configuration. Is at the heart of AVD^{sizing}. The convergence logic will take the output and feed it back through the geometry trajectory and constraints until convergence

Further description

Additional weight relationships:

$W_{\text{sys}} = C_{\text{sys}} + f_{\text{sys}} W_{\text{dry}}$ $\quad 0.16 \le f_{\text{sys}} \le 0.24$ ton/ton

$C_{\text{sys}} = C_{un} + f_{\text{mnd}} N_{\text{crew}}$ $\quad 1.9 \le C_{un} \le 2.1$ ton

$1.45 \le f_{\text{mnd}} \le 1.05$ ton/person

$W_{\text{cprv}} = f_{\text{cprv}} N_{\text{crew}}$ $\quad 0.45 \le f_{\text{crew}} \le 0.50$ ton/person

$W_{\text{eng}} = \frac{TW_o W_R}{E_{TW}} \left(W_{\text{dry}} + W_{\text{pay}} + W_{\text{crew}}\right)$ $\quad 4.0 \le E_{TW} \le 25$ kg thrust/kg weight

Additional volumetric relationships:

$V_{\text{pay}} = W_{\text{pay}} / \rho_{\text{pay}}$ $\quad 48 \le \rho_{\text{pay}} \le 130$ kg/m^3

$V_{\text{crew}} = N_{\text{crew}} \left(V_{\text{pcrv}} + k_{\text{crew}}\right)$ $\quad 0.9 \le k_{\text{crew}} \le 2.0$ m^3/person

$6.0 \le V_{\text{pcrv}} \le 5.0$ m^3/person

$V_{\text{void}} = k_{vv} V_{tot}$ $\quad 0.10 \le k_{vv} \le 0.20$ m^3/m^3

$V_{\text{crew}} = N_{\text{crew}} \left(V_{\text{pcrv}} + k_{\text{crew}}\right)$ $\quad 0.9 \le k_{\text{crew}} \le 2.0$ m^3/person

$6.0 \le V_{\text{pcrv}} \le 5.0$ m^3/person

$V_{\text{sys}} = V_{\text{fix}} + k_{vs} V_{\text{tot}}$ $\quad 0.02 \le k_{vs} \le 0.04$ m^3/m^3

$V_{\text{fix}} = V_{un} + f_{\text{crew}} N_{\text{crew}}$ $\quad 5.0 \le V_{un} \le 7.0$ m^3

$11.0 \le f_{\text{crew}} \le 12.0$ m^3/person

$V_{\text{eng}} = k_{ve} (T/W)_{\text{max}} W_R W_{OE}$ $\quad 0.25 \le k_{ve} \le 0.75$; m^3/ton thrust

$$V_{\text{ppl}} = W_{OE} \left(\frac{W_R - 1}{\rho_{\text{ppl}}} \right)$$

4. Structural weight

Table A-5. Structural Index Estimation Method

Method overview				
Discipline Structure	**Design phase** Sizing	**Method title** Structural index	**Categorization** Empirical	**Author** Czysz
Reference: Czysz, P.A., *"Hypersonic Convergence,"* Volume 1, Air Force Research Laboratory, Wright Patterson Air Force Base, AFRL-VA-WP-TR-2004-3114, 2004.				
Brief description Empirical methods for structural weight derived as a function of planform area, OEW, and the shape factor K_{str}. K_{str} represents the structural efficiency that is required for given hypersonic vehicle slenderness (τ).				
Assumptions Blended-body or wing-body hypersonic cruiser or launch vehicle Integrated thermal projection and structural sandwich		**Applicability** Both passive and actively cooled structures Hypersonic cruisers and launch vehicles		
Execution of method				
Input: τ, S_{pln}, S_{wet}, OEW				
Analysis description Compute structural weight and structural index required for a given τ, S_{pln}, S_{wet}, and OEW: $W_{str} = I_{str} \cdot S_{wet} = K_{str} \cdot S_{pln}^{0.138} \cdot OEW$				
Output: W_{str}, I_{str}				
Experience				
Accuracy Has worked well for a variety of hypersonic cruisers projects at MAC Proves valid for the Sanger II		**General comments** Due to the transition from hot to cold structure, the structural index does not need to be greater than 18 kg/m^2. The rule of thumb at MAC is 21 kg/m^2 for demonstrators (with cheap and heavier materials) and 18 kg/m^2 for operational vehicles.		

Further description:

The structural index is selected from Figure A-4 based on the predicted maximum.

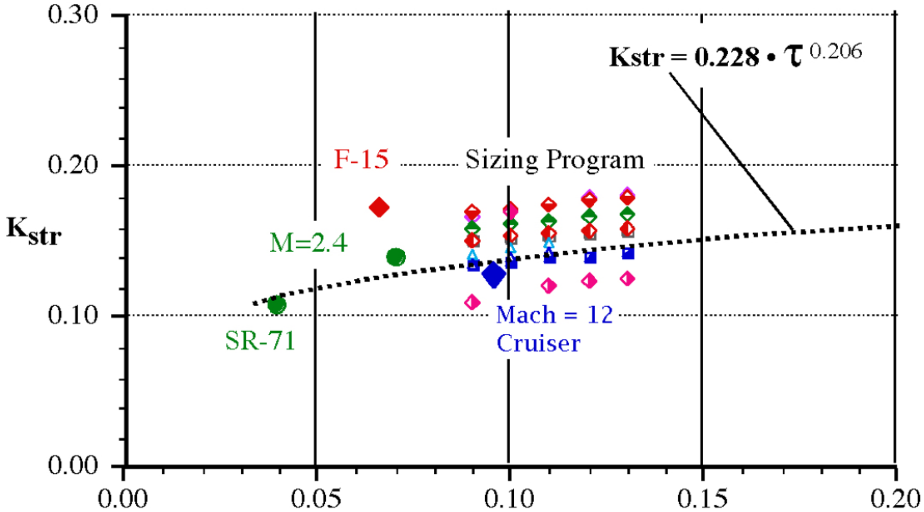


Fig. A-4. Structural index prediction description**.**

Appendix B. Trade-Study Assumptions and Database

B-1 TRADE 001: AIR-LAUNCHED, MACH 6, HYDROGEN FUEL

Mission summary: Table B-1.1 summarizes the mission constants for this trade study.

Table B-1.1. Air-Launched, Mach 6, Hydrogen Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	LH, LOX
Fuel density	74.63kg/m^3 (4.65 lb/ft^3)
Oxidizer density	1287 kg/m^3 (803.34 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by using hypersonic convergence.[6]

Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7)[11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

Structure and thermal protection
Structural shape factor K_{str} from MAC[5]

Propulsion
Rocket engine
Using the constants that are given in Table B-1.2, the sizing process determines the number of rockets required, which yields a minimum vehicle TOGW. Atmospheric losses were accounted for by using the P&W method.

Table B-1.2. Summary of Rocket Accelerators Explored

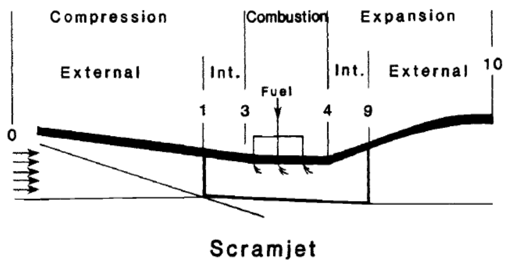
	RL-10A-5, P&W	Vulcain, SEP
E_{TW} – Engine thrust-to-weight ratio	46.12	61.36
ISP_{vac} – Vacuum ISP	373.0 s	440
T_{vac} – Vacuum thrust	64.7 kN (14,500 lb)	1015 kN (lb)
ε – Nozzle-expansion ratio	4.0	45.0
P_c – combustion-chamber pressure	38.6 atm	102.0 atm
O/F – oxidizer-to-fuel ratio	6.0	5.6

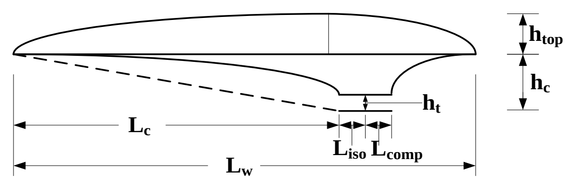
Dual-Mode ram-scramjet

The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that were assumed in the stream thrust analysis for this trade are summarized below in Table B-1.3.

Table B-1.3. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
H_{pr} (kJ/kg)	119954.0
f (stoichiometric)	0.0291
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.10
C_{ev}	0.99
C_{pe}	1.59
C_{ea}	1.00
γ_c	1.362
γ_e	1.22
Geometric constants	
l_c/l_w	0.65
h_c/l_c	0.088
h_{iso}/l_{iso}	0.1
L_{comb}	0.762 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance
Hypersonic convergence weight and volume formulation[6]

Table B-1.4. Summary of Weight and Volume Constants

Weight	
E_{TW_rkt} – Rocket thrust-to-weight ratio (T/W_{eng})	46.12 or 61.0 kg/kg
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_rkt} – rocket volume per kg thrust (V_{RKT}/T)	0.000133 or 0.000088 m^3/kg
K_{ve_DMR} – dual mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crew} – fixed crew volume coefficient	0.0

Performance
The energy-integration method was used to compute the trajectory.
The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 65 percent of body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design point database file: Table B-1.5 summarizes the design-point data collected by AVD^{sizing}.

