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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.

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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 |
| $(C_f/2 A_w/A_3)_c$ | dimensionless boundary-layer skin-friction quantity |
| $(C_f A_w/A_3)_b$ | 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_l | 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 |
| <i>MLW</i> | Maximum Landing Weight |
| MSTC | Multiple Stages To Cruise |
| <i>OEW</i> | Operating Empty Weight |
| <i>OWE_w</i> | Operating Weight Empty from weight budget |
| <i>OWE_v</i> | 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/SiMMC | 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 protection systems (TPS), and any operational peculiarities of long-duration hypersonic flight (e.g., maintenance, turnaround, practical range, etc.).

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

This study concludes that an air-launched, liquid-hydrogen-fueled, 30 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

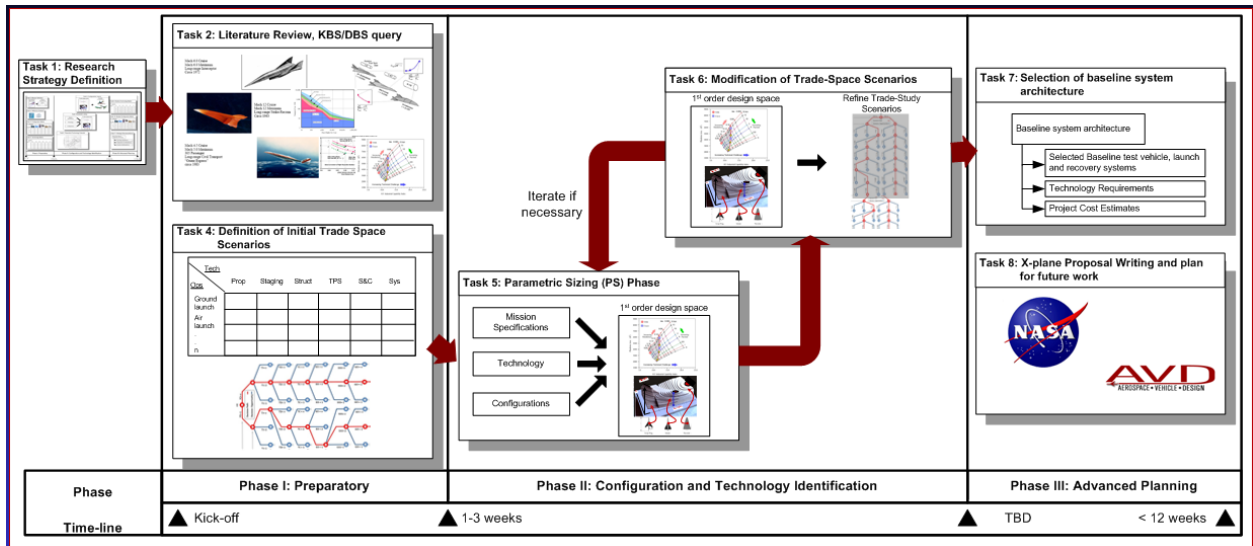


Fig. 2-1. Study approach to develop reusable hypersonic endurance test bed.

Task 1: Research Strategy Definition

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.

Task 2: Literature Review, DB/KB Query

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.

Task 3: Reference Vehicle Definition

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).

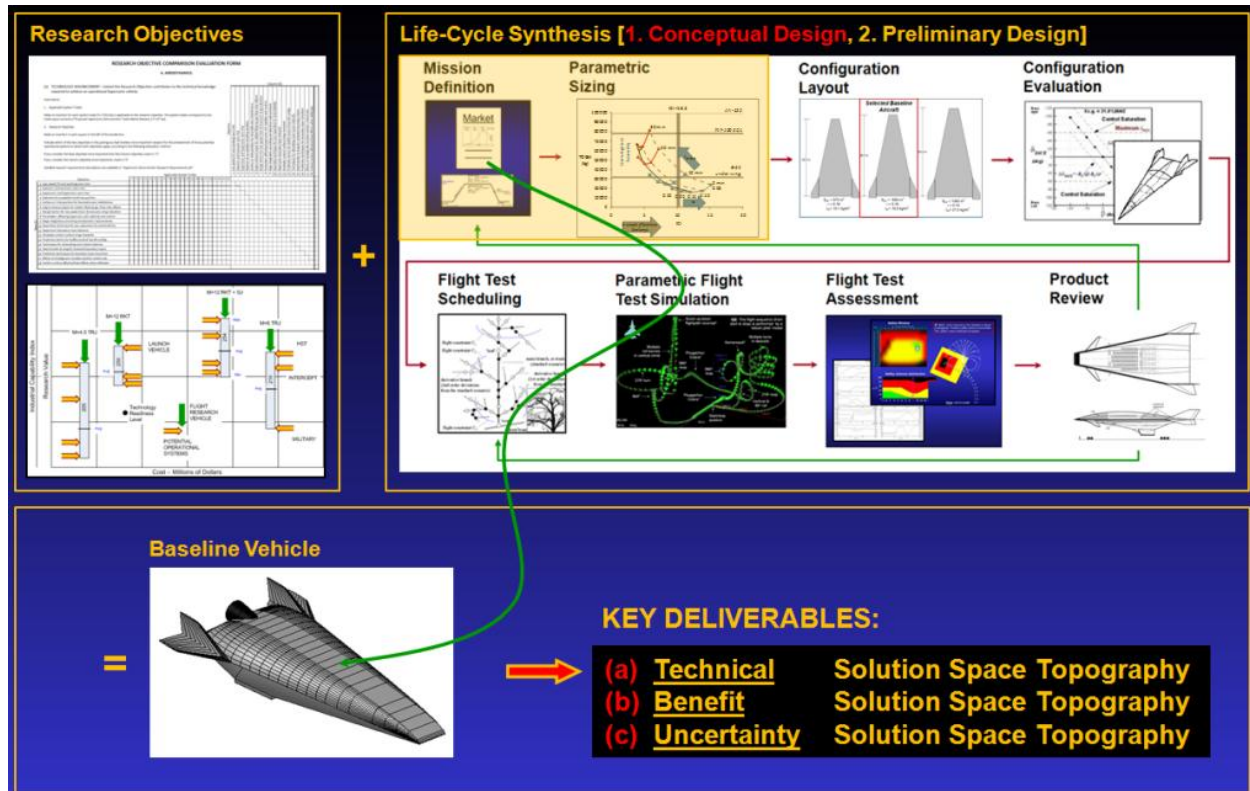


Fig. 2-2. AVD Laboratory integrated design life-cycle process.

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.

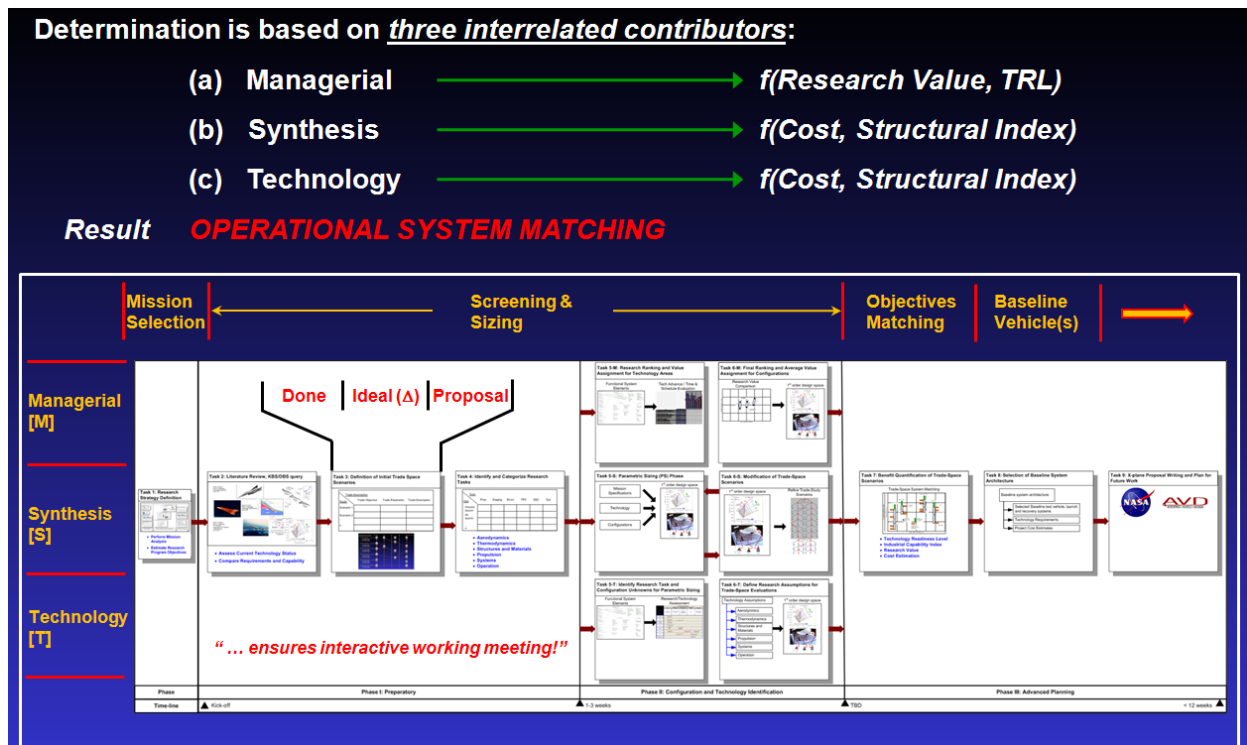


Fig. 2-3. AVD Laboratory integrated VAB-AVD team study approach.

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.

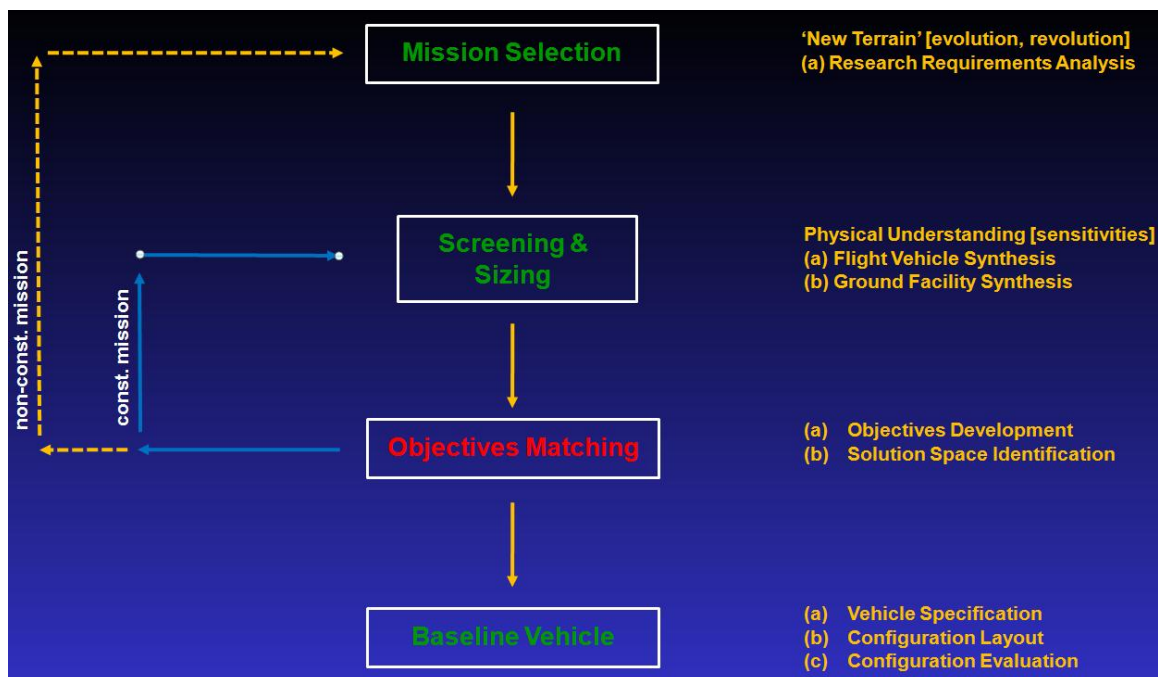


Fig. 3-1. Iterative nature of the mission & objectives & baseline vehicle(s) selection process.

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).

- **HYFAC included participation of 66 government and industry representatives:**
 - NASA Langley Research Center
 - NASA Flight Research Center
 - NASA Lewis Research Center
 - NASA Ames Research Center
 - United States Air Force
 - McDonnell Aircraft
 - McDonnell Douglas Astronautics
- **Flight vehicle synthesis evaluation was supported by:**
 - AIRResearch Manufacturing Division – Garrett Corporation
 - GE Company
 - Marquardt Company
 - Pratt and Whitney Aircraft
- **Ground facility synthesis evaluation was supported by:**
 - Cabot Corporation
 - Allis-Chalmers
 - FluidDyne Engineering Company

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.

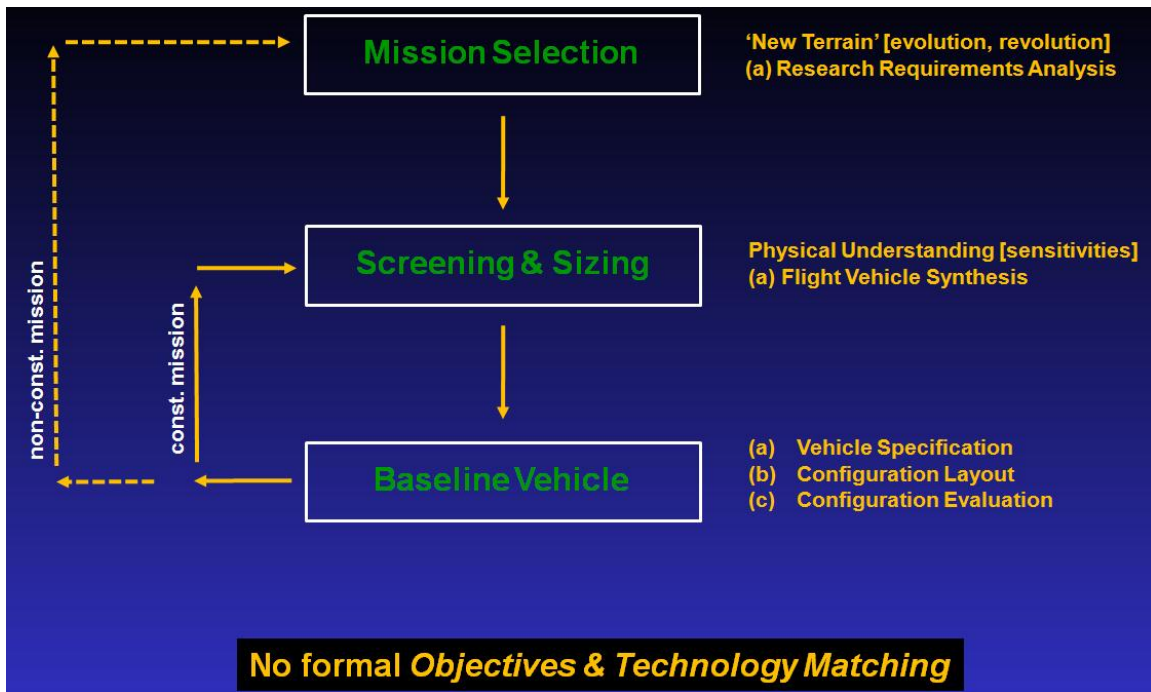


Fig. 3-3. VAB/AVD Laboratory baseline vehicle development sequence.

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 | <i>Manned Hypersonic Cruise Vehicle</i> , some description of a demonstrator |
| 1967 | 1968 | UHTV | Vought | <i>Universal Hypersonic Test Vehicle</i> , flexible and modular hypersonic test vehicle |
| 1967 | 1969 | X-15 Delta | North American/NASA | Delta wing X-15 |
| 1969 | 1970 | HYFAC | MAC/NASA | <i>HYPERSONIC FACILITIES</i> study, 32 rocket/air-breather configurations explored |
| 1969 | 1969 | X-15 SERJ | Marquardt | <i>Super Charged Ejector Ramjet</i> (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 | | <i>Propulsion Performance Demonstrator</i> , vertical takeoff cone with four scramjets around its periphery; rocket acceleration to test speed |
| 1975 | 1977 | X-24C NHFRF | Lockheed/NASA | <i>National Hypersonic Flight Research Facility</i> , 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 | | <i>Shuttle Launch Research Vehicle</i> , Mach 8 aerodynamic configuration demonstrator |
| 1985 | 1985 | RSFTP | | <i>Ramjet/Scramjet Flight Test Program</i> , 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.

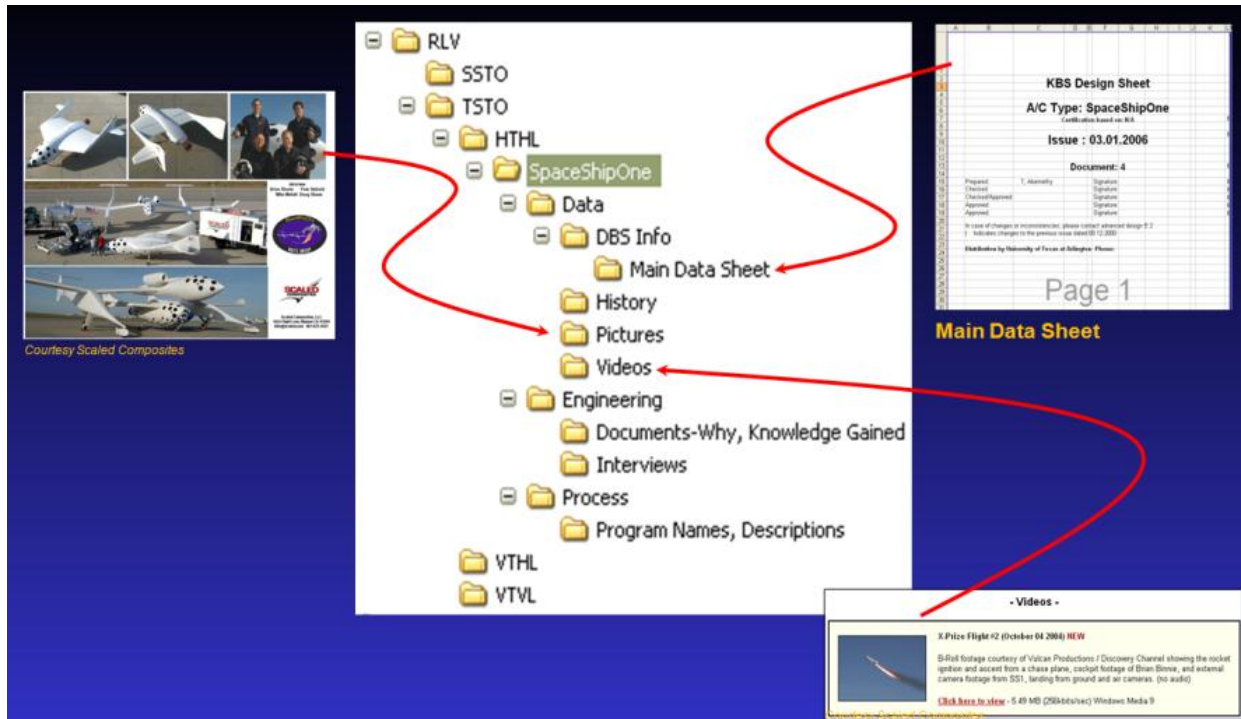


Fig. 4-1. Dedicated AVD Laboratory DB and organization scheme.

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 *reference list* containing meaningful entries; (DB)
2. availability of these references as a *hardcopy* on the table; (DB)
3. utilization of time to *absorb* the data & information; (DB)
4. *review, select, classify, subtract, and document* the data & information provided; (DB)
5. *extraction, combination and utilization* 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).

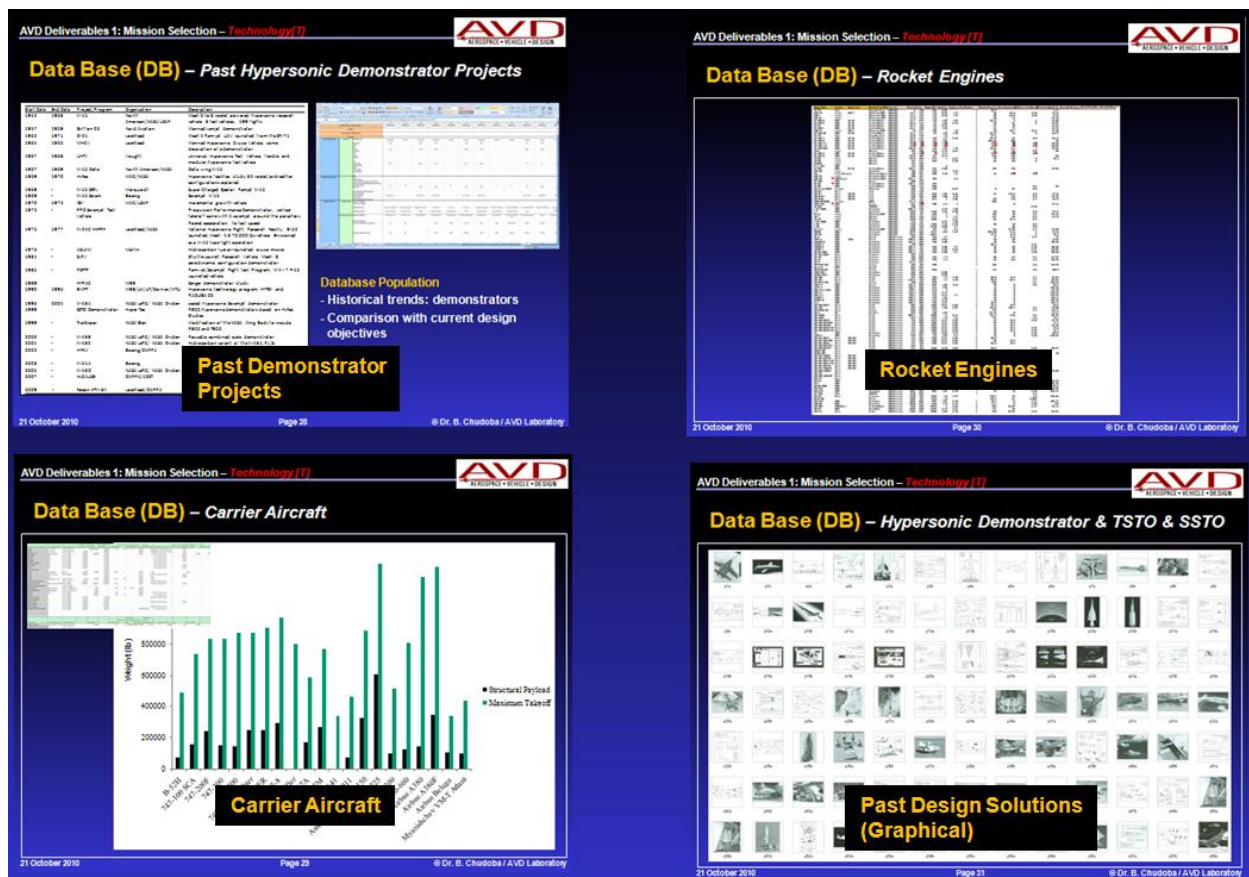


Fig. 4-2. Selected AVD Laboratory data-base (DB) entries.

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 commonalities 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 , $w(\alpha)$, 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.

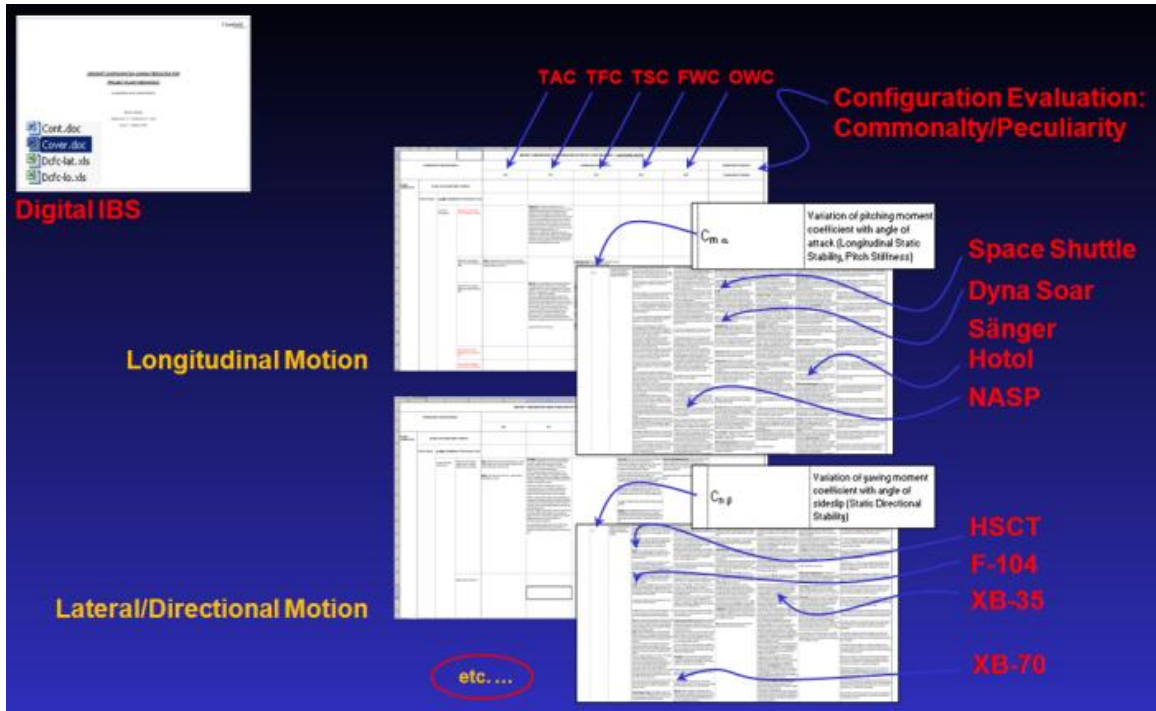


Fig. 4-3. Design lessons-learned of selected design case-studies.