Table B-1.5. Trade 001, Air-Launched, Mach 6, Hydrogen-Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	30
	Design Mach number	D_MACH	6
	(NA)	D_MVIHN	0
	(NA)	D_WR	1

Table B.1.5. ***Continued***

	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	4520
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic Acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	11000
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0
	Air-breathing transition Mach number	AMACH_TJS	3
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	1
	Fuel density	FUEL_DEN	74.63
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.125
	Planform area	SPLN	103.30815
	Ratio of wetted area to planform area	AKW	2.36792
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.1612

Table B.1.5. ***Continued***

	Total vehicle length	AL_TOTAL	18.00049
	Span	BPLN	9.56531
	Height above centerline	BASE_HEIGHT	2.83738
	Spatular width	CSPAT	1.91306
	Capture area	ACAP	5.62205
	Length of external compression	ALC	11.70032
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	1.43662
	Width of cowl at inlet	W3	3.34968
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00858
	Height of cowl to length of isolator	ALI_L	0.0858
	Height at combustor exit to nozzle length	H_LN	0.05581
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	82389762.44
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald's efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.01106
	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	5.40469
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.54888
Trajectory summary	Climb range	CLRANGE	180394.6293
	Cruise range	CRRANGE	3236961.266
	Decent range	DERANGE	853093.8265
	Total range	RANGE_TOTAL	4270449.722
	Climb time	T_CLIMB	2.68974
	Cruise time	T_CRUISE	30
	Descent time	T_DESCENT	22.32068
	Total flight time	T_FLT	55.01042
	Mach number at max rocket *T/W*	AMACH_TJ	1.38
	Maximum rocket *T/W*	TW_TJ_TM	1.78764
	(NA)	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	0.847
	Maximum capture area of scramjet (NA)	AC_W_MAX	5.62205
	(NA)	AMACH_ACAP	0.81

Table B.1.5. ***Continued***

	(NA)	QBAR_ACAP	10171.29338
	(NA)	ALT_ACAP	11000
	(NA)	CFN_ACAP	0
	Average cruise *L/D*	LD_CRUISE	2.46135
	Average cruise I_{sp}	ISP_CRUISE	2613.15135
	Minimum acceleration during scramjet mode	ANMIN	0.41159
	Oxidizer-to-fuel ratio	OF_TRAJ	0.86403
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	22136.37226
	Propellant weight	WPPL	10046.82982
	Total fuel weight	WFUEL	5357.2487
	Fuel 1 weight	WFUEL1	5357.2487
	Weight of oxidizer	Wox	4689.58113
	Manufacturer's zero-fuel weight	AMZFW	12089.54244
	Operating weight empty	OWE	12089.54244
	Operating empty weight	OEW	12089.54244
	Weight margin	WMARGIN	1099.04931
	Operational items weight	WOPER	0
	Systems weight	WSYS	3834.32679
	Structural weight	WSTR	4735.68883
	Rocket propulsion system weight	WP_TJ	858.02115
	Ram/scramjet weight	WP_SC	1562.45636
	Total fuel fraction	FF_TOTAL	0.45386
	Structural weight fraction	WSTR_TOGW	0.21393
	Total weight ratio	WR	1.83103
	Total volume	V_TOTAL	131.25381
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	10.25015
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	75.42793
	Total fuel volume	V_FUELI1	71.78412
	Total oxidizer volume	V_OX	3.64381
	Total propellant density	PPL_DEN	133.19775
	Total fuel density	FUEL_DEN	74.63
	Total oxidizer density	OX_DEN	1287
	Total rocket volume	VENG_TJ	5.26307

Table B.1.5. ***Concluded***

	Total ram/scramjet volume	VENG_SC	14.06211
	Total engine volume	VENG	19.32517
	Total void volume	VVOID	26.25076
Convergence check	Operating-weight-empty weight budget	OWE_W	12089.54244
	Operating-weight-empty volume budget	OWE_V	12089.51592
	Planform area	SPLN	103.30815
	Capture-area required	AC_RE	5.62205
	Capture-area available	AC_AV	5.62205
	Structural index	AISTR	19.35895
	Propulsion index	AIP	160.2794
	T/W rocket	TW_TJ_MAX	1.78764
	T/W scramjet	TW_SC_MAX	0.847
	Wing loading	WS	214.27517

B-2 TRADE 002: AIR-LAUNCHED, MACH 8, HYDROGEN FUEL

Mission summary: Table B-2.1 summarizes the mission constants for this trade study.

Table B-2.1. Air-Launched, Mach 8, Hydrogen-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	LH, LOX
Fuel density	74.63kg/m^3 (4.65 lb/ft^3)
Oxidizer density	1287 kg/m^3 (803.34 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by using hypersonic convergence.[6]

Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7) [11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

Structure and thermal protection
Structural shape factor K_{str} from MAC[5].

Propulsion
Rocket engine
Using the constants that are given in Table B-2.2, the sizing process determines the number of rockets required, which yields a minimum vehicle TOGW. Atmospheric losses were accounted for by using the P&W method.

Table B-2.2. Summary of Rocket Accelerators Explored

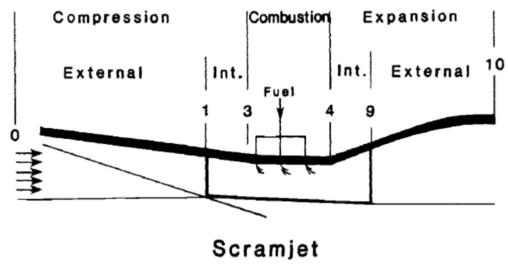
	RL-10A-5, P&W	Vulcain, SEP
E_{TW} – Engine thrust-to-weight ratio	46.12	61.36
ISP_{vac} – Vacuum ISP	373.0 s	440
T_{vac} – Vacuum thrust	64.7 kN (14,500 lb)	1015 kN (lb)
ε – Nozzle-expansion ratio	4.0	45.0
P_c – combustion-chamber pressure	38.6 atm	102.0 atm
O/F – oxidizerto-fuel ratio	6.0	5.6

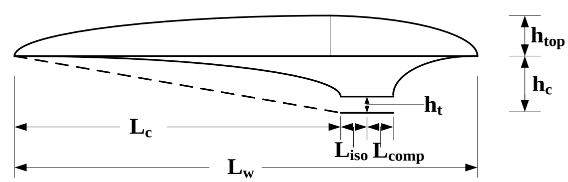
Dual-mode ram-scramjet

The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that are assumed in the stream thrust analysis for this trade are summarized in Table B-2.3.

Table B-2.3. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
Hpr (kJ/kg)	119954.0
f (stoichiometric)	0.0291
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.10
C_{ev}	0.99
C_{pe}	1.59
C_{ea}	1.00
γ_c	1.362
γ_e	1.22
Geometric constants	
l_c/l_w	0.65
h_c/l_c	0.088
h_{iso}/l_{iso}	0.1
L_{comb}	0.762 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance
The hypersonic convergence weight and volume formulation is summarized in Table B-2.4.

Table B-2.4. Summary of Weight and Volume Constants

Weight	
E_{TW_rkt} – Rocket thrust-to-weight ratio (T/W_{eng})	46.12 or 61.0 kg/kg
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (Wsys/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_rkt} – rocket volume per kg thrust (V_{RKT}/T)	0.000133 or 0.000088 m^3/kg
K_{ve_DMR} – dual-mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crw} – fixed crew volume coefficient	0.0

Performance
The energy-integration method was used to compute the trajectory.
The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 65 percent of the body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design-point database file: Table B-2.5 summarizes the design-point data that were collected by AVD^{sizing}.

Table B-2.5. Trade 002, Air-Launched, Mach 8, Hydrogen-Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	30
	Design Mach number	D_MACH	8
	(NA)	D_MVIHN	0
	(NA)	D_WR	1

Table B.2.5. *Continued*

	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	4520
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonicacceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	11000
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant q climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0
	Air-breathing transition Mach number	AMACH_TJS	3
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	1
	Fuel density	FUEL_DEN	74.63
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.15
	Planform area	SPLN	161.1835
	Ratio of wetted area to planform area	AKW	2.42036
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.19721

Table B.2.5. *Continued*

	Total vehicle length	AL_TOTAL	22.4842
	Span	BPLN	11.94791
	Height above centerline	BASE_HEIGHT	3.97159
	Spatular width	CSPAT	2.38958
	Capture area	ACAP	8.77163
	Length of external compression	ALC	14.61473
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	1.79446
	Width of cowl at inlet	W3	4.18405
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00617
	Height of cowl to length of isolator	ALI_L	0.06173
	Height at combustor exit to nozzle length	H_LN	0.03318
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	102912054.3
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald's efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.01196
	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	5.17812
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.4934
Trajectory summary	Climb range	CLRANGE	646761.7275
	Cruise range	CRRANGE	4353951.878
	Decent range	DERANGE	1299474.693
	Total range	RANGE_TOTAL	6300188.299
	Climb time	T_CLIMB	6.3516
	Cruise time	T_CRUISE	30
	Descent time	T_DESCENT	24.89358
	Total flight time	T_FLT	61.24517
	Mach number at max rocket *T/W*	AMACH_TJ	0.93
	Maximum rocket *T/W*	TW_TJ_TM	2.5297
	(NA)	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	1.20697
	Maximum capture area of scramjet (NA)	AC_W_MAX	8.77163

Table B.2.5. ***Continued***

	(NA)	AMACH_ACAP	0.81

	(NA)	QBAR_ACAP	10171.29338
	(NA)	ALT_ACAP	11000
	(NA)	CFN_ACAP	0
	Average cruise *L/D*	LD_CRUISE	2.30527
	Average cruise I_{sp}	ISP_CRUISE	2246.44966
	Minimum acceleration during scramjet mode	ANMIN	0.2189
	Oxidizer-to-fuel ratio	OF_TRAJ	0.57576
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	40900.46186
	Propellant weight	WPPL	20821.12118
	Total fuel weight	WFUEL	13149.3266
	Fuel 1 weight	WFUEL1	13149.3266
	Weight of oxidizer	Wox	7671.79458
	Manufacturer's zero-fuel weight	AMZFW	20079.34068
	Operating weight empty	OWE	20079.34068
	Operating empty weight	OEW	20079.34068
	Weight margin	WMARGIN	1825.39461
	Operational items weight	WOPER	0
	Systems weight	WSYS	5112.69451
	Structural weight	WSTR	7341.23756
	Rocket propulsion system weight	WP_TJ	1686.21222
	Ram/scramjet weight	WP_SC	4113.80178
	Total fuel fraction	FF_TOTAL	0.50907
	Structural weight fraction	WSTR_TOGW	0.17949
	Total weight ratio	WR	2.03694
	Total volume	V_TOTAL	306.95318
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	17.27813
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	182.15457
	Total fuel volume	V_FUELI1	176.19358
	Total oxidizer volume	V_OX	5.96099
	Total propellant density	PPL_DEN	114.30469
	Total fuel density	FUEL_DEN	74.63
	Total oxidizer density	OX_DEN	1287

Table B.2.5. ***Concluded***

	Total rocket volume	VENG_TJ	9.10501

	Total ram/scramjet volume	VENG_SC	37.02422
	Total engine volume	VENG	46.12922
	Total void volume	VVOID	61.39064
Convergence check	Operating-weight-empty weight budget	OWE_W	20079.34068
	Operating-weight-empty volume budget	OWE_V	20079.39617
	Planform area	SPLN	161.1835
	Capture-area required	AC_RE	8.77163
	Capture-area available	AC_AV	8.77163
	Structural index	AISTR	18.81777
	Propulsion index	AIP	110.23243
	T/W rocket	TW_TJ_MAX	2.5297
	T/W scramjet	TW_SC_MAX	1.20697
	Wing loading	WS	253.75092

B-3 TRADE 003: AIR-LAUNCHED, MACH 6, KEROSENE FUEL

Mission summary: Table B-3.1 summarizes the mission constants for this trade study.