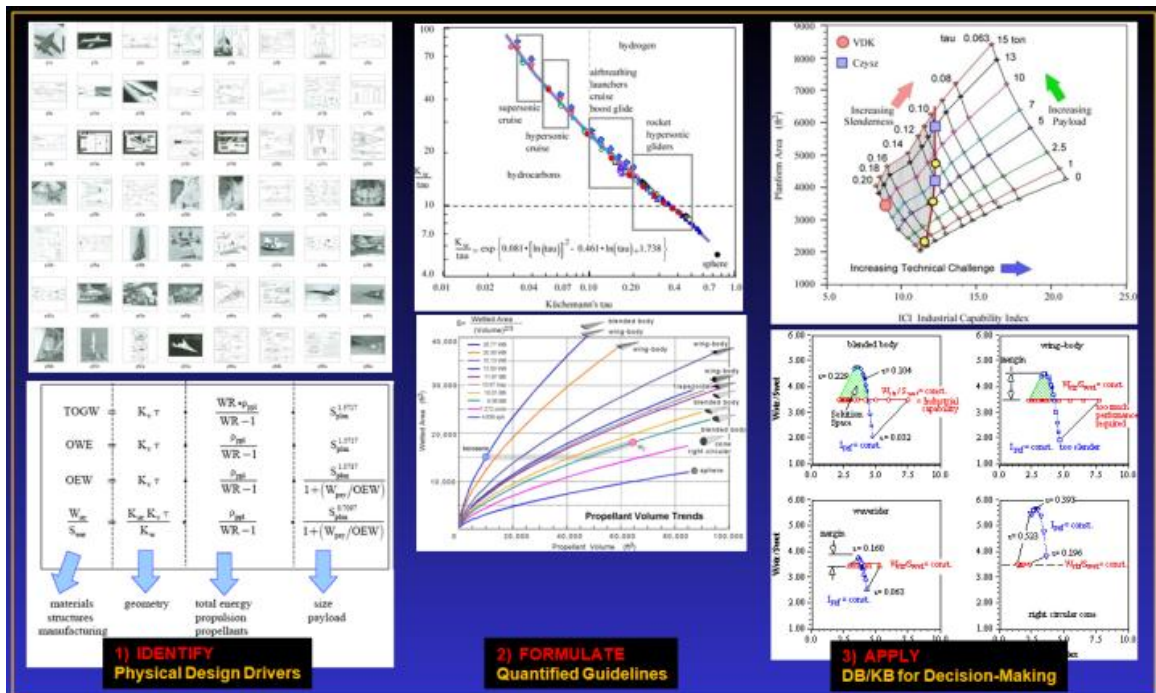


Fig. 4-4. KB development steps resulting in numerical design guidelines.

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.



AVDS^{DESIGN} representing a product development environment:

| | |
|--------------------------------|---|
| <u>Data Domain</u> | Subsonic, supersonic, hypersonic vehicle data, pictures, movies, references, interviews, etc. |
| <u>Knowledge Domain</u> | Displays lessons learned, interpretations, visualizations, <u>generic design trends</u>, <u>design guidelines</u>. |
| <u>Process Domain</u> | Generic product <u>life-cycle synthesis system</u> [database system, processes, methods library, visualization]. |

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

| Trade # | MISSION | | | | STAGING CONFIGURATION | | OPERATIONS CONCEPT | | HARDWARE CONCEPT | | |
|---------|---------------|---------------|--------------------|----------------|-----------------------|--------------------|--------------------|-----|------------------|----------|-----------|
| | Atmospheric | | Test Range Options | | TSTC | | Launch | | Fuel Selection | | |
| | 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 | |

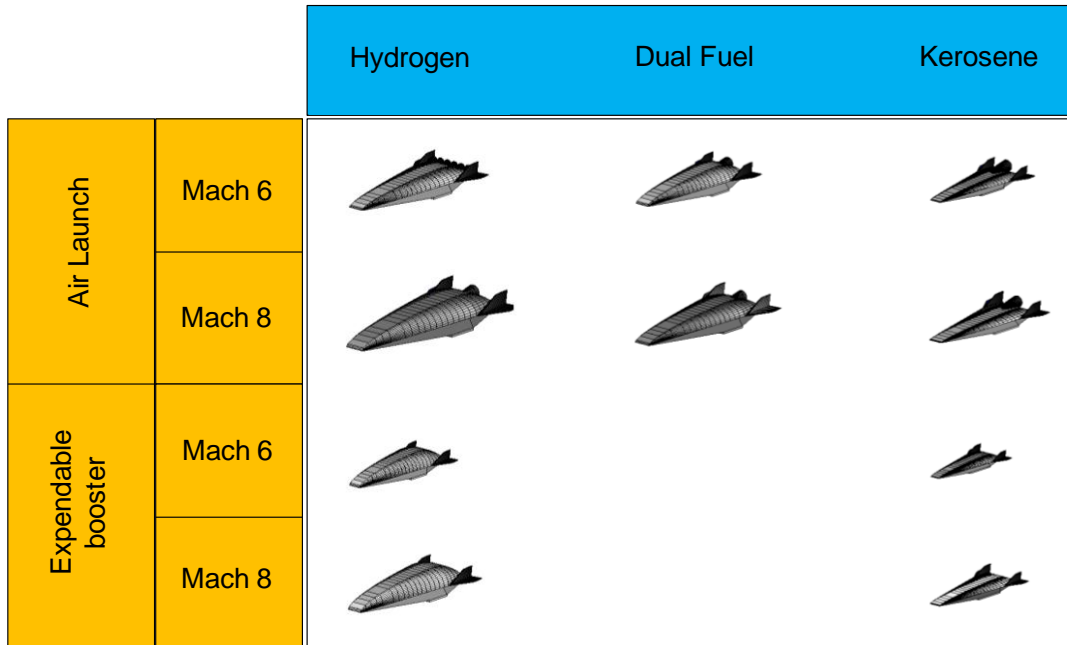


Fig. 5-1. Reduced trade-space explored.

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.

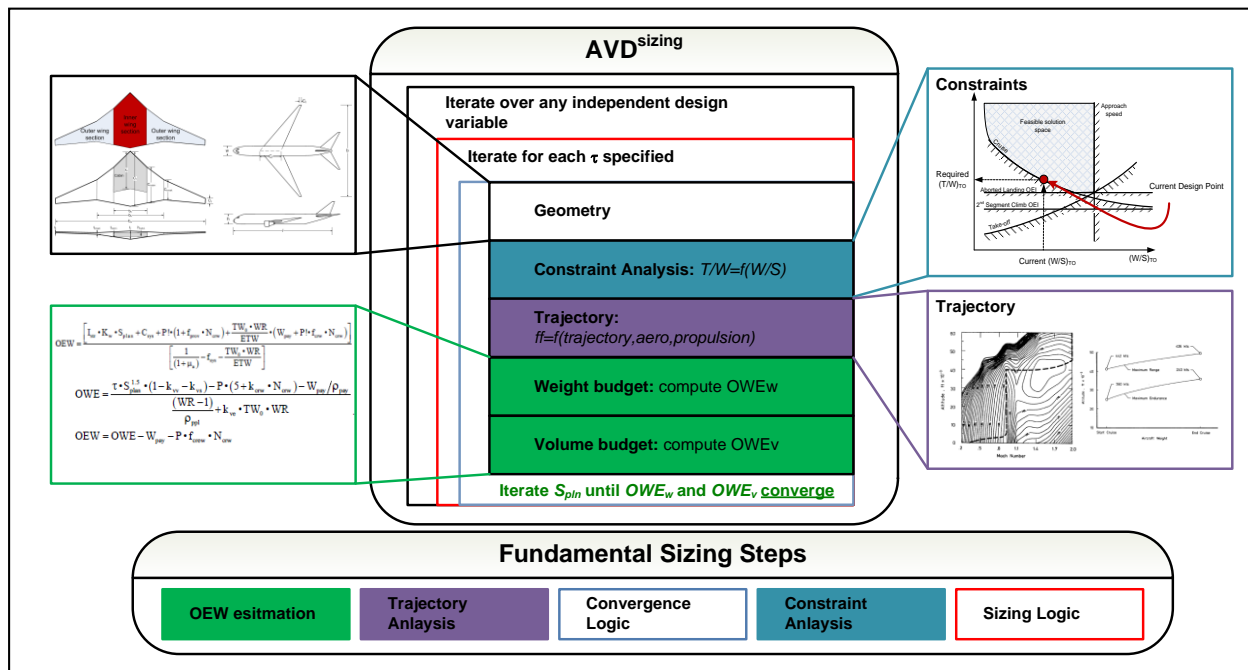


Fig. 6-1. AVD^{sizing} methodology visualized via Nassi-Schneidermann structogram.

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 |
|------------------------------|---|---|--------------------------------------|
| <i>Geometry</i> | 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 |
| <i>Aerodynamics</i> | 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 |
| <i>Propulsion</i> | 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] |
| <i>Performance</i> | 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 |
| <i>Stability and Control</i> | Trim effects | Engine cowl location effect on trim drag. | HyFAC [3] Czysz [6] |
| <i>Weight and Volume</i> | 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.

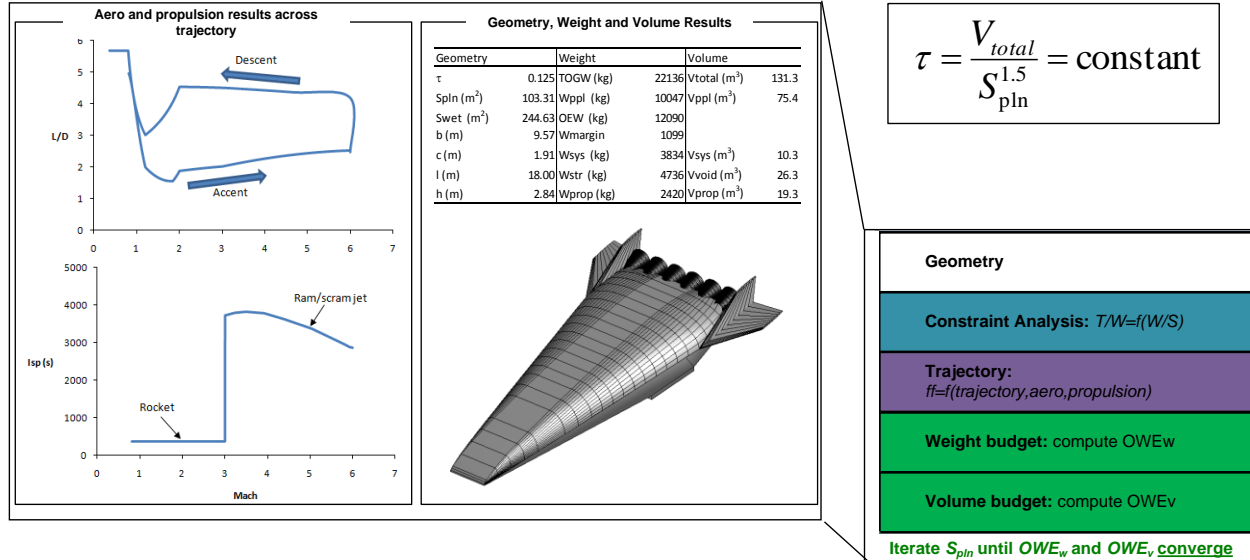


Fig. 6-2. Each design point represents a converged complete hypersonic vehicle (Example: Mach-6, 30 minutes, cruiser configuration).

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.