Table B-3.1. Air-Launched, Mach 6, Kerosene-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	RP-1, LOX
Fuel density	820.0 kg/m^3 (51.2 lb/ft^3)
Oxidizer density	1287 kg/m^3 (803.34 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

<u>Geometry</u>
The blended-body configuration as defined by using hypersonic convergence.[6]

<u>Aerodynamics</u>
$C_{L\max}$ = 0.50 (FDL-7) [11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

<u>Structure and thermal protection</u>
Structural shape factor K_{str} from MAC[6].

<u>Propulsion</u>
Rocket engine
Using the constants that are given in Table B-3.2, the sizing process determines the number of rockets required, which yields a minimum vehicle TOGW. Atmospheric losses were accounted for by using the P&W method.

Table B-3.2. Summary of Rocket Accelerators Explored

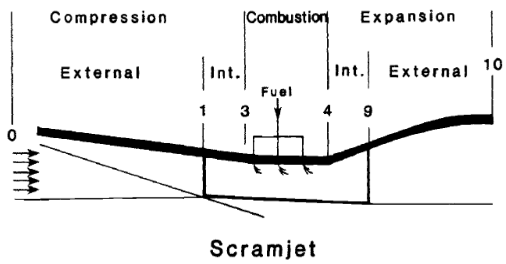
	Merlin , Space X
E_{TW} – Engine thrust-to-weight ratio	96.0
ISP_{vac} – Vacuum ISP	304.0 s
T_{vac} – Vacuum thrust	512.0 kN (115.0 lb)
ε – Nozzle-expansion ratio	14.0
P_c – combustion-chamber pressure	60.69 atm
O/F – oxidizer-to-fuel ratio	2.17

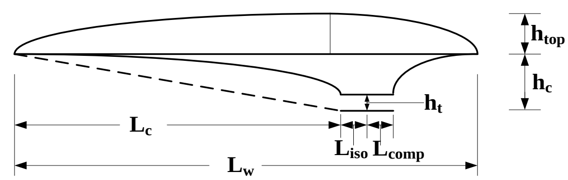
Dua- mode ram-scramjet

The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that were assumed in the stream thrust analysis for this trade are summarized in Table B-3.3.

Table B-3.3. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
H_{pr} (kJ/kg)	43380.0
f (stoichiometric)	0.0680
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.40
C_{ev}	0.99
C_{pe}	1.51
C_{ea}	0.98
γ_c	1.362
γ_e	1.28
Geometric constants	
l_c/l_w	0.50
h_c/l_c	0.067
h_{iso}/l_{iso}	0.1
L_{comb}	2.0 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance
Hypersonic convergence weight and volume formulation.[6]

Table B-3.4. Summary of Weight and Volume Constants

Weight	
E_{TW_rkt} – Rocket thrust-to-weight ratio (T/W_{eng})	96.0 kg/kg
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_rkt} – rocket volume per kg thrust (V_{RKT}/T)	0.000088 m^3/kg
K_{ve_DMR} – dual-mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crew} – fixed crew volume coefficient	0.0

Performance
The energy-integration method was used to compute the trajectory.
The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 50 percent of body length to keep the trim drag manageable.[6].
Cost
No cost model was utilized.

Design-point database file: Table B-3.5 summarizes the design-point data that were collected by AVD[sizing].

Table B-3.5. Trade 003, Air-Launched, Mach 6, Kerosene-Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	20
	Design Mach number	D_MACH	6
	(NA)	D_MVIHN	0
	(NA)	D_WR	1

Table B.3.5. *Continued*

	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	4572
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	11000
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0
	Air-breathing transition Mach number	AMACH_TJS	3
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	1
	Fuel density	FUEL_DEN	820
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.07
	Planform area	SPLN	58.38376
	Ratio of wetted area to planform area	AKW	2.30811
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.09352

Table B.3.5. ***Continued***

	Total vehicle length	AL_TOTAL	13.53204

	Span	BPLN	7.19081
	Height above centerline	BASE_HEIGHT	1.41398
	Spatular width	CSPAT	1.43816
	Capture area	ACAP	2.19091
	Length of external compression	ALC	6.76602
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	0.83076
	Width of cowl at inlet	W3	2.26892
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00803
	Height of cowl to length of isolator	ALI_L	0.08034
	Height at combustor exit to nozzle length	H_LN	0.04212
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	61937258.73
	Mach number for approach	AMACH	0.1884
	Landing gear drag	DCD_LG	0.0015
	Oswald's efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.00953
	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	5.90312
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.45864
Trajectory summary	Climb range	CLRANGE	304462.8653
	Cruise range	CRRANGE	2158897.648
	Decent range	DERANGE	1078335.405
	Total range	RANGE_TOTAL	3541695.918
	Climb time	T_CLIMB	3.92479
	Cruise time	T_CRUISE	20
	Descent time	T_DESCENT	26.46614
	Total flight time	T_FLT	50.39093
	Mach number at max rocket *T/W*	AMACH_TJ	0.81
	Maximum rocket *T/W*	TW_TJ_TM	3.34752
	(NA)	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	0.54832

Table B.3.5. ***Continued***

	Maximum capture area of scramjet (NA)	AC_W_MAX	2.19091
	(NA)	AMACH_ACAP	0.81
	(NA)	QBAR_ACAP	10171.29338

	(NA)	ALT_ACAP	11000
	(NA)	CFN_ACAP	0
	Average cruise *L/D*	LD_CRUISE	3.79014
	Average cruise I_{sp}	ISP_CRUISE	942.59695
	Minimum acceleration during scramjet mode	ANMIN	0.19489
	Oxidizer-to-fuel ratio	OF_TRAJ	0.47237
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	14191.36724
	Propellant weight	WPPL	7715.23442
	Total fuel weight	WFUEL	5217.89052
	Fuel 1 weight	WFUEL1	5217.89052
	Weight of oxidizer	Wox	2497.3439
	Manufacturer's zero-fuel weight	AMZFW	6476.13282
	Operating weight empty	OWE	6476.13282
	Operating empty weight	OEW	6476.13282
	Weight margin	WMARGIN	588.73935
	Operational items weight	WOPER	0
	Systems weight	WSYS	2936.18125
	Structural weight	WSTR	1759.09396
	Rocket propulsion system weight	WP_TJ	543.66565
	Ram/scramjet weight	WP_SC	648.45261
	Total fuel fraction	FF_TOTAL	0.54366
	Structural weight fraction	WSTR_TOGW	0.12396
	Total weight ratio	WR	2.19133
	Total volume	V_TOTAL	31.22742
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	6.2491
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	8.30372
	Total fuel volume	V_FUELI1	6.36328
	Total oxidizer volume	V_OX	1.94044
	Total propellant density	PPL_DEN	929.12997

Table B.3.5. ***Concluded***

	Total fuel density	FUEL_DEN	820
	Total oxidizer density	OX_DEN	1287
	Total rocket volume	VENG_TJ	4.59289
	Total ram/scramjet volume	VENG_SC	5.83607

	Total engine volume	VENG	10.42896
	Total void volume	VVOID	6.24548
Convergence check	Operating-weight-empty weight budget	OWE_W	6476.13282
	Operating-weight-empty volume budget	OWE_V	6476.18811
	Planform area	SPLN	58.38376
	Capture-area required	AC_RE	2.19091
	Capture-area available	AC_AV	2.19091
	Structural index	AISTR	13.05393
	Propulsion index	AIP	779.90749
	T/W rocket	TW_TJ_MAX	3.67772
	T/W scramjet	TW_SC_MAX	0.54832
	Wing loading	WS	243.07046

B-4 TRADE 004: AIR-LAUNCHED, MACH 8, KEROSENE FUEL

Mission summary: Table B-4.1 summarizes the mission constants for this trade study.

Table B-4.1. Air-Launched, Mach 6, Kerosene-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	RP-1, LOX
Fuel density	820.0 kg/m^3 (51.2 lb/ft^3)
Oxidizer density	1287 kg/m^3 (803.34 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by hypersonic convergence.[6]

Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7) [11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

Structure and thermal protection
Structural shape factor K_{str} from MAC[6]

Propulsion
Rocket engine
Using the constants that are given in Table B-4.2, the sizing process determines the number of rockets required, which yields a minimum vehicle TOGW. Atmospheric losses were accounted for by using the P&W method.

Table B-4.2. Summary of Rocket Accelerators Explored

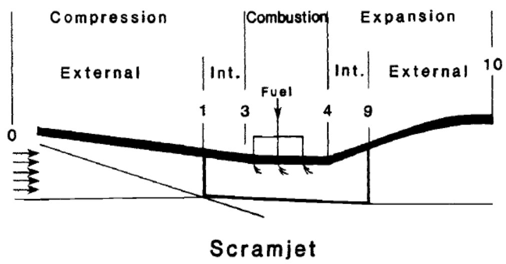
	Merlin, Space X
E_{TW} – Engine thrust-to-weight ratio	96.0
ISP_{vac} – Vacuum ISP	304.0 s
T_{vac} – Vacuum thrust	512.0 kN (115.0 lb)
ε – Nozzle-expansion ratio	14.0
P_c – combustion-chamber pressure	60.69 atm
O/F – oxidizer-to-fuel ratio	2.17

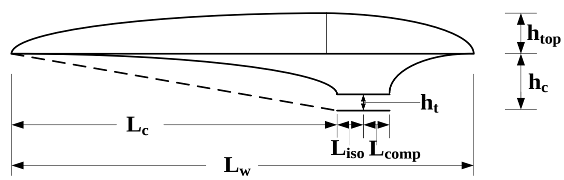
Dual-mode ram-scramjet

The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that were assumed in the stream thrust analysis for this trade are summarized in Table B-4.3.

Table B-4.3. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
Hpr (kJ/kg)	43380.0
f (stoichiometric)	0.0680
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.40
C_{ev}	0.99
C_{pe}	1.51
C_{ea}	0.98
γ_c	1.362
γ_e	1.28
Geometric constants	
l_c/l_w	0.50
h_c/l_c	0.067
h_{iso}/l_{iso}	0.1
L_{comb}	2.0 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance
Hypersonic convergence weight and volume formulation.[6]

Table B-4.4. Summary of Weight and Volume Constants

Weight	
E_{TW_rkt} – Rocket thrust-to-weight ratio (T/W_{eng})	96.0 kg/kg
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_rkt} – rocket volume per kg thrust (V_{RKT}/T)	0.000088 m^3/kg
K_{ve_DMR} – dual-mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crew} – fixed crew volume coefficient	0.0

Performance
The energy-integration method was used to compute the trajectory.
The required approach speed wascomputed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 50 percent of the body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design-Point database file: Table B-4.5 summarizes the design-point data that were collected by AVD^{sizing}.