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

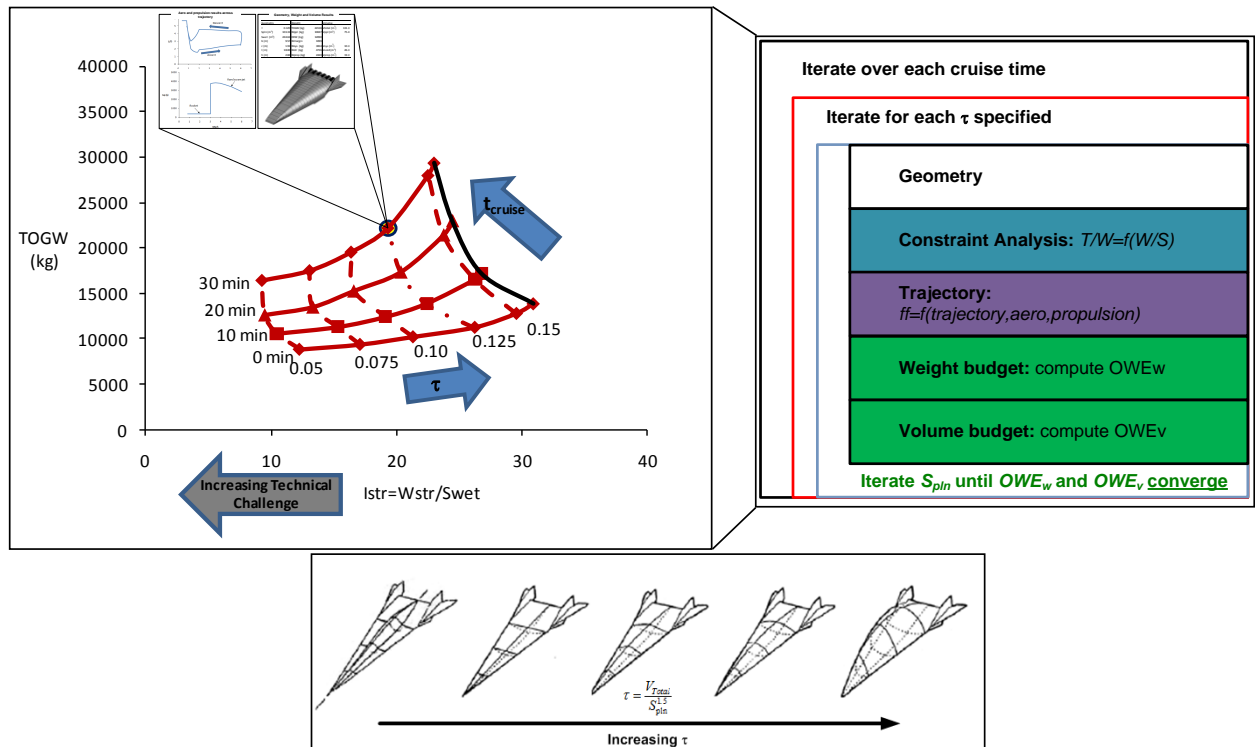


Fig. 6-3. Solution space carpet plot of $TOGW$ and I_{str} for varying vehicle slenderness (τ) and cruise time.

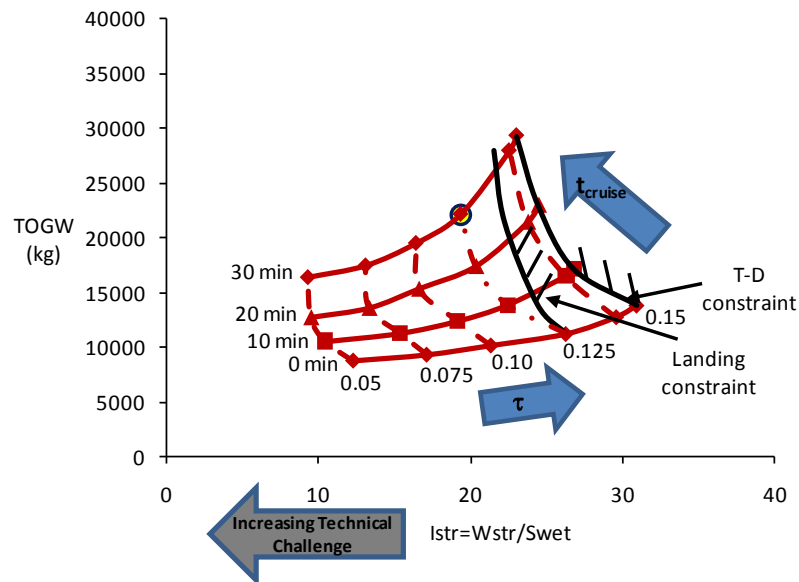


Fig. 6-4. Landing and $T-D$ constraints imposed on the solution space. For the Mach 6 demonstrator, the landing constraint is more constraining than $T-D$.

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.

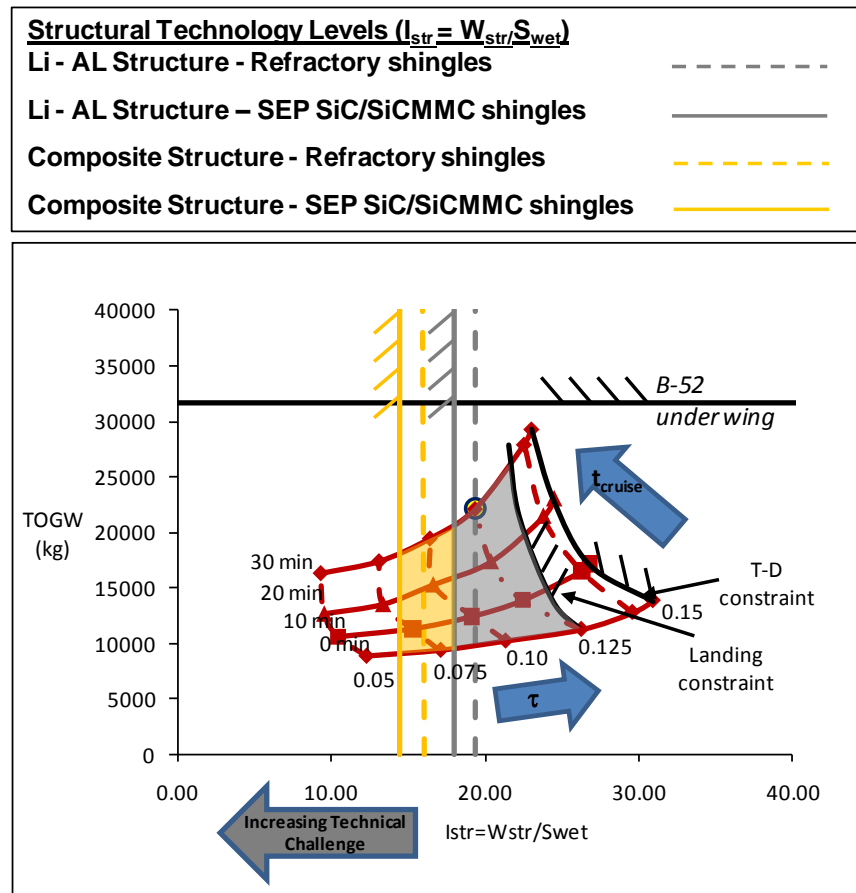


Fig. 6-5. Superposition of structural indices provides the final constraint to determine the technical solution space.

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 plume. 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.

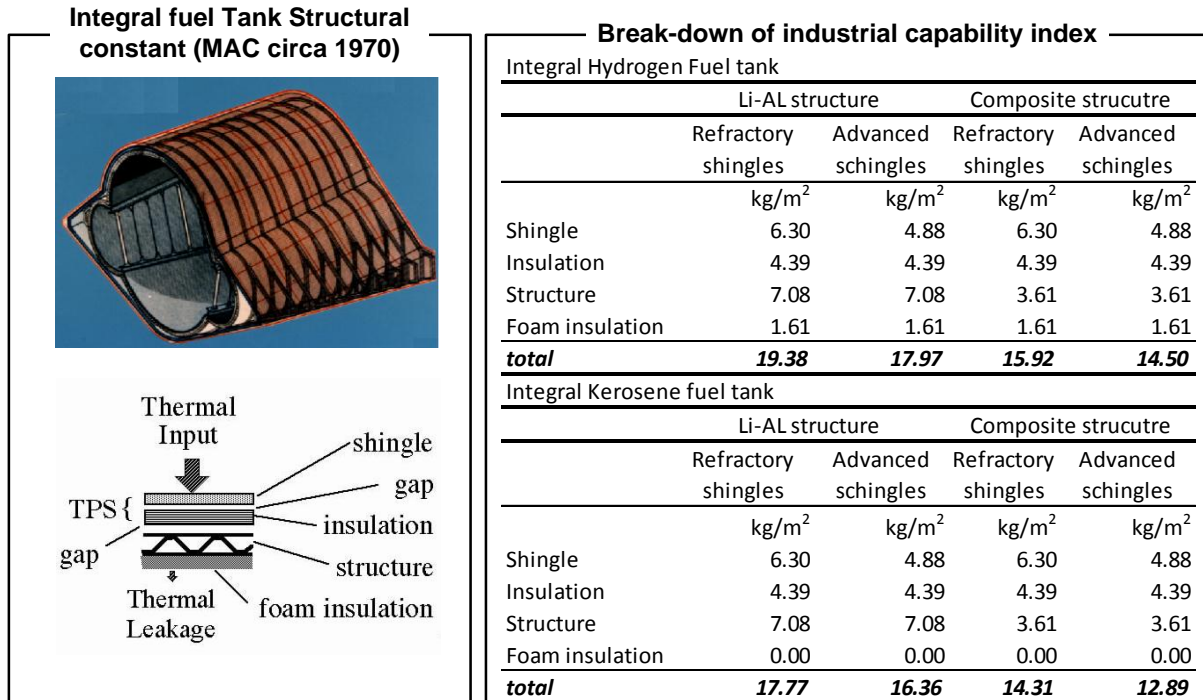


Fig. 6-6. Definition of structural capability indices used for this study. (Ref 6)

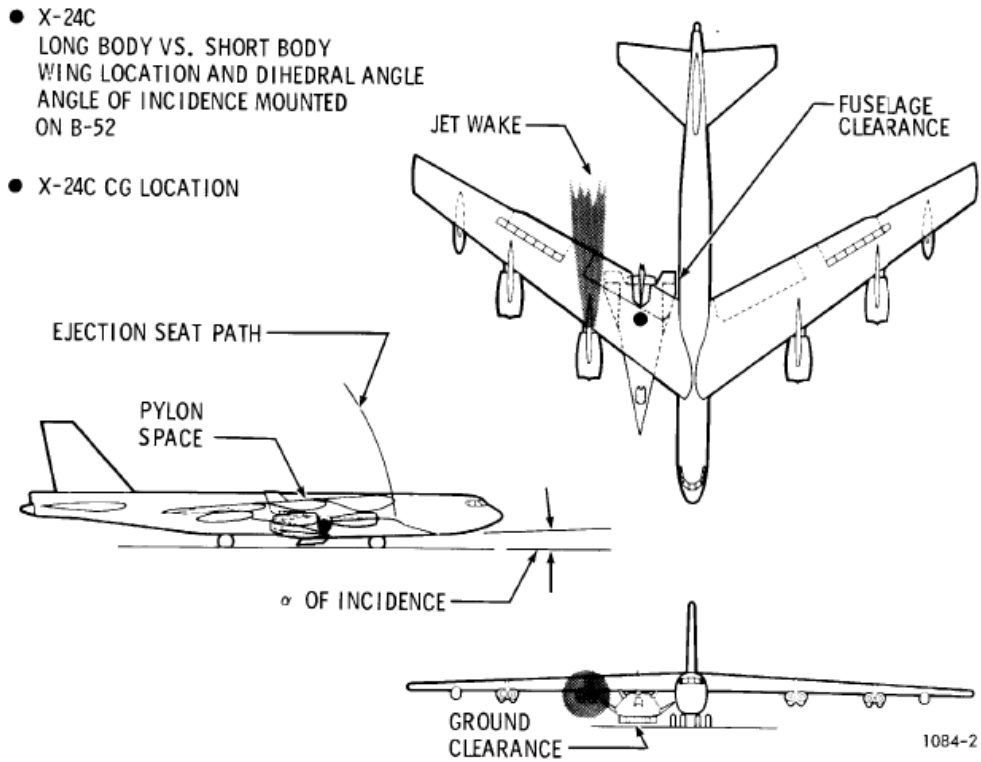


Fig. 6-7. B-52H under-wing mount geometric constraints. (Ref 15)

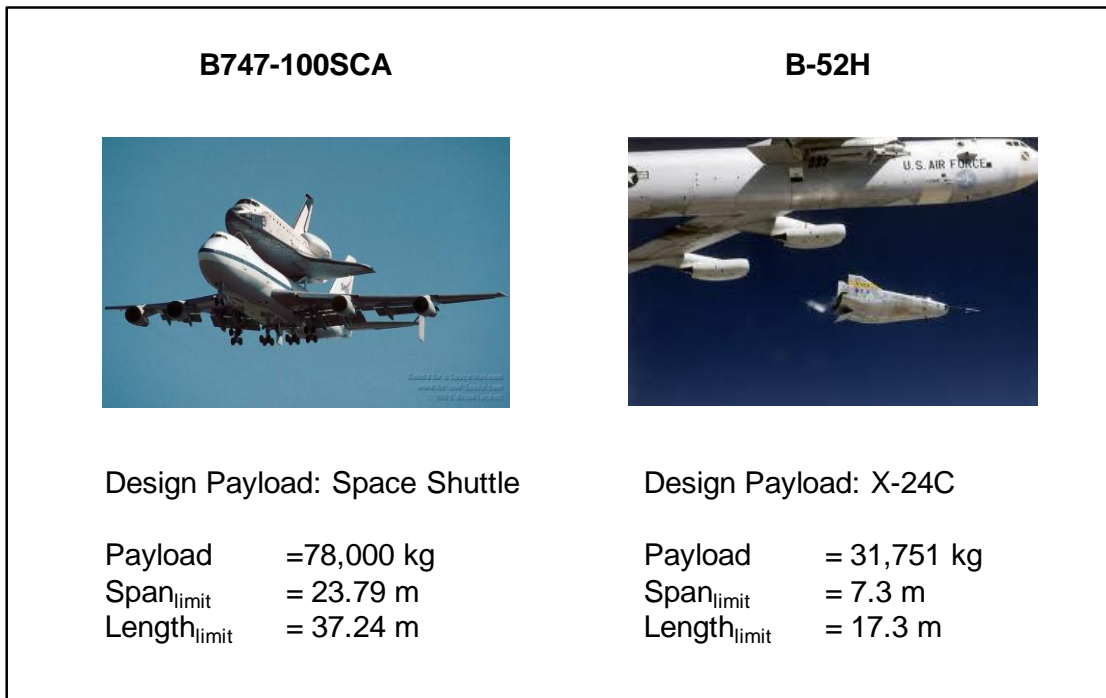


Fig. 6-8. Summary of B747-SCA and B-52H constraints for the hypersonic demonstrator study. (Ref 15,16)

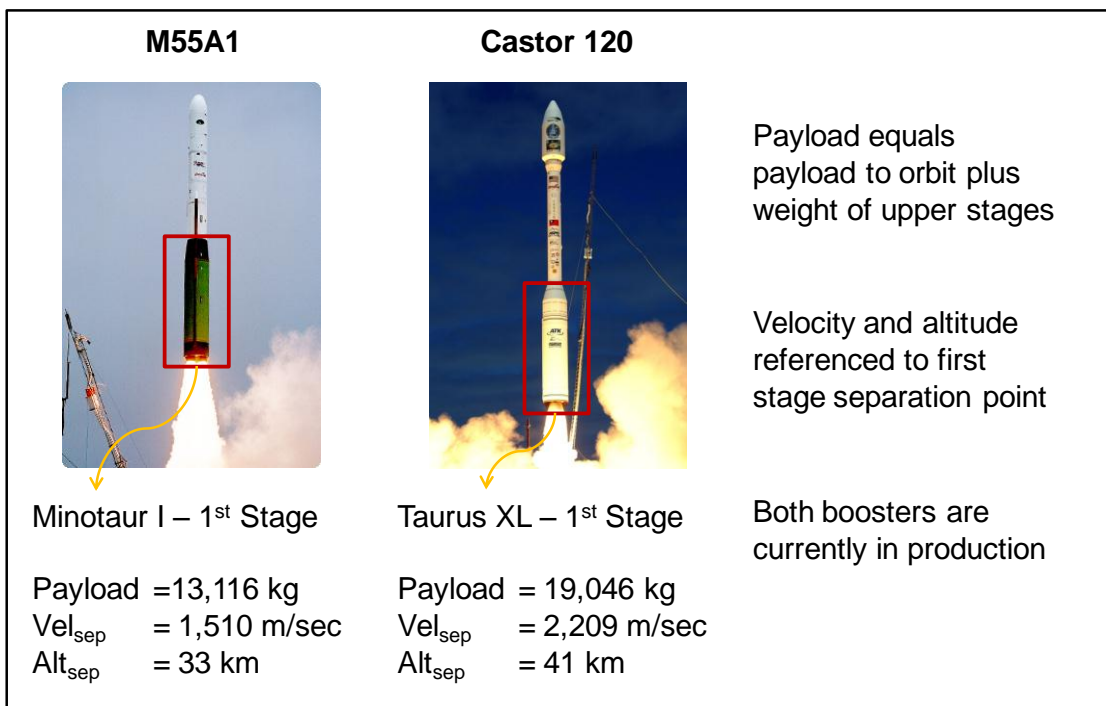


Fig. 6-9. Summary of Minotaur I and Taurus XL 1st stage constraints for the hypersonic demonstrator study. (Ref 17)

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.

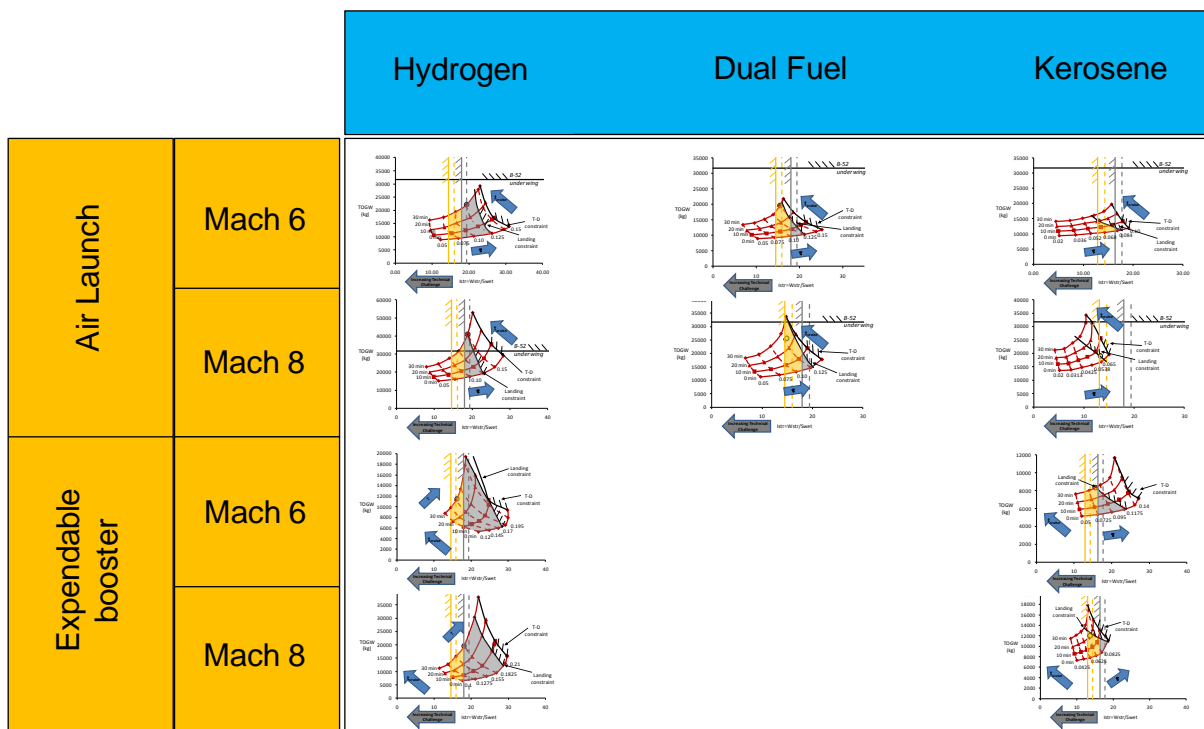


Fig. 6-10. Relative comparison of solution spaces for each design trade explored.

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.

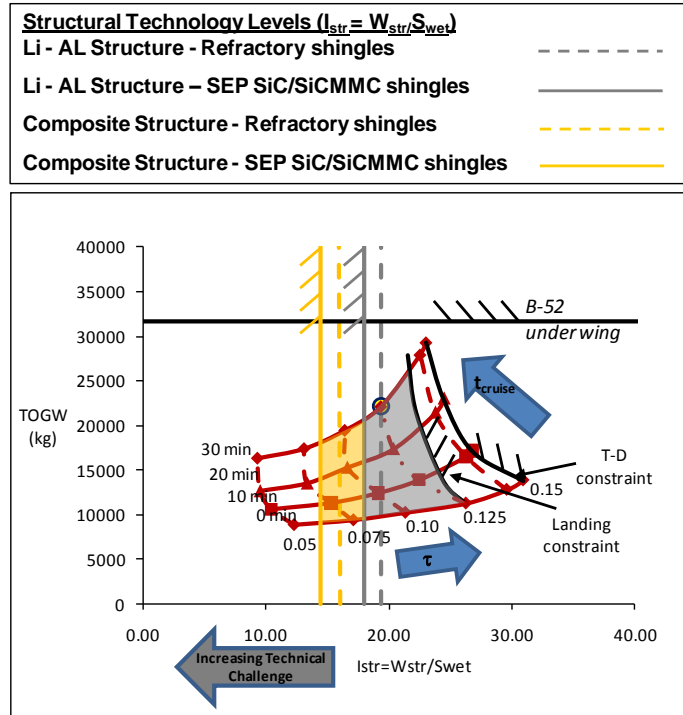


Fig. 6-11. Air-launched Mach 6 hydrogen-fueled trade solution space.

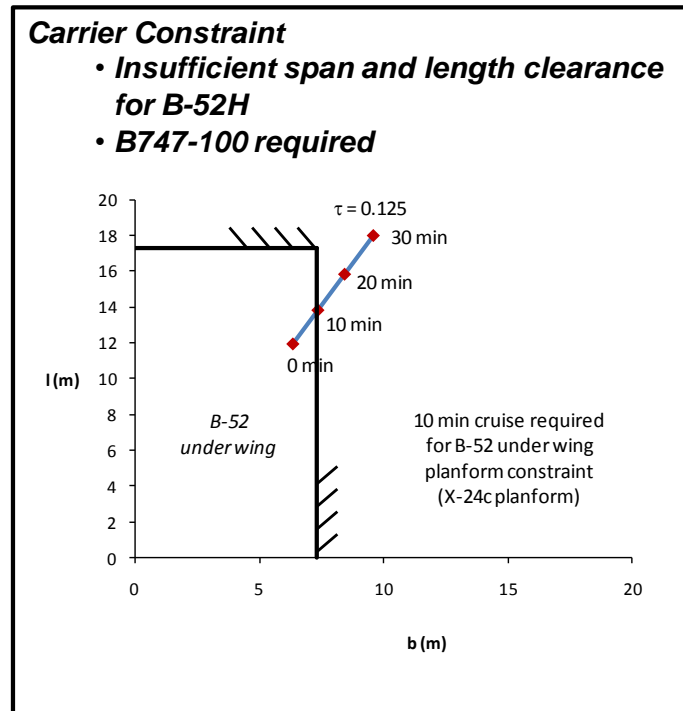


Fig. 6-12. B-52H planform area constraint and suggested design point, Mach 6, hydrogen-fuel trade.

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.

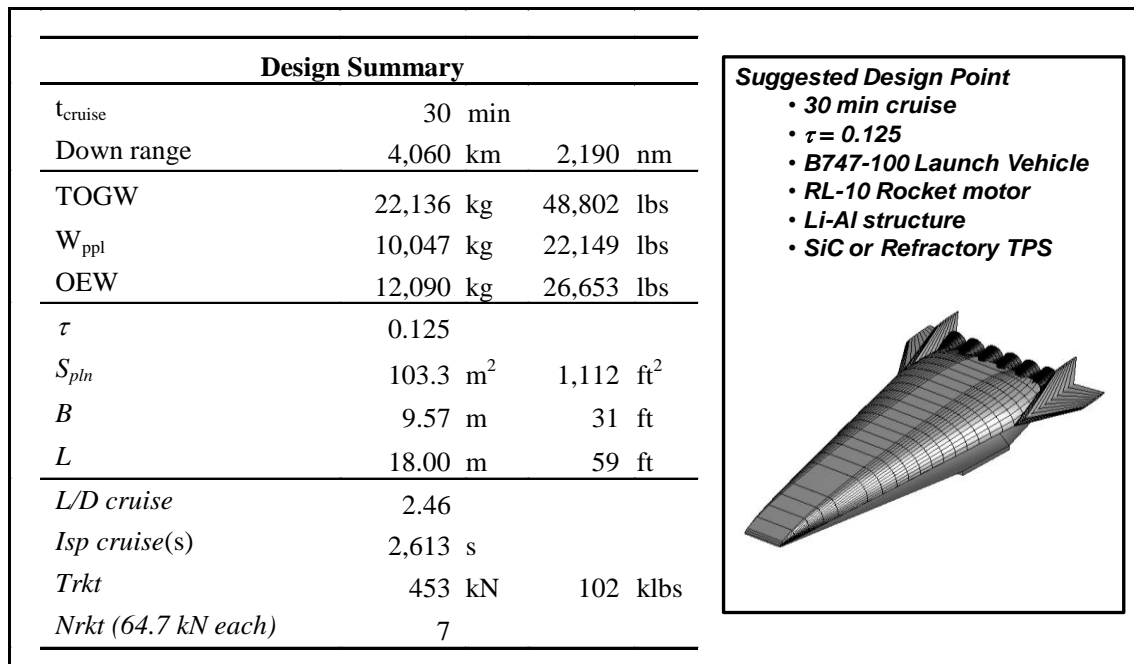


Fig. 6-13. Summary of suggested design point for the air-launched, Mach 6 hydrogen-fuel trade.

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

- The Mach 6 cruise mission is feasible with LH₂ 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 2nd 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.