Table B-4.5. Trade 004, Air-Launched, Mach 8, Kerosene-Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	4.5
	Design Mach number	D_MACH	8
	(NA)	D_MVIHN	0
	(NA)	D_WR	1

Table B.4.5. ***Continued***

	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	2400
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	11000
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0
	Air-breathing transition Mach number	AMACH_TJS	3
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	1
	Fuel density	FUEL_DEN	820
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.0675
	Planform area	SPLN	76.73385
	Ratio of wetted area to planform area	AKW	2.30252
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.08529
	Total vehicle length	AL_TOTAL	15.51353

Table B.4.5. ***Continued***

	Span	BPLN	8.24376
	Height above centerline	BASE_HEIGHT	1.6733
	Spatular width	CSPAT	1.64875
	Capture area	ACAP	3.44037
	Length of external compression	ALC	8.84271
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	1.08575
	Width of cowl at inlet	W3	2.7345
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00692
	Height of cowl to length of isolator	ALI_L	0.06922
	Height at combustor exit to nozzle length	H_LN	0.04097
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	71006721
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald's efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.00945
	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	5.92578
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.44328
Trajectory summary	Climb range	CLRANGE	788626.134
	Cruise range	CRRANGE	652138.1791
	Decent range	DERANGE	1826877.811
	Total range	RANGE_TOTAL	3267642.124
	Climb time	T_CLIMB	7.34318
	Cruise time	T_CRUISE	4.5
	Descent time	T_DESCENT	32.73813
	Total flight time	T_FLT	44.58131
	Mach number at max rocket *T/W*	AMACH_TJ	1.2
	Maximum rocket *T/W*	TW_TJ_TM	2.74501
	(NA)	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	0.9407
	Maximum capture area of scramjet (NA)	AC_W_MAX	3.44037
	(NA)	AMACH_ACAP	0.81

Table B.4.5. ***Continued***

	(NA)	QBAR_ACAP	10171.29338
	(NA)	ALT_ACAP	11000
	(NA)	CFN_ACAP	0
	Average cruise *L/D*	LD_CRUISE	3.38824
	Average cruise I_{sp}	ISP_CRUISE	752.86825
	Minimum acceleration during scramjet mode	ANMIN	0.13563
	Oxidizer-to-fuel ratio	OF_TRAJ	0.45572
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	19013.29831
	Propellant weight	WPPL	10627.20547
	Total fuel weight	WFUEL	7271.3604
	Fuel 1 weight	WFUEL1	7271.3604
	Weight of oxidizer	Wox	3355.84507
	Manufacturer's zero-fuel weight	AMZFW	8386.09284
	Operating weight empty	OWE	8386.09284
	Operating empty weight	OEW	8386.09284
	Weight margin	WMARGIN	762.37208
	Operational items weight	WOPER	0
	Systems weight	WSYS	3241.77485
	Structural weight	WSTR	2347.78996
	Rocket propulsion system weight	WP_TJ	543.66424
	Ram/scramjet weight	WP_SC	1490.49171
	Total fuel fraction	FF_TOTAL	0.55894
	Structural weight fraction	WSTR_TOGW	0.12348
	Total weight ratio	WR	2.26724
	Total volume	V_TOTAL	45.37162
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	6.81486
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	11.47501
	Total fuel volume	V_FUELI1	8.86751
	Total oxidizer volume	V_OX	2.60749
	Total propellant density	PPL_DEN	926.11757
	Total fuel density	FUEL_DEN	820
	Total oxidizer density	OX_DEN	1287
	Total rocket volume	VENG_TJ	4.59288

Table B.4.5. ***Concluded***

	Total ram/scramjet volume	VENG_SC	13.41443
	Total engine volume	VENG	18.0073
	Total void volume	VVOID	9.07432
Convergence check	Operating-weight-empty weight budget	OWE_W	8386.09284
	Operating-weight-empty volume budget	OWE_V	8386.12797
	Planform area	SPLN	76.73385
	Capture-area required	AC_RE	3.44037
	Capture-area available	AC_AV	3.44037
	Structural index	AISTR	13.2883
	Propulsion index	AIP	730.81375
	T/W rocket	TW_TJ_MAX	2.74501
	T/W scramjet	TW_SC_MAX	0.9407
	Wing loading	WS	247.7824

B-5 TRADE 005: AIR-LAUNCHED, MACH 6, DUAL FUEL

Mission summary: Table B-5.1 summarizes the mission constants for this trade study.

Table B-5.1. Air-Launched, Mach 6, Dual-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	RP-1, LH, LOX
Kerosene-fuel density	820.0 kg/m^3 (51.2 lb/ft^3)
Hydrogen-fuel density	74.63kg/m^3 (4.65 lb/ft^3)
Oxidizer density	1287 kg/m^3 (803.34 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by using hypersonic convergence.[6]

Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7) [11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

Structure and thermal protection
Structural shape factor K_{str} from MAC[6]

Propulsion
Rocket engine
Using the constants that are given in Table B-5.2, the sizing process determines the number of rockets required, which yields a minimum vehicle TOGW. Atmospheric losses were accounted for by using the P&W method.

Table B-5.2. Summary of Rocket Accelerators Explored

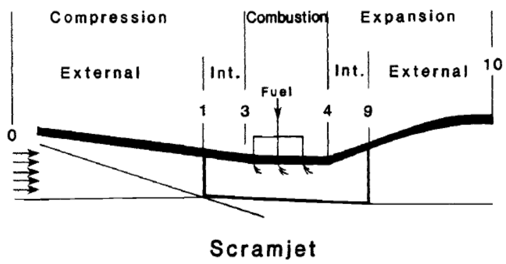
	Merlin, Space X
E_{TW} – Engine thrust-to-weight ratio	96.0
ISP_{vac} – Vacuum ISP	304.0 s
T_{vac} – Vacuum thrust	512.0 kN (115.0 lb)
ε – Nozzle-expansion ratio	14.0
P_c – combustion-chamber pressure	60.69 atm
O/F – oxidizer-to-fuel ratio	2.17

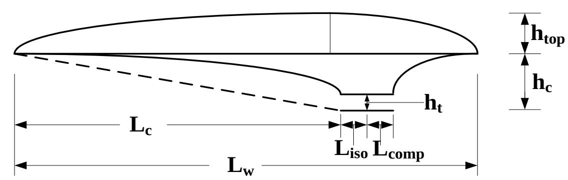
Dual-mode ram-scramjet

The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that are assumed in the stream thrust analysis for this trade are summarized in Table B-5.3.

Table B-5.3 Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
H_{pr} (kJ/kg)	119954.0
f (stoichiometric)	0.0291
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.10
C_{ev}	0.99
C_{pe}	1.59
C_{ea}	1.00
γ_c	1.362
γ_e	1.22
Geometric constants	
l_c/l_w	0.65
h_c/l_c	0.088
$h_{\text{iso}}/l_{\text{iso}}$	0.1
L_{comb}	0.762 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance
Hypersonic convergence weight and volume formulation[6]

Table B-5.4. Summary of Weight and Volume Constants

Weight	
E_{TW_rkt} – Rocket thrust-to-weight ratio (T/W_{eng})	96.0 kg/kg
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_rkt} – rocket volume per kg thrust (V_{RKT}/T)	0.000133 or 0.000088 m^3/kg
K_{ve_DMR} – dual-mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crew} – fixed crew volume coefficient	0.0

Performance
The energy-integration method was used to compute the trajectory.
The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 65 percent of body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design-point database file: Table B-5.5. summarizes the design-point data that were collected by AVD^{sizing}.

Table B-5.5. Trade 005, Air-Launched, Mach 6, Dual-Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	30
	Design Mach number	D_MACH	6
	(NA)	D_MVIHN	0
	(NA)	D_WR	1

Table B.5.5. ***Continued***

	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	2400
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	11000
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0
	Air-breathing transition Mach number	AMACH_TJS	3
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	2
	Fuel density	FUEL_DEN	820
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.15
	Planform area	SPLN	84.74165
	Ratio of wetted area to planform area	AKW	2.41685
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.19496

Table B.5.5. ***Continued***

	Total vehicle length	AL_TOTAL	16.30293
	Span	BPLN	8.66324
	Height above centerline	BASE_HEIGHT	2.86038
	Spatular width	CSPAT	1.73265
	Capture area	ACAP	4.61165
	Length of external compression	ALC	10.5969
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	1.30114
	Width of cowl at inlet	W3	3.03378
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00858
	Height of cowl to length of isolator	ALI_L	0.0858
	Height at combustor exit to nozzle length	H_LN	0.05694
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	74619857.12
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald's efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.01195
	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	5.17812
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.48596
Trajectory summary	Climb range	CLRANGE	213817.6566
	Cruise range	CRRANGE	3238239.258
	Decent range	DERANGE	773931.1643
	Total range	RANGE_TOTAL	4225988.079
	Climb time	T_CLIMB	2.90413
	Cruise time	T_CRUISE	30
	Descent time	T_DESCENT	21.20696
	Total flight time	T_FLT	54.11109
	Mach number at max rocket *T/W*	AMACH_TJ	2.62051
	Maximum rocket *T/W*	TW_TJ_TM	2.66202
	(NA)	Amach_sc	0
	Maximum scramjet *T/W*	TW_SC_TM	0.90956
	Maximum capture area of scramjet (NA)	AC_W_MAX	4.61165
	(NA)	Amach_acap	0.81