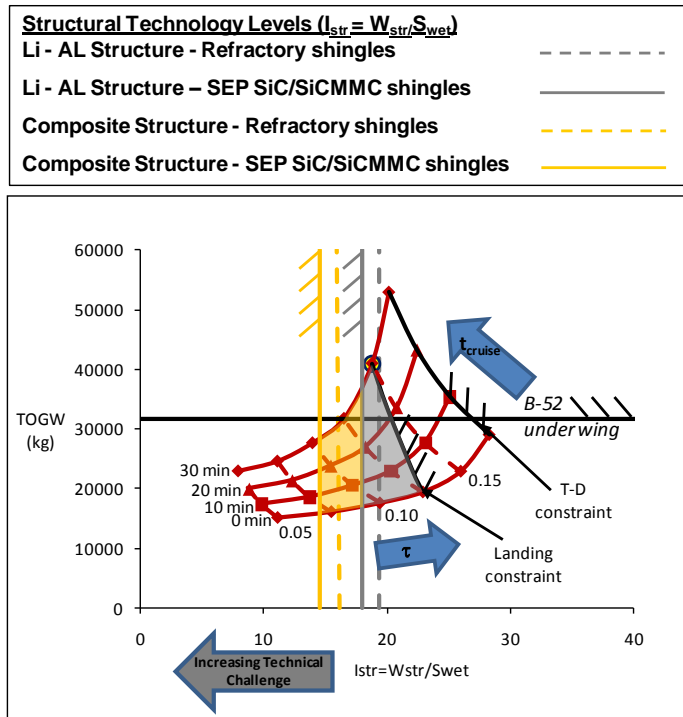


Fig. 6-14. Hydrogen-fuel, Mach 8 air-launch trade solution space.

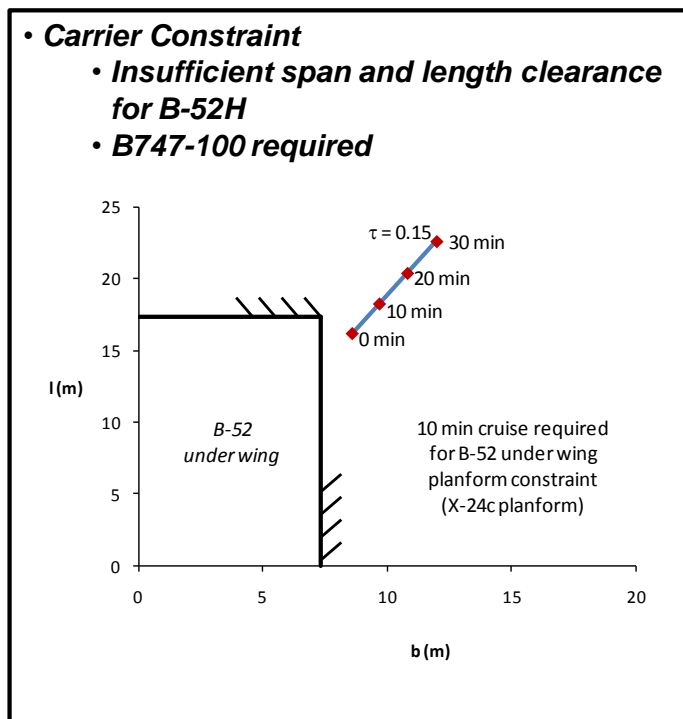


Fig. 6-15. B-52H planform area constraint and suggested design point, Mach 8, hydrogen-fuel trade.

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 than 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.

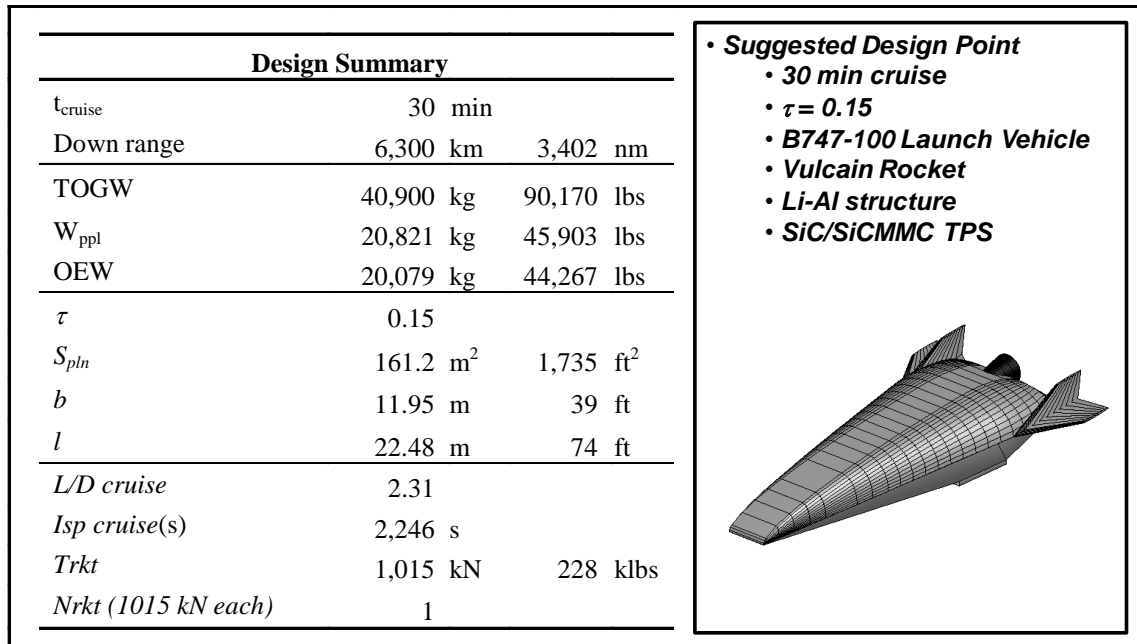


Fig. 6-16. Summary of suggested design point for the air-launched, Mach 8 hydrogen-fuel trade.

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

- The Mach 8 cruise mission is feasible with LH₂ fuel, aluminum structure and refractory metal TPS.
- The Vulcain rocket is a satisfactory of-the-shelf rocket for this mission; however, a LH₂ 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.

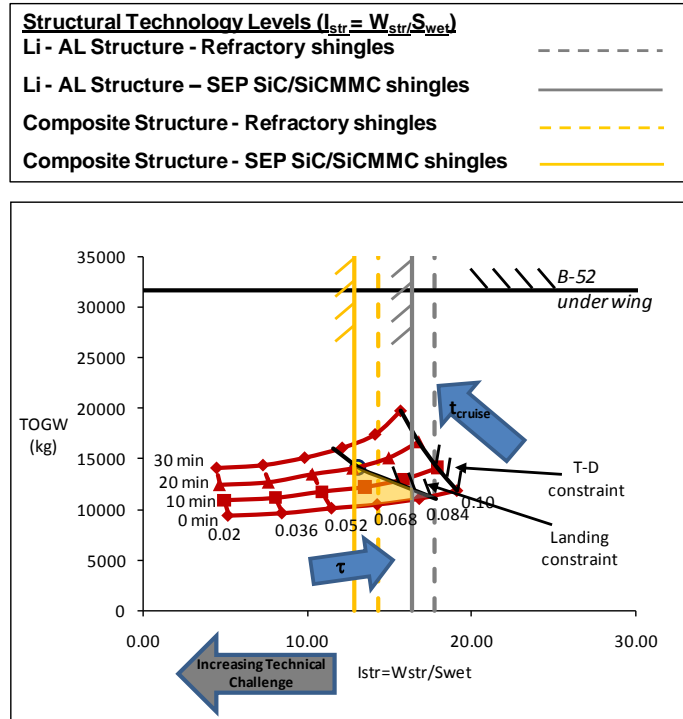


Fig. 6-17. Kerosene-fuel Mach-6 air-launched trade solution space.

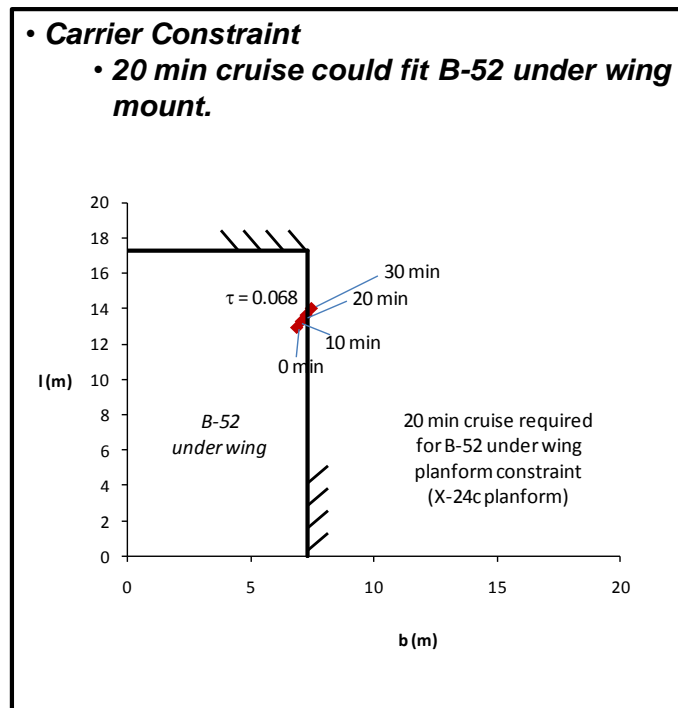


Fig. 6-18. B-52 planform area constraint and suggested design point, Mach 6, kerosene-fuel trade.

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.

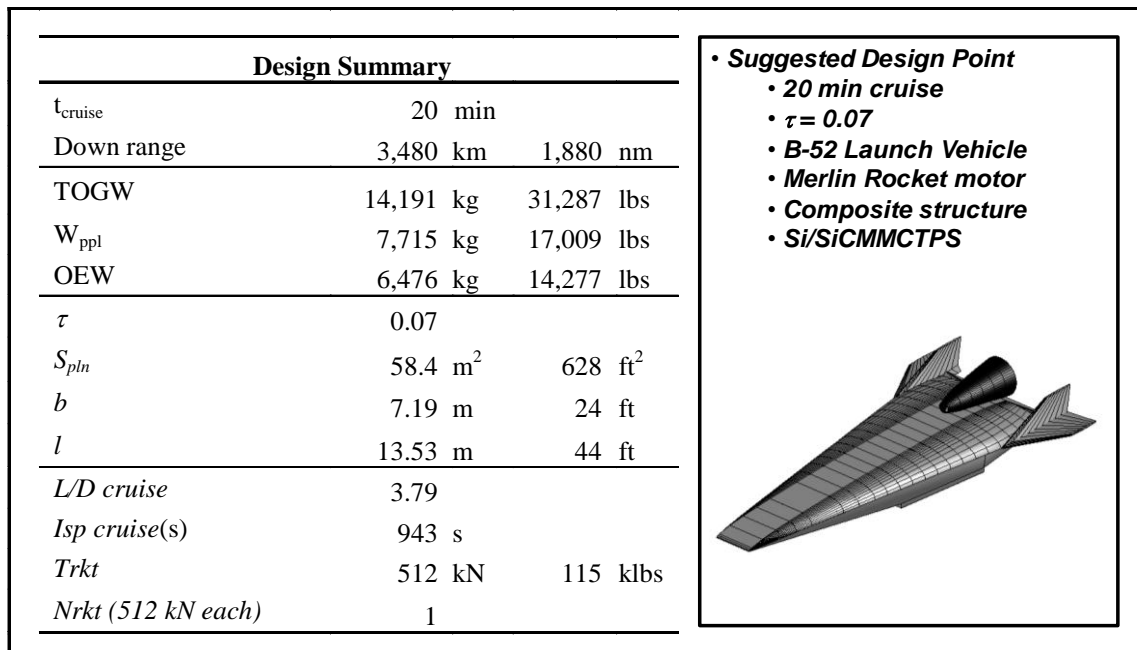


Fig. 6-19. Summary of suggested design point for the air-launched, Mach 6 kerosene-fuel trade.

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.

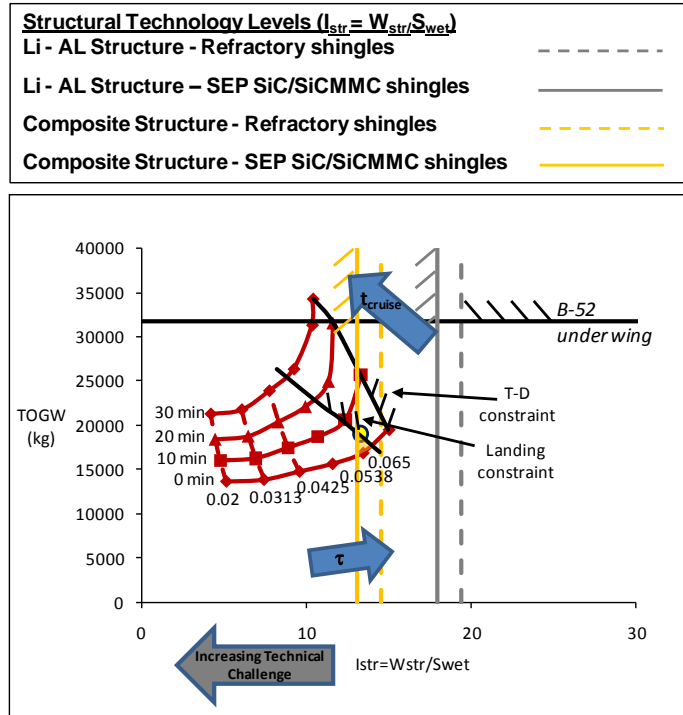


Fig. 6-20. Kerosene-fuel Mach 8 air-launched trade solution space.