Table B.5.5. ***Continued***

	(NA)	Qbar_acap	10171.29338
	(NA)	Alt_acap	11000
	(NA)	Cfn_acap	0
	Average cruise *L/D*	LD_CRUISE	2.02834
	Average cruise I_{sp}	ISP_CRUISE	2618.93452
	Minimum acceleration during scramjet mode	ANMIN	0.27328
	Oxidizer-to-fuel ratio	OF_TRAJ	0.60278
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	19606.07443
	Propellant weight	WPPL	10125.86402
	Total fuel weight	WFUEL	6287.96357
	Fuel 1 weight	WFUEL1	1746.66415
	Fuel 2 weight	WFUEL2	4541.29942
	Weight of oxidizer	Wox	3837.90045
	Manufacturer's zero-fuel weight	AMZFW	9480.21041
	Operating weight empty	OWE	9480.21041
	Operating empty weight	OEW	9480.21041
	Weight margin	WMARGIN	861.83731
	Operational items weight	WOPER	0
	Systems weight	WSYS	3416.83367
	Structural weight	WSTR	3171.79376
	Rocket propulsion system weight	WP_TJ	543.66375
	Ram/scramjet weight	WP_SC	1486.08192
	Total fuel fraction	FF_TOTAL	0.51647
	Structural weight fraction	WSTR_TOGW	0.16178
	Total weight ratio	WR	2.06811
	Total volume	V_TOTAL	117.01368
	Fixed systems volume	V_FIX	5
	Total systems volume	V_sys	9.68055
	Total payload volume	V_pay	0
	Total crew volume	V_crew	0
	Total propellant volume	V_ppl	65.96299
	Fuel 1 volume	V_fueli1	2.13008
	Fuel 2 volume	V_fueli2	60.85086
	Total oxidizer volume	V_ox	2.98205
	Total propellant density	Ppl_den	153.50827
	Total fuel density	Fuel_den	820

Table B.5.5. ***Concluded***

	Total oxidizer density	Ox_den	1287
	Total rocket volume	Veng_tj	4.59287
	Total ram/scramjet volume	Veng_sc	13.37474
	Total engine volume	Veng	17.96761
	Total void volume	Vvoid	23.40274
Convergence check	Operating-weight-empty weight budget	OWE_W	9480.21041
	Operating-weight-empty volume budget	OWE_V	9480.18806
	Planform area	Spln	84.74165
	Capture-area required	Ac_re	4.61165
	Capture-area available	Ac_av	4.61165
	Structural index	Aistr	15.48668
	Propulsion index	Aip	143.72015
	T/W rocket	TW_TJ_MAX	2.66202
	T/W scramjet	TW_SC_MAX	0.90956
	Wing loading	Ws	231.3629

B-6 TRADE 006: AIR-LAUNCHED, MACH 8, DUAL FUEL

Mission summary: Table B-6.1 summarizes the mission constants for this trade study.

Table B.6.1. Air-Launched, Mach 8, Dual-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	11,000 m (36,000 ft)
Launch velocity	0.8 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	RP-1, LH, LOX
Kerosene-fuel density	820.0 kg/m^3 (51.2 lb/ft^3)
Hydrogen-fuel density	74.63kg/m^3 (4.65 lb/ft^3)
Oxidizer density	1287 kg/m^3 (803.34 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by using hypersonic convergence.[6]

Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7)[11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

Structure and thermal protection
Structural shape factor K_{str} from MAC[6]

Propulsion
Rocket engine
From the constants that are given in Table B-6.2, the sizing process determines the number of rockets required, which yields a minimum vehicle TOGW. Atmospheric losses were accounted for by using the P&W method.

Table B-6.2. Summary of Rocket Accelerators Explored

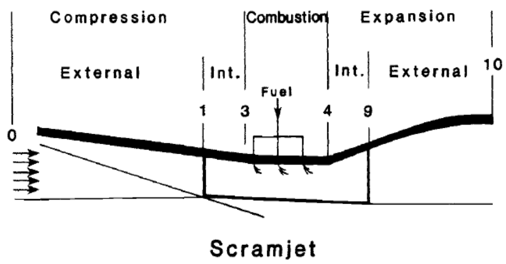
	Merlin, Space X
E_{TW} – Engine thrust-to-weight ratio	96.0
ISP_{vac} – Vacuum ISP	304.0 s
T_{vac} – Vacuum thrust	512.0 kN (115.0 lb)
ε – Nozzle-expansion ratio	14.0
P_c – combustion-chamber pressure	60.69 atm
O/F – oxidizer-to-fuel ratio	2.17

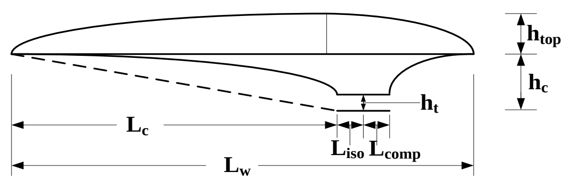
Dual-mode ram-scramjet

The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that are assumed in the stream thrust analysis for this trade are summarized in Table B-6.3.

Table B-6.3. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
H_{pr} (kJ/kg)	119954.0
f (stoichiometric)	0.0291
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.10
C_{ev}	0.99
C_{pe}	1.59
C_{ea}	1.00
γ_c	1.362
γ_e	1.22
Geometric constants	
l_c/l_w	0.65
h_c/l_c	0.088
h_{iso}/l_{iso}	0.1
L_{comb}	0.762 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance
Hypersonic convergence weight and volume formulation[6]

Table B-6.4. Summary of Weight and Volume Constants

Weight	
E_{TW_rkt} – Rocket thrust-to-weight ratio (T/W_{eng})	96.0 kg/kg
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_rkt} – rocket volume per kg thrust (V_{RKT}/T)	0.000133 or 0.000088 m^3/kg
K_{ve_DMR} – dual mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crw} – fixed crew volume coefficient	0.0

Performance
The energy-integration method was used to compute the trajectory.
The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 65 percent of body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design-point database file: Table B-6.5 summarizes the design-point data that were collected by AVD[sizing].

Table B-6.5. Trade 006, Air-Launched, Mach 8, Dual-Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	25
	Design Mach number	D_MACH	8
	(NA)	D_MVIHN	0
	(NA)	D_WR	1

Table B.6.5. *Continued*			
	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	2400
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	11000
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0
	Air-breathing transition Mach number	AMACH_TJS	3
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	2
	Fuel density	FUEL_DEN	820
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.13
	Planform area	SPLN	114.37446
	Ratio of wetted area to planform area	AKW	2.37932
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.1696

Table B.6.5. *Continued*

	Total vehicle length	AL_TOTAL	18.94007
	Span	BPLN	10.06459
	Height above centerline	BASE_HEIGHT	3.06947
	Spatular width	CSPAT	2.01292
	Capture area	ACAP	6.22428
	Length of external compression	ALC	12.31105
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	1.51161
	Width of cowl at inlet	W3	3.52452
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00617
	Height of cowl to length of isolator	ALI_L	0.06173
	Height at combustor exit to nozzle length	H_LN	0.03403
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	86690295.96
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald's efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.01124
	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	5.35937
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.46921
Trajectory summary	Climb range	CLRANGE	519231.8808
	Cruise range	CRRANGE	3627110.709
	Decent range	DERANGE	1409570.9
	Total range	RANGE_TOTAL	5555913.49
	Climb time	T_CLIMB	5.29807
	Cruise time	T_CRUISE	25
	Descent time	T_DESCENT	27.39591
	Total flight time	T_FLT	57.69398
	Mach number at max rocket *T/W*	AMACH_TJ	1.23
	Maximum rocket *T/W*	TW_TJ_TM	2.03595
	NA	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	1.15596
	Maximum capture area of scramjet (NA)	AC_W_MAX	6.22428
	(NA)	AMACH_ACAP	0.81

Table B.6.5. ***Continued***

	(NA)	QBAR_ACAP	10171.29338
	(NA)	ALT_ACAP	11000
	(NA)	CFN_ACAP	0
	Average cruise *L/D*	LD_CRUISE	2.27915
	Average cruise I_{sp}	ISP_CRUISE	2246.37844
	Minimum acceleration during scramjet mode	ANMIN	0.29657
	Oxidizer-to-fuel ratio	OF_TRAJ	0.603
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	25635.0344
	Propellant weight	WPPL	13666.90797
	Total fuel weight	WFUEL	8488.3351
	Fuel 1 weight	WFUEL1	2358.72421
	Fuel 2 weight	WFUEL2	6129.6109
	Weight of oxidizer	Wox	5178.57286
	Manufacturer’s zero-fuel weight	AMZFW	11968.12644
	Operating weight empty	OWE	11968.12644
	Operating empty weight	OEW	11968.12644
	Weight margin	WMARGIN	1088.01149
	Operational items weight	WOPER	0
	Systems weight	WSYS	3814.90023
	Structural weight	WSTR	4052.12375
	Rocket propulsion system weight	WP_TJ	543.66377
	Ram/scramjet weight	WP_SC	2469.42719
	Total fuel fraction	FF_TOTAL	0.53313
	Structural weight fraction	WSTR_TOGW	0.15807
	Total weight ratio	WR	2.14194
	Total volume	V_TOTAL	159.01458
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	11.36058
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	89.03358
	Fuel 1 volume	V_FUELI1	2.87649
	Fuel 2 volume	V_FUELI2	82.13334
	Total oxidizer volume	V_OX	4.02376
	Total propellant density	PPL_DEN	153.50284
	Total fuel density	FUEL_DEN	820

Table B.6.5. ***Concluded***

	Total oxidizer density	OX_DEN	1287
	Total rocket volume	VENG_TJ	4.59287
	Total ram/scramjet volume	VENG_SC	22.22484
	Total engine volume	VENG	26.81772
	Total void volume	VVOID	31.80292
Convergence check	Operating-weight-empty weight budget	OWE_W	11968.12644
	Operating-weight-empty volume budget	OWE_V	11968.10381
	Planform area	SPLN	114.37446
	Capture-area required	AC_RE	6.22428
	Capture-area available	AC_AV	6.22428
	Structural index	AISTR	14.89021
	Propulsion index	AIP	134.42261
	T/W rocket	TW_TJ_MAX	2.03595
	T/W scramjet	TW_SC_MAX	1.15596
	Wing loading	WS	224.1325

B-7 TRADE 007: EXPENDABLE BOOSTER, MACH 6, HYDROGEN FUEL

Mission summary: Table B-7.1 summarizes the mission constants for this trade study.

Table B-7.1. Expendable-Booster, Mach 6, Hydrogen-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	17,260 m (56,630 ft)
Launch velocity	3.0 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	LH
Hydrogen-fuel density	74.63kg/m^3 (4.65 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by using hypersonic convergence.[6]

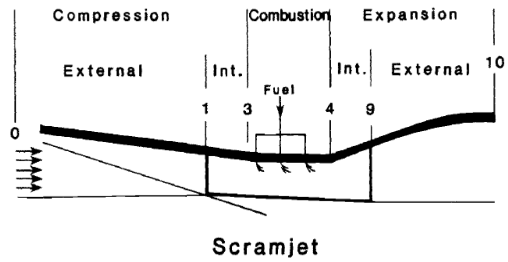
Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7) [11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

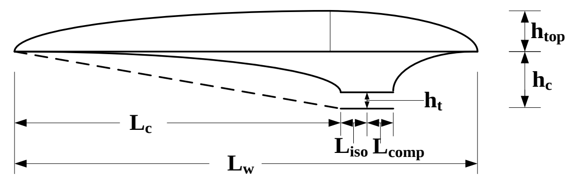
Structure and thermal protection
Structural shape factor K_{str} from MAC[6]

Propulsion
Dual-mode ram-scramjet
The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that are assumed in the stream thrust analysis for this trade are summarized in Table B-7.2.

Table B-7.2. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
H_{pr} (kJ/kg)	119954.0
f (stoichiometric)	0.0291
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.10
C_{ev}	0.99
C_{pe}	1.59
C_{ea}	1.00
γ_c	1.362
γ_e	1.22
Geometric constants	
l_c/l_w	0.60
h_c/l_c	0.08
h_{iso}/l_{iso}	0.1
L_{comb}	0.762 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





<u>Weight, volume, and balance</u>
Hypersonic convergence weight and volume formulation.[6]

Table B-7.3. Summary of Weight and Volume Constants

Weight	
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_DMR} – dual-mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crw} – fixed crew volume coefficient	0.0

<u>Performance</u>
The energy-integration method was used to compute the trajectory.
The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 60 percent of body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design-point database file: Table B-7.4 summarizes the design-point data that were collected by AVD^{sizing}.

Table B-7.4. Trade 007, Expendable-Booster, Mach 6, Hydrogen-Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	30
	Design Mach number	D_MACH	6
	(NA)	D_MVIHN	0
	(NA)	D_WR	1
	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	2400
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	17260
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0

Table B.7.4. ***Continued***

	Air-breathing transition Mach number	AMACH_TJS	2.5
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	1
	Fuel density	FUEL_DEN	74.63
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.175
	Planform area	SPLN	63.4503
	Ratio of wetted area to planform area	AKW	2.48815
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.23607
	Total vehicle length	AL_TOTAL	14.10698
	Span	BPLN	7.49633
	Height above centerline	BASE_HEIGHT	2.69141
	Spatular width	CSPAT	1.49927
	Capture area	ACAP	3.05364
	Length of external compression	ALC	8.46419
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	1.03927
	Width of cowl at inlet	W3	2.53854
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00885
	Height of cowl to length of isolator	ALI_L	0.0885
	Height at combustor exit to nozzle length	H_LN	0.04976
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	64568809.22
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald's efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.01306

Table B.7.4. ***Continued***

	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	4.95156
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.67345
Trajectory summary	Climb range	CLRANGE	170096.1216
	Cruise range	CRRANGE	3238877.436
	Decent range	DERANGE	709365.5088
	Total range	RANGE_TOTAL	4118339.066
	Climb time	T_CLIMB	2.07588
	Cruise time	T_CRUISE	30
	Descent time	T_DESCENT	19.55827
	Total flight time	T_FLT	51.63415
	Mach number at max rocket *T/W*	AMACH_TJ	0
	Maximum rocket *T/W*	TW_TJ_TM	0
	(NA)	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	1.37328
	Maximum capture area of scramjet (NA)	AC_W_MAX	3.05364
	(NA)	AMACH_ACAP	3
	(NA)	QBAR_ACAP	53177.74012
	(NA)	ALT_ACAP	17260
	(NA)	CFN_ACAP	0.76981
	Average cruise *L/D*	LD_CRUISE	1.88078
	Average cruise I_{sp}	ISP_CRUISE	2600.27308
	Minimum acceleration during scramjet mode	ANMIN	0.33083
	Oxidizer-to-fuel ratio	OF_TRAJ	0
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	11504.86122
	Propellant weight	WPPL	3795.67775
	Total fuel weight	WFUEL	3756.93813
	Fuel 1 weight	WFUEL1	3756.93813
	Weight of oxidizer	Wox	38.73962
	Manufacturer’s zero-fuel weight	AMZFW	7709.18347
	Operating weight empty	OWE	7709.18347
	Operating empty weight	OEW	7709.18347
	Weight margin	WMARGIN	700.83486

Table B.7.4. ***Concluded***

	Operational items weight	WOPER	0
	Systems weight	WSYS	3133.46936
	Structural weight	WSTR	2558.26102
	Rocket propulsion system weight	WP_TJ	0
	Ram/scramjet weight	WP_SC	1316.61824
	Total fuel fraction	FF_TOTAL	0.32992
	Structural weight fraction	WSTR_TOGW	0.22236
	Total weight ratio	WR	1.49236
	Total volume	V_TOTAL	88.4481
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	8.53792
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	50.37096
	Total fuel volume	V_FUELI1	50.34086
	Total oxidizer volume	V_OX	0.0301
	Total propellant density	PPL_DEN	75.35449
	Total fuel density	FUEL_DEN	74.63
	Total oxidizer density	OX_DEN	1287
	Total rocket volume	VENG_TJ	0
	Total ram/scramjet volume	VENG_SC	11.84956
	Total engine volume	VENG	11.84956
	Total void volume	VVOID	17.68962
Convergence check	Operating-weight-empty weight budget	OWE_W	7709.18347
	Operating-weight-empty volume budget	OWE_V	7709.188
	Planform area	SPLN	63.4503
	Capture-area required	AC_RE	3.05364
	Capture-area available	AC_AV	3.05364
	Structural index	AISTR	16.20449
	Propulsion index	AIP	153.04818
	T/W rocket	TW_TJ_MAX	0
	T/W scramjet	TW_SC_MAX	1.37328
	Wing loading	WS	181.32085

B-8 TRADE 008: EXPENDABLE BOOSTER, MACH 8, HYDROGEN FUEL

Mission summary: Table B-8.1 summarizes the mission constants for this trade study.

Table B-8.1. Expendable-Booster, Mach 8, Hydrogen-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	17,260 m (56,630 ft)
Launch velocity	3.0 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,400 ft)
Propellant selection	LH
Hydrogen-fuel density	74.63kg/m^3 (4.65 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by using hypersonic convergence.[6]

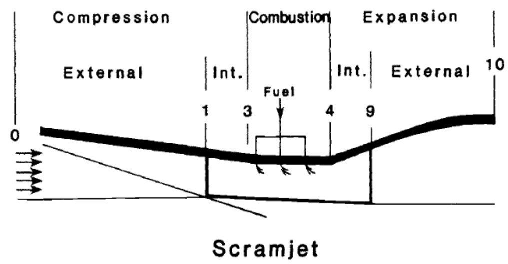
Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7)[11]
HyFAC database, MAC circa 1970[3]
Spatular corrections from Pike

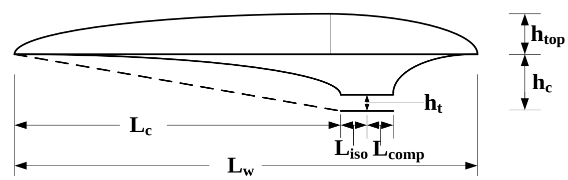
Structure and thermal protection
Structural shape factor K_{str} from MAC[6]

Propulsion
Dual-mode ram-scramjet
The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that are assumed in the stream thrust analysis for this trade are summarized in Table B-8.2.

Table B-8.2. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
H_{pr} (kJ/kg)	119954.0
f (stoichiometric)	0.0291
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.10
C_{ev}	0.99
C_{pe}	1.59
C_{ea}	1.00
γ_c	1.362
γ_e	1.22
Geometric constants	
l_c/l_w	0.65
h_c/l_c	0.09
h_{iso}/l_{iso}	0.1
L_{comb}	0.762 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance

Hypersonic convergence weight and volume formulation[6]

Table B-8.3. Summary of Weight and Volume Constants

Weight	
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_DMR} – dual-mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crew} – fixed crew volume coefficient	0.0

Performance

The energy-integration method was used to compute the trajectory.

The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 60 percent of body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design-point database file: Table B-8.4 summarizes the design-point data that were collected by AVD^{sizing}.

Table B-8.4. Trade 008, Expendable-Booster, Mach 8, Hydrogen-Fuel, Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	30
	Design Mach number	D_MACH	8
	(NA)	D_MVIHN	0
	(NA)	D_WR	1
	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	2400
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	17260
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0

Table B.8.4. ***Continued***

	Air-breathing transition Mach number	AMACH_TJS	2.5
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	1
	Fuel density	FUEL_DEN	74.63
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.1825
	Planform area	SPLN	95.66821
	Ratio of wetted area to planform area	AKW	2.4918
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.24083
	Total vehicle length	AL_TOTAL	17.32212
	Span	BPLN	9.20482
	Height above centerline	BASE_HEIGHT	3.45871
	Spatular width	CSPAT	1.84096
	Capture area	ACAP	5.20628
	Length of external compression	ALC	11.25938
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	1.38248
	Width of cowl at inlet	W3	3.22344
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00617
	Height of cowl to length of isolator	ALI_L	0.06173
	Height at combustor exit to nozzle length	H_LN	0.03455
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	79284769.75
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald’s efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.01333

Table B.8.4. ***Continued***

	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	4.88359
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.62393
Trajectory summary	Climb range	CLRANGE	482063.403
	Cruise range	CRRANGE	4355546.828
	Decent range	DERANGE	1161834.763
	Total range	RANGE_TOTAL	5999444.993
	Climb time	T_CLIMB	4.47102
	Cruise time	T_CRUISE	30
	Descent time	T_DESCENT	22.87244
	Total flight time	T_FLT	57.34346
	Mach number at max rocket *T/W*	AMACH_TJ	0
	Maximum rocket *T/W*	TW_TJ_TM	0
	(NA)	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	1.77687
	Maximum capture area of scramjet (NA)	AC_W_MAX	5.20628
	(NA)	AMACH_ACAP	3
	(NA)	QBAR_ACAP	53177.74012
	(NA)	ALT_ACAP	17260
	(NA)	CFN_ACAP	0.76981
	Average cruise *L/D*	LD_CRUISE	1.98418
	Average cruise I_{sp}	ISP_CRUISE	2248.34719
	Minimum acceleration during scramjet mode	ANMIN	0.30152
	Oxidizer-to-fuel ratio	OF_TRAJ	0
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	19576.79851
	Propellant weight	WPPL	7423.31196
	Total fuel weight	WFUEL	7362.23917
	Fuel 1 weight	WFUEL1	7362.23917
	Weight of oxidizer	Wox	61.0728
	Manufacturer's zero-fuel weight	AMZFW	12153.48654
	Operating weight empty	OWE	12153.48654
	Operating empty weight	OEW	12153.48654
	Weight margin	WMARGIN	1104.86241