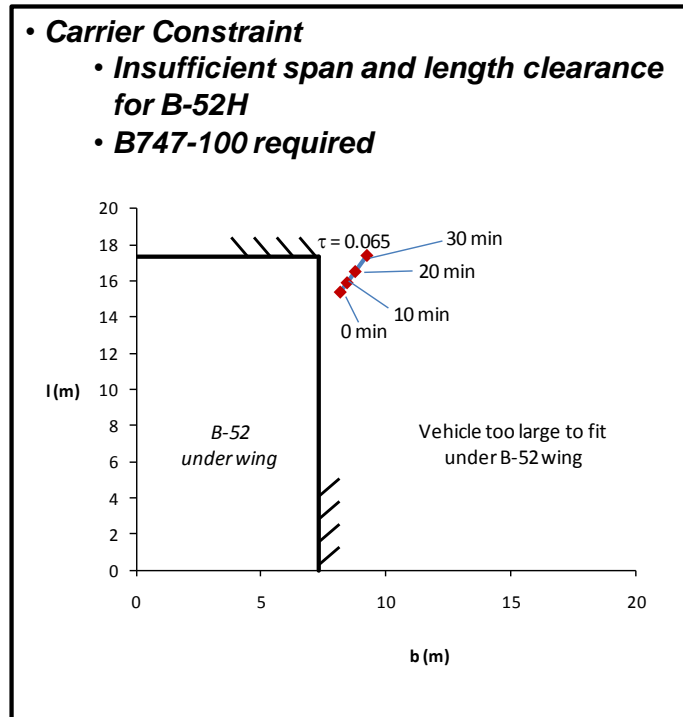


Fig. 6-21. B-52H planform area constraint and suggested design point, Mach 8, kerosene-fuel trade.

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.

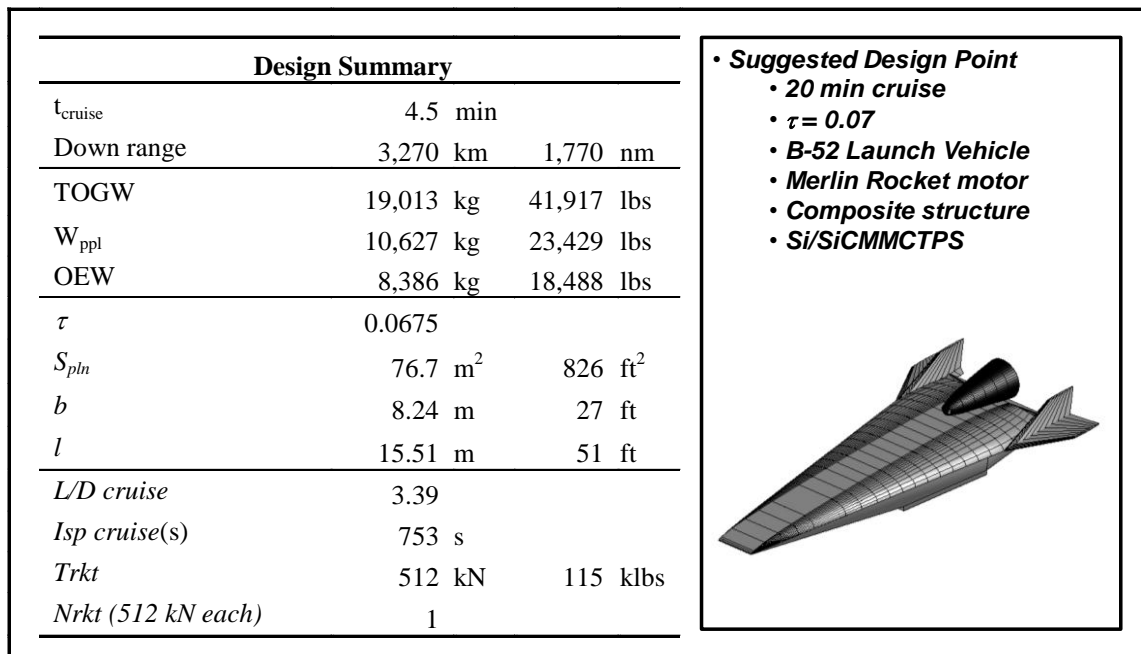


Fig. 6-22. Summary of suggested design point for the air-launched, Mach 8 kerosene-fuel trade.

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.

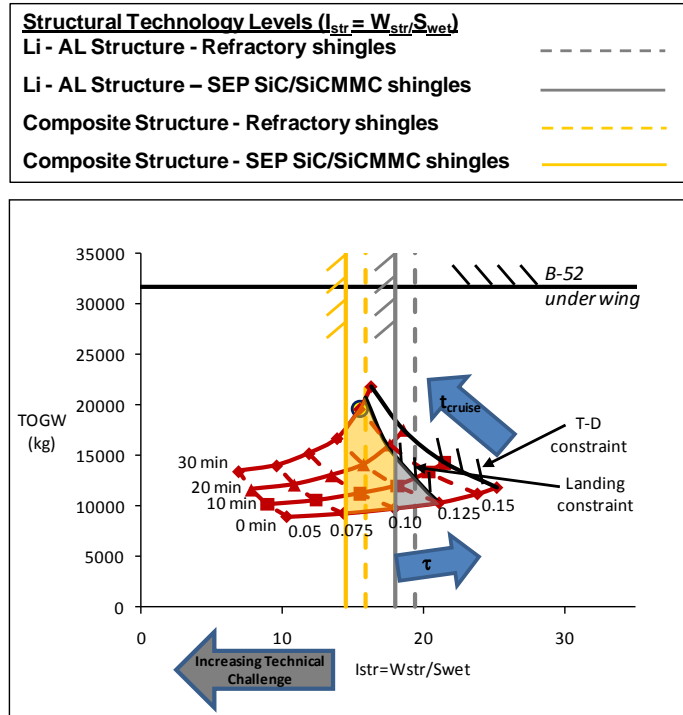


Fig. 6-23. Dual-fuel Mach 6 air-launched trade solution space.

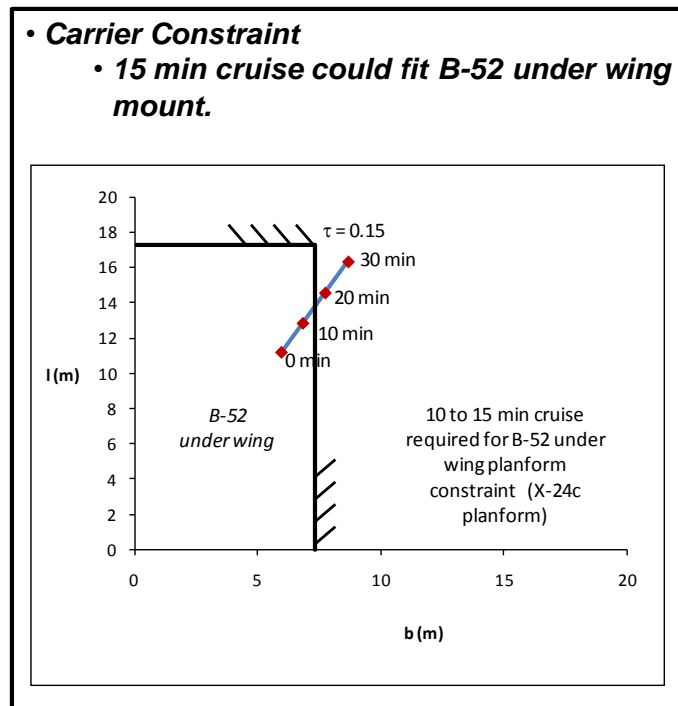


Fig. 6-24. B-52H planform area constraint and suggested design point, Mach 6, dual-fuel trade.

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.

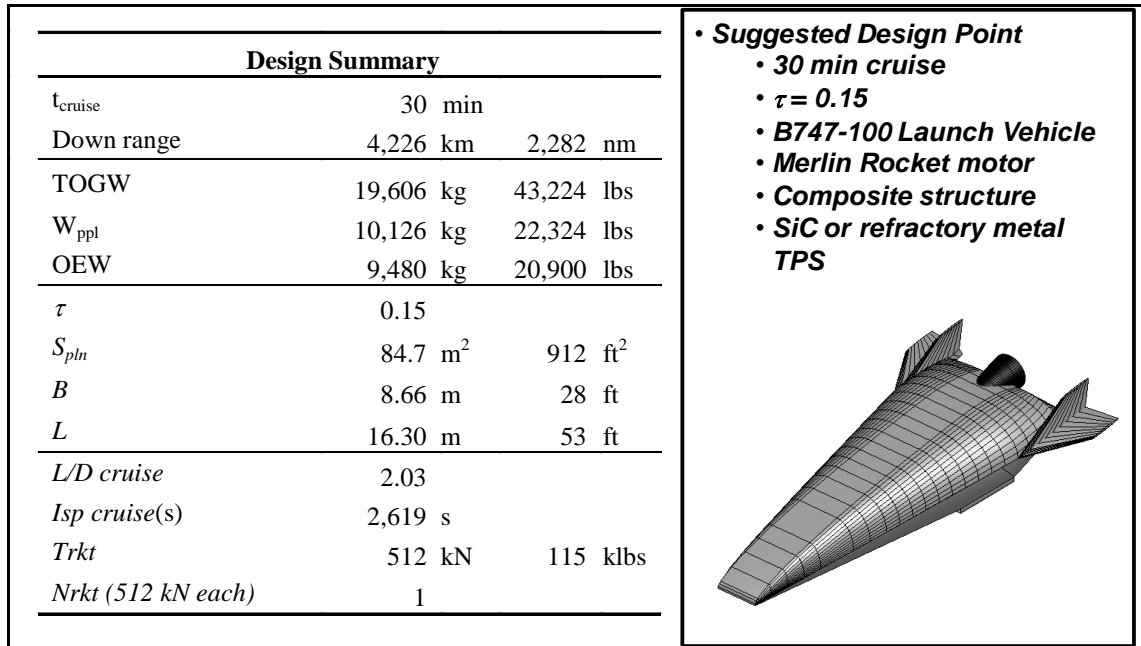


Fig. 6-25. Summary of suggested design point for the air-launched, Mach 6 dual-fuel trade.

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.

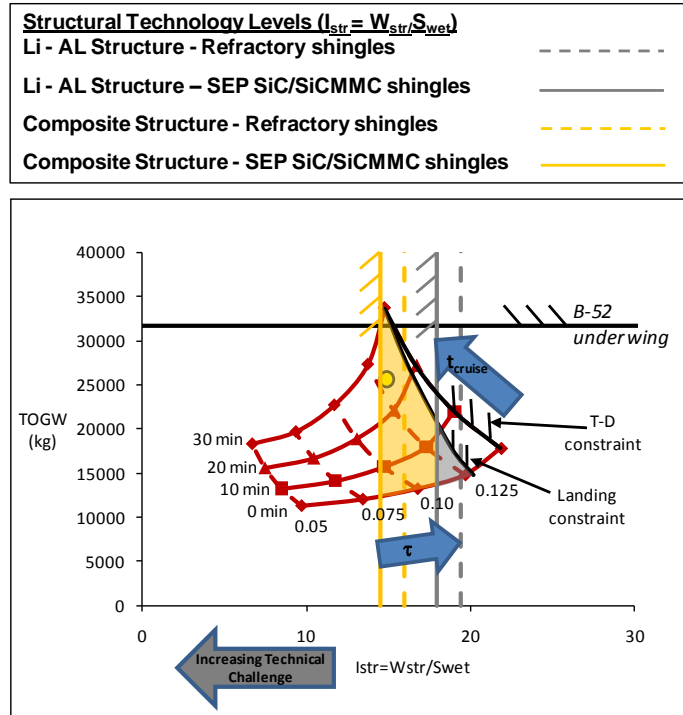


Fig. 6-26. Dual-fuel, Mach-8 air-launched trade solution space.