Table B.8.4. ***Concluded***

	Operational items weight	WOPER	0
	Systems weight	WSYS	3844.55785
	Structural weight	WSTR	4305.28354
	Rocket propulsion system weight	WP_TJ	0
	Ram/scramjet weight	WP_SC	2898.78275
	Total fuel fraction	FF_TOTAL	0.37919
	Structural weight fraction	WSTR_TOGW	0.21992
	Total weight ratio	WR	1.6108
	Total volume	V_TOTAL	170.77108
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	11.83084
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	98.69732
	Total fuel volume	V_FUELI1	98.64986
	Total oxidizer volume	V_OX	0.04745
	Total propellant density	PPL_DEN	75.21291
	Total fuel density	FUEL_DEN	74.63
	Total oxidizer density	OX_DEN	1287
	Total rocket volume	VENG_TJ	0
	Total ram/scramjet volume	VENG_SC	26.08904
	Total engine volume	VENG	26.08904
	Total void volume	VVOID	34.15422
Convergence check	Operating-weight-empty weight budget	OWE_W	12153.48654
	Operating-weight-empty volume budget	OWE_V	12153.45331
	Planform area	SPLN	95.66821
	Capture-area required	AC_RE	5.20628
	Capture-area available	AC_AV	5.20628
	Structural index	AISTR	18.06016
	Propulsion index	AIP	123.13898
	T/W rocket	TW_TJ_MAX	0
	T/W scramjet	TW_SC_MAX	1.77687
	Wing loading	WS	204.63223

B-9 TRADE 009: EXPENDABLE BOOSTER, MACH 6, KEROSENE FUEL

Mission summary: Table B-9.1 summarizes the mission constants for this trade study.

Table B-9.1. Expendable-Booster, Mach 6, Kerosene-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	17,260 m (56,630 ft)
Launch velocity	3.0 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	26.2 km (86,000 ft)
Propellant selection	RP-1
Kerosene-fuel density	820.0 kg/m^3 (51.2 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by using hypersonic convergence.[6]

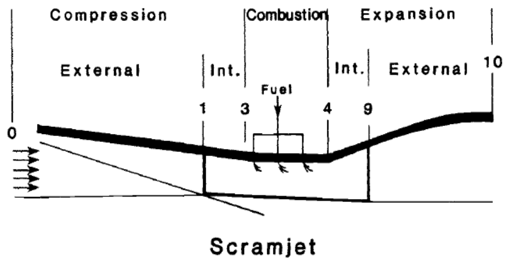
Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7)[11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

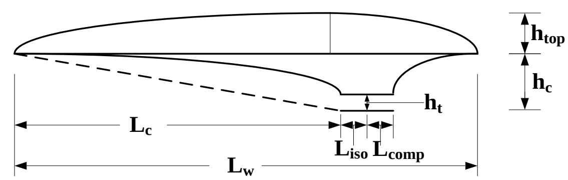
Structure and thermal protection
Structural shape factor K_{str} from MAC[6]

Propulsion
Dual-mode ram-scramjet
The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that are assumed in the stream thrust analysis for this trade are summarized below in Table B-9.2.

TableB-9.2. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
H_{pr} (kJ/kg)	43380.0
f (stoichiometric)	0.0680
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.20
C_{ev}	0.99
C_{pe}	1.59
C_{ea}	1.00
γ_c	1.362
γ_e	1.22
Geometric constants	
l_c/l_w	0.50
h_c/l_c	0.07
h_{iso}/l_{iso}	0.1
L_{comb}	0.762 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance

Hypersonic convergence weight and volume formulation[6]

Table B-9.3. Summary of Weight and Volume Constants

Weight	
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_DMR} – dual-mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crew} – fixed crew volume coefficient	0.0

Performance

The energy-integration method was used to compute the trajectory.
The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 60 percent of body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design-point database file: Table B-9.4 summarizes the design-point data that were collected by AVD^{sizing}.

Table B-9.4. Trade 009, Expendable Booster, Mach 6, Kerosene–Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	30
	Design Mach number	D_MACH	6
	(NA)	D_MVIHN	0
	(NA)	D_WR	1
	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	2400
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	17260
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10

Table B.9.4. *Continued*

	Initial descent range (NA)	ALT_DE	0

	Air-breathing transition Mach number	AMACH_TJS	2.5
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	1
	Fuel density	FUEL_DEN	820
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.085
	Planform area	SPLN	34.74619
	Ratio of wetted area to planform area	AKW	2.32289
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.11371
	Total vehicle length	AL_TOTAL	10.43928
	Span	BPLN	5.54735
	Height above centerline	BASE_HEIGHT	1.20217
	Spatular width	CSPAT	1.10947
	Capture area	ACAP	1.30401
	Length of external compression	ALC	5.21964
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	0.64089
	Width of cowl at inlet	W3	1.75036
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00803
	Height of cowl to length of isolator	ALI_L	0.08035
	Height at combustor exit to nozzle length	H_LN	0.05021
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	47781475.36
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald’s efficiency factor correction for flaps	DE_LG	0

Table B.9.4. ***Continued***

	Form drag	CD0	0.00993

	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	5.76719
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.57912
Trajectory summary	Climb range	CLRANGE	273006.9779
	Cruise range	CRRANGE	3240789.329
	Decent range	DERANGE	1009672.294
	Total range	RANGE_TOTAL	4523468.601
	Climb time	T_CLIMB	3.31144
	Cruise time	T_CRUISE	30
	Descent time	T_DESCENT	23.99917
	Total flight time	T_FLT	57.31061
	Mach number at max rocket *T/W*	AMACH_TJ	0
	Maximum rocket *T/W*	TW_TJ_TM	0
	(NA)	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	0.62777
	Maximum capture area of scramjet (NA)	AC_W_MAX	1.30401
	(NA)	AMACH_ACAP	3
	(NA)	QBAR_ACAP	53177.74012
	(NA)	ALT_ACAP	17260
	(NA)	CFN_ACAP	0.70822
	Average cruise *L/D*	LD_CRUISE	4.07714
	Average cruise I_{sp}	ISP_CRUISE	969.91017
	Minimum acceleration during scramjet mode	ANMIN	0.21849
	Oxidizer-to-fuel ratio	OF_TRAJ	0
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	8344.88894
	Propellant weight	WPPL	3536.36068
	Total fuel weight	WFUEL	3512.19722
	Fuel 1 weight	WFUEL1	3512.19722
	Weight of oxidizer	Wox	24.16346
	Manufacturer’s zero-fuel weight	AMZFW	4808.52825
	Operating weight empty	OWE	4808.52825
	Operating empty weight	OEW	4808.52825

Table B.9.4. ***Concluded***

	Weight margin	WMARGIN	437.13893

	Operational items weight	WOPER	0
	Systems weight	WSYS	2669.36452
	Structural weight	WSTR	1265.47176
	Rocket propulsion system weight	WP_TJ	0
	Ram/scramjet weight	WP_SC	436.55305
	Total fuel fraction	FF_TOTAL	0.42378
	Structural weight fraction	WSTR_TOGW	0.15165
	Total weight ratio	WR	1.73544
	Total volume	V_TOTAL	17.40924
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	5.69637
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	4.30194
	Total fuel volume	V_FUELI1	4.28317
	Total oxidizer volume	V_OX	0.01878
	Total propellant density	PPL_DEN	822.03813
	Total fuel density	FUEL_DEN	820
	Total oxidizer density	OX_DEN	1287
	Total rocket volume	VENG_TJ	0
	Total ram/scramjet volume	VENG_SC	3.92898
	Total engine volume	VENG	3.92898
	Total void volume	VVOID	3.48185
Convergence check	Operating-weight-empty weight budget	OWE_W	4808.52825
	Operating-weight-empty volume budget	OWE_V	4808.58679
	Planform area	SPLN	34.74619
	Capture-area required	AC_RE	1.30401
	Capture-area available	AC_AV	1.30401
	Structural index	AISTR	15.67892
	Propulsion index	AIP	1117.75748
	T/W rocket	TW_TJ_MAX	0
	T/W scramjet	TW_SC_MAX	0.62777
	Wing loading	WS	240.16701

B-10 TRADE 010: EXPENDABLE BOOSTER, MACH 8, KEROSENE FUEL

Mission summary: Table B-10.1 summarizes the mission constants for this trade study.

Table B-10.1 Expendable-Booster, Mach 8, Kerosene-Fuel Mission Summary

Mission requirements	
Endurance	0, 10, 20, and 30 min
Payload	0 kg (0 lb)
Launch altitude	17,260 m (56,630 ft)
Launch velocity	3.0 M
Max dynamic pressure	53.6 kPa (1,120 psf)
Cruise altitude	30.0 km (98,425 ft)
Propellant selection	RP-1
Kerosene-fuel density	820.0 kg/m^3 (51.2 lb/ft^3)
Operational constraints	
Takeoff field length	4,572.0 m (15,000 ft)
Landing field length	4,572.0 m (15,000 ft)
MLW/TOGW	1.0
Maximum axial acceleration	3.0 g

Relevant method assumptions and constants: The geometry, aerodynamic, structural, propulsion weight and volume, performance, stability and control, and cost methods and constants are summarized below.

Geometry
The blended-body configuration, as defined by using hypersonic convergence.[6]

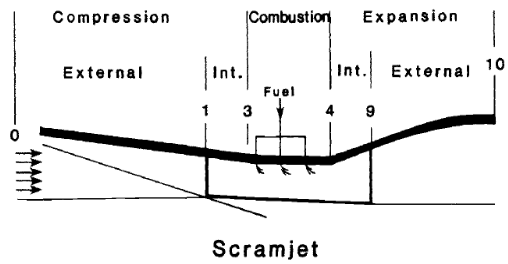
Aerodynamics
$C_{L\max}$ = 0.50 (FDL-7)[11]
Hyfac database, MAC circa 1970[3]
Spatular corrections from Pike

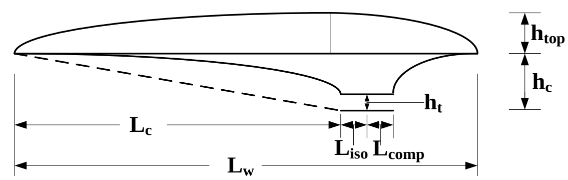
Structure and thermal protection
Structural shape factor K_{str} from MAC[6]

Propulsion
Dual-mode ram-scramjet
The dual-mode ram-scramjet for this trade is a composite of Marquardt ramjet data[14] from Mach 3 to 6 and one-dimensional stream thrust analysis[12] from Mach 6 to 8. The constants that are assumed in the stream thrust analysis for this trade are summarized below in Table B-10.2.

Table B-10.2. Summary of Scramjet Stream Thrust Constants

Cycle constants	Value
H_{pr} (kJ/kg)	43380.0
f (stoichiometric)	0.0680
V_{fx}/V_3	0.50
V_f/V_3	0.50
η_1	0.95
η_b	0.90
$\left(\frac{C_f}{2}\frac{A_w}{A_3}\right)_c$	0.01
$\left(C_f\frac{A_w}{A_3}\right)_b$	0.20
C_{ev}	0.99
C_{pe}	1.59
C_{ea}	1.00
γ_c	1.362
γ_e	1.22
Geometric constants	
l_c/l_w	0.50
h_c/l_c	0.07
h_{iso}/l_{iso}	0.1
L_{comb}	0.762 m
Shock on lip Mach number	8.0
θ_{1n}	22.0
θ_{2n}	9.0





Weight, volume, and balance
Hypersonic convergence weight and volume formulation.[6]

Table B-10.3. Summary of Weight and Volume Constants

Weight	
E_{TW_DMR} – Dual-mode ramjet thrust-to-weight ratio (T/W_{eng})	12.0 kg/kg
μ – empty weight margin (OEW/OEW)	0.10
F_{sys} – variable systems weight (W_{sys}/OEW)	0.16 kg/kg
C_{un} – fixed unmanned systems weight	1,900 kg
W_{crew} – weight of crew per person (W_{crew}/person)	0.0
f_{prv} – crew provision weight per person (W_{prv}/person)	0.0
Volume	
K_{ve_DMR} – dual-mode ramjet per kg thrust (V_{DMR}/T)	0.00075 m^3/kg
K_{vv} – void volume coefficient (V_{void}/V_{total})	0.20 m^3/m^3
K_{vs} – systems volume coefficient (V_{sys}/V_{total})	0.02 m^3/m^3
V_{un} – fixed unmanned system volume	5.0 m^3
V_{pcrew} – variable crew volume coefficient (V_{crew}/person)	0.0
F_{crew} – fixed crew volume coefficient	0.0

Performance
The energy-integration method was used to compute the trajectory.
The required approach speed was computed from the assumed $C_{L\max}$.

Stability and control
No direct computation of stability and control; the scramjet cowl location was constrained to 60 percent of body length to keep the trim drag manageable.[6]

Cost
No cost model was utilized.

Design-point database file: Table B-10.4 summarizes the design-point data that were collected by AVD^{sizing}.

Table B-10.4. Trade 010, Expendable-Booster, Mach 8, Kerosene-Fuel Output Database

Category	Description	Variable	Value
Mission input check	Number of design passengers	APAXD	0
	Maximum number of passengers	APAXMAX	0
	Number of crew members	CREW	0
	Weight per passenger	WPAX	100
	Weight per crew member	WCREW	129
	Cargo weight	WCARGO	0
	Cruise switch (0 range, 1 endurance)	NCRUISE	1
	Design range or endurance	D_RANGE	20
	Design Mach number	D_MACH	8
	(NA)	D_MVIHN	0
	(NA)	D_WR	1
	Takeoff field length (NA)	TOFL	3337.56
	Altitude at takeoff	ALT_TO	0
	Landing field length	SLAND	2400
	Altitude at landing	ALT_LAND	0
	(NA)	MP_TO	0
	(NA)	MP_LAND	0
	(NA)	MP_TRAJ	0
	(NA)	NTRAJ_ST	0
	Maximum axial load factor	AN_MAX	3
	Cruise normal load factor	AN_NORM	1
	Altitude step for climb out (NA)	ASTEP_CO	10
	Velocity at climb out (NA)	V_CLIMBOUT	180
	Altitude for initial climb (NA)	ALT_IC	3048
	Acceleration Mach step	AMSTEP_AC	0.01
	Altitude step for climb to transonic acceleration	ASTEP_AC	10
	Altitude for transonic acceleration	ALT_TC	17260
	Mach step for transonic acceleration	AMSTEP_TA	0.01
	Altitude step for constant *q* climb	ASTEP_QC	10
	Initial descent range (NA)	ALT_DE	0

Table B.10.4. *Continued*

	Air-breathing transition Mach number	AMACH_TJS	2.5
	Range step for cruise	DDCRUISE	0.5
	Number of fuels	NFUEL	1
	Fuel density	FUEL_DEN	820
	Oxidizer density	OX_DEN	1287
	Takeoff climb gradient (NA)	TO_CGR	0.024
	Takeoff climb gradient (NA)	TO_OEI	1
	Landing climb gradient (NA)	ALAND_CGR	0.021
	Landing climb gradient (NA)	ALAND_OEI	1
	Landing weight ratio	ALAND_WR	1
	Altitude for reserve mission (NA)	ALTRES	3048
	Range for reserve mission (NA)	R_MACH	0
	Endurance for reserve mission (NA)	TIMERES	120
	Configuration (1-lifting body)	NBASE	1
Geometry	Slenderness parameter	TAU	0.075
	Planform area	SPLN	51.27501
	Ratio of wetted area to planform area	AKW	2.31308
	Spatular width to wing semispan	CS_SPAT	0.5
	Ratio of frontal area to planform area	SF_SREF	0.10127
	Total vehicle length	AL_TOTAL	12.68148
	Span	BPLN	6.73883
	Height above centerline	BASE_HEIGHT	1.37701
	Spatular width	CSPAT	1.34777
	Capture area	ACAP	1.92415
	Length of external compression	ALC	6.34074
	Length of cowl	ALLC	1.44862
	Width of cowl outside spatular	WCOUT	0.77855
	Width of cowl at inlet	W3	2.12631
	Height of cowl	HCOWL	0.01222
	Height of throat	HCOWLI	0.00618
	Height of cowl to length of isolator	ALI_L	0.06179
	Height at combustor exit to nozzle length	H_LN	0.0297
Stall/approach performance	Velocity for approach calculation	VREL	64.11653
	Reynolds number	REYNOLDS	58044199.41
	Mach number for approach	AMACH	0.1884
	Landing-gear drag	DCD_LG	0.0015
	Oswald’s efficiency factor correction for flaps	DE_LG	0
	Form drag	CD0	0.00966

Table B.10.4. ***Continued***

	Induced drag factor	ALIND	0.7
	Maximum *L/D*	ALDMAX	5.85781
	Approach speed	VA_LC	83.34419
	Stall speed	VS_LC	64.11092
	Wing loading at stall	WS_STALL	243.87905
	Weight ratio	WR_TJ	0.49743
Trajectory summary	Climb range	CLRANGE	943176.4315
	Cruise range	CRRANGE	2904215.76
	Decent range	DERANGE	1792538.799
	Total range	RANGE_TOTAL	5639930.99
	Climb time	T_CLIMB	8.39916
	Cruise time	T_CRUISE	20
	Descent time	T_DESCENT	31.7583
	Total flight time	T_FLT	60.15745
	Mach number at max rocket *T/W*	AMACH_TJ	0
	Maximum rocket *T/W*	TW_TJ_TM	0
	(NA)	AMACH_SC	0
	Maximum scramjet *T/W*	TW_SC_TM	0.94606
	Maximum capture area of scramjet (NA)	AC_W_MAX	1.92415
	(NA)	AMACH_ACAP	3
	(NA)	QBAR_ACAP	53177.74012
	(NA)	ALT_ACAP	17260
	(NA)	CFN_ACAP	0.70822
	Average cruise *L/D*	LD_CRUISE	3.92361
	Average cruise I_{sp}	ISP_CRUISE	731.50305
	Minimum acceleration during scramjet mode	ANMIN	0.11526
	Oxidizer-to-fuel ratio	OF_TRAJ	0
Weight and volume	Weight of crew	WCRW	0
	Weight of design payload	WPAY_D	0
	Weight of max payload	WPAY_MAX	0
	Takeoff gross weight	TOGW	12027.0251
	Propellant weight	WPPL	6074.29065
	Total fuel weight	WFUEL	6044.37741
	Fuel 1 weight	WFUEL1	6044.37741
	Weight of oxidizer	Wox	29.91324
	Manufacturer’s zero-fuel weight	AMZFW	5952.73445
	Operating weight empty	OWE	5952.73445
	Operating empty weight	OEW	5952.73445
	Weight margin	WMARGIN	541.15768

Table B.10.4. ***Concluded***

	Operational items weight	WOPER	0
	Systems weight	WSYS	2852.43751
	Structural weight	WSTR	1610.94574
	Rocket propulsion system weight	WP_TJ	0
	Ram/scramjet weight	WP_SC	948.19352
	Total fuel fraction	FF_TOTAL	0.50505
	Structural weight fraction	WSTR_TOGW	0.13394
	Total weight ratio	WR	2.02042
	Total volume	V_TOTAL	27.53721
	Fixed systems volume	V_FIX	5
	Total systems volume	V_SYS	6.10149
	Total payload volume	V_PAY	0
	Total crew volume	V_CREW	0
	Total propellant volume	V_PPL	7.39443
	Total fuel volume	V_FUELI1	7.37119
	Total oxidizer volume	V_OX	0.02324
	Total propellant density	PPL_DEN	821.4679
	Total fuel density	FUEL_DEN	820
	Total oxidizer density	OX_DEN	1287
	Total rocket volume	VENG_TJ	0
	Total ram/scramjet volume	VENG_SC	8.53374
	Total engine volume	VENG	8.53374
	Total void volume	VVOID	5.50744
Convergence check	Operating-weight-empty weight budget	OWE_W	5952.73445
	Operating-weight-empty volume budget	OWE_V	5952.77207
	Planform area	SPLN	51.27501
	Capture-area required	AC_RE	1.92415
	Capture-area available	AC_AV	1.92415
	Structural index	AISTR	13.58262
	Propulsion index	AIP	805.02902
	T/W rocket	TW_TJ_MAX	0
	T/W scramjet	TW_SC_MAX	0.94606
	Wing loading	WS	234.5592

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REPORT DOCUMENTATION PAGE

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14. ABSTRACT
This report documents a parametric sizing study performed to develop a program strategy for research and development and procurement of a feasible next-generation hypersonic air-breathing endurance demonstrator. Overall project focus has been on complementing technical and managerial decision-making during the earliest conceptual design phase towards minimization of operational, technical, and managerial risks.

15. SUBJECT TERMS
Hypersonic aircraft; Hypersonics; Life cycle analysis; Vehicle design

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