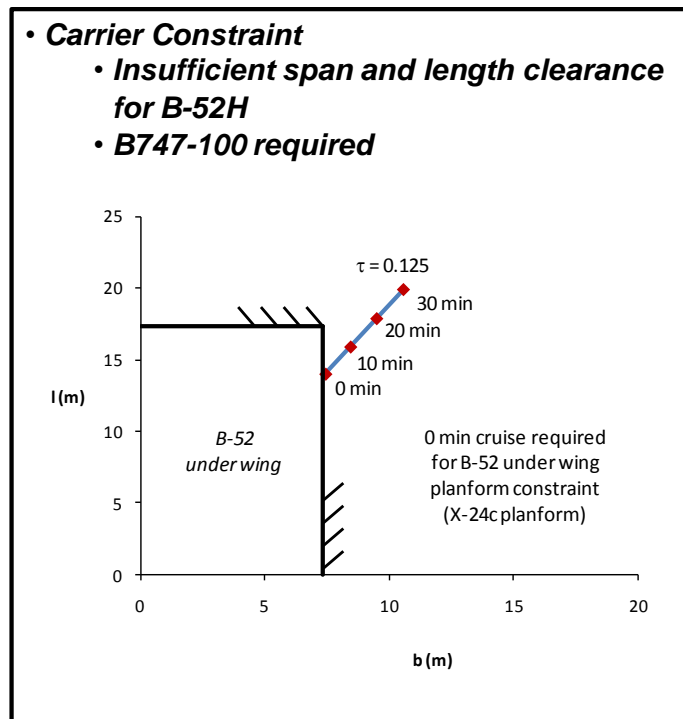


Fig. 6-27. B-52H planform area constraint and suggested design point, Mach 8, dual-fuel trade.

Carrier Constraints: While the B-52H could support the weight of the vehicle, however, its platform 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.

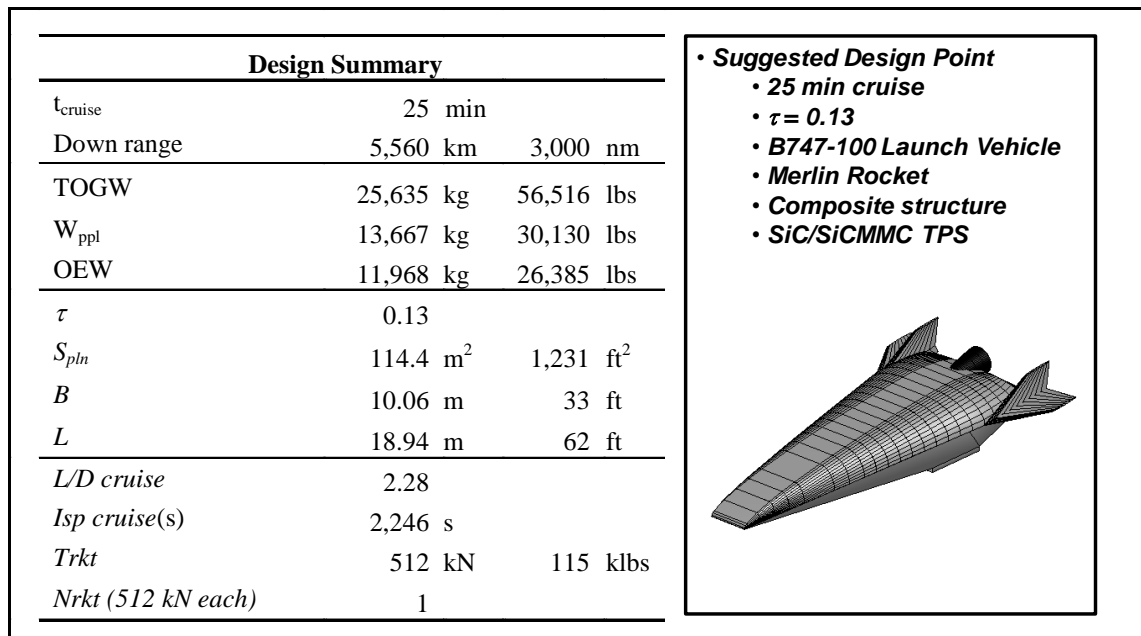


Fig. 6-28. Summary of suggested design point for the air-launched, Mach 8 dual-fuel trade.

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.

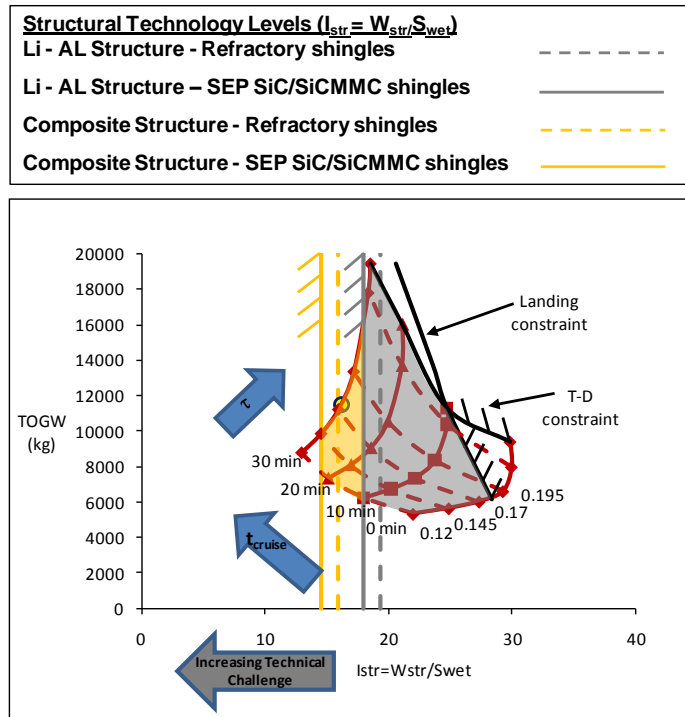


Fig. 6-29. Hydrogen-fuel, Mach 6 expendable booster trade solution space.

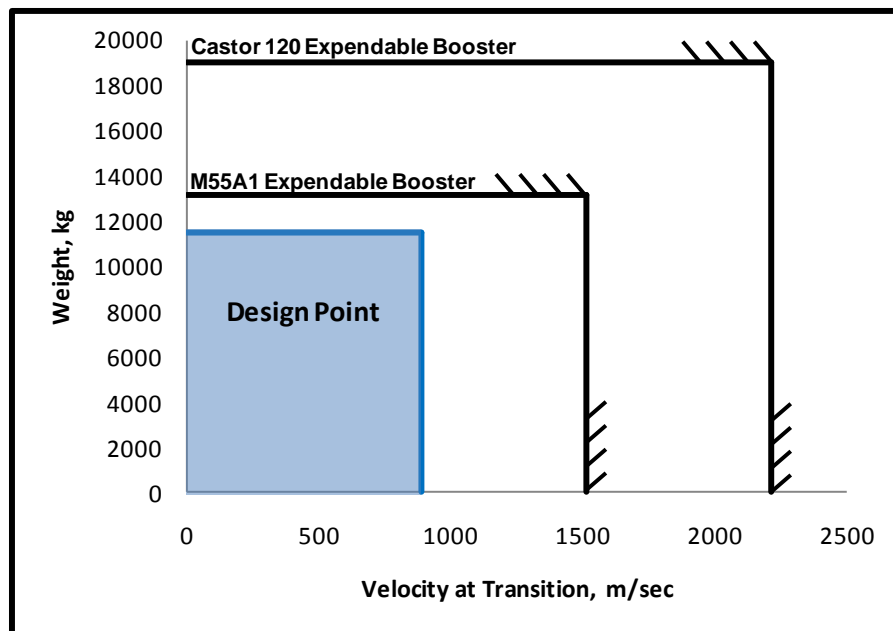


Fig. 6-30. Expendable booster constraints and suggested design point, Mach 6, hydrogen-fuel trade.

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.

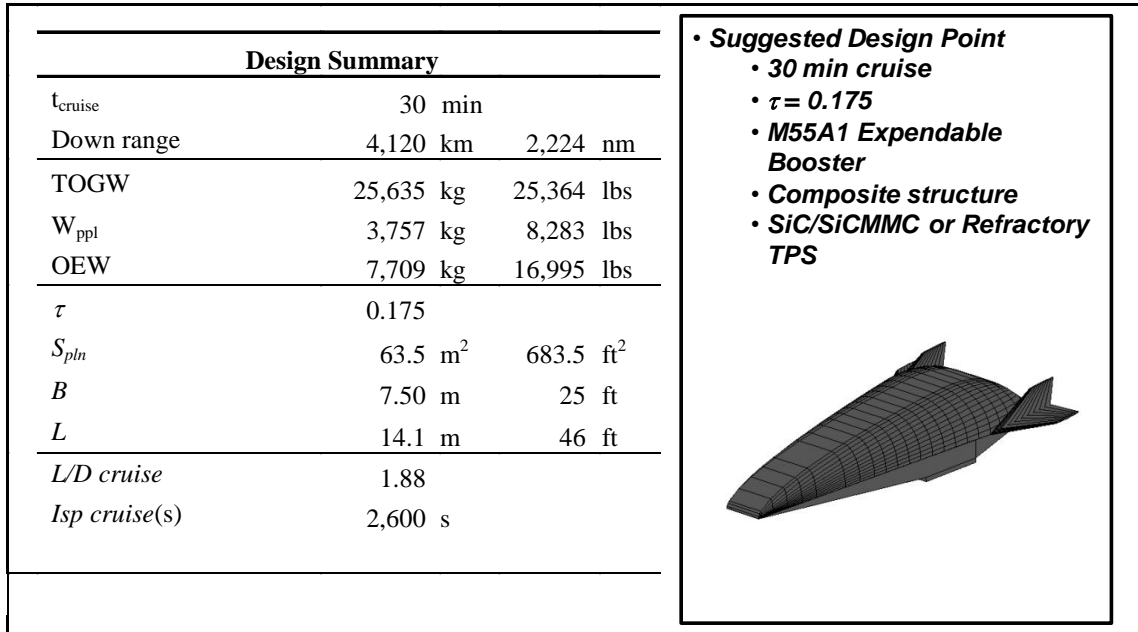


Fig. 6-31. Summary of suggested design point for the expendable booster, Mach 6 hydrogen- fuel trade.

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.

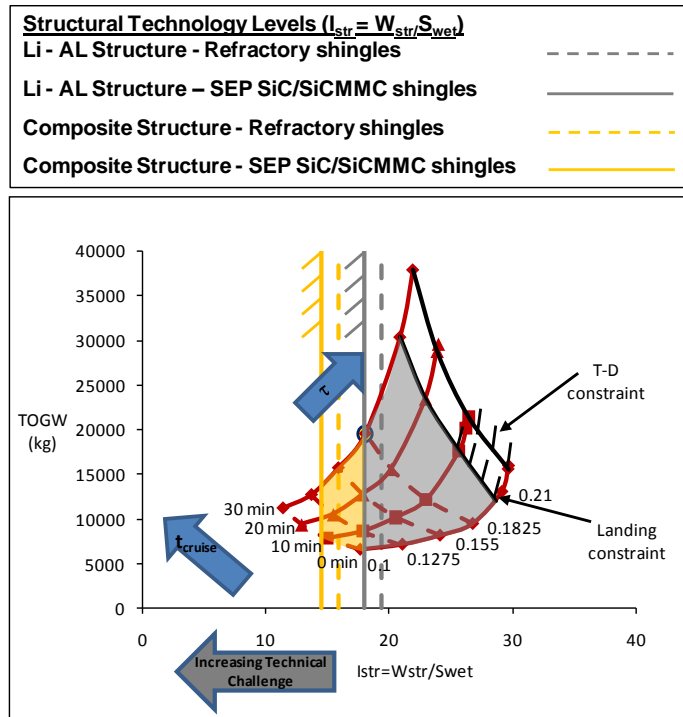


Fig. 6-32. Hydrogen-fuel, Mach 8 expendable booster trade solution space.

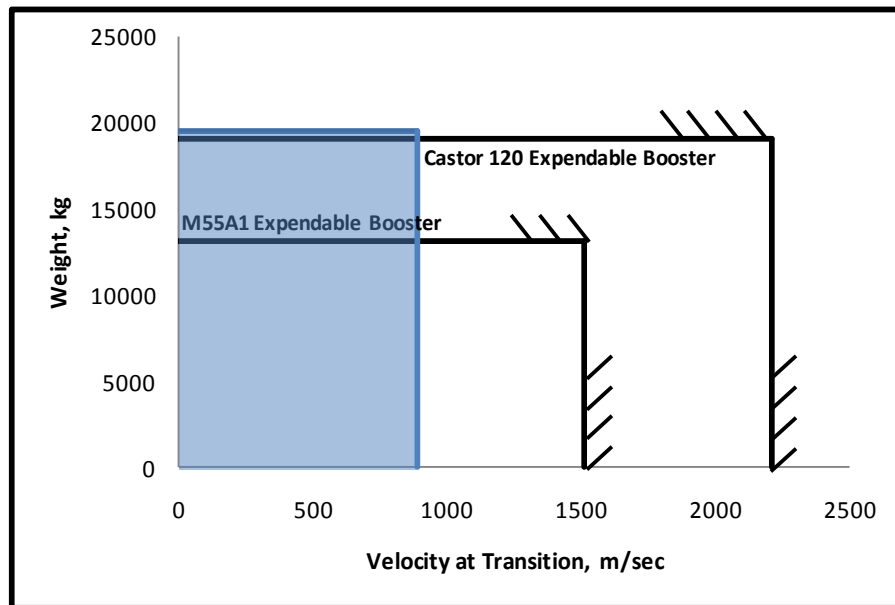


Fig. 6-33. Expendable booster constraints and suggested design point, Mach 8, hydrogen-fuel trade.

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.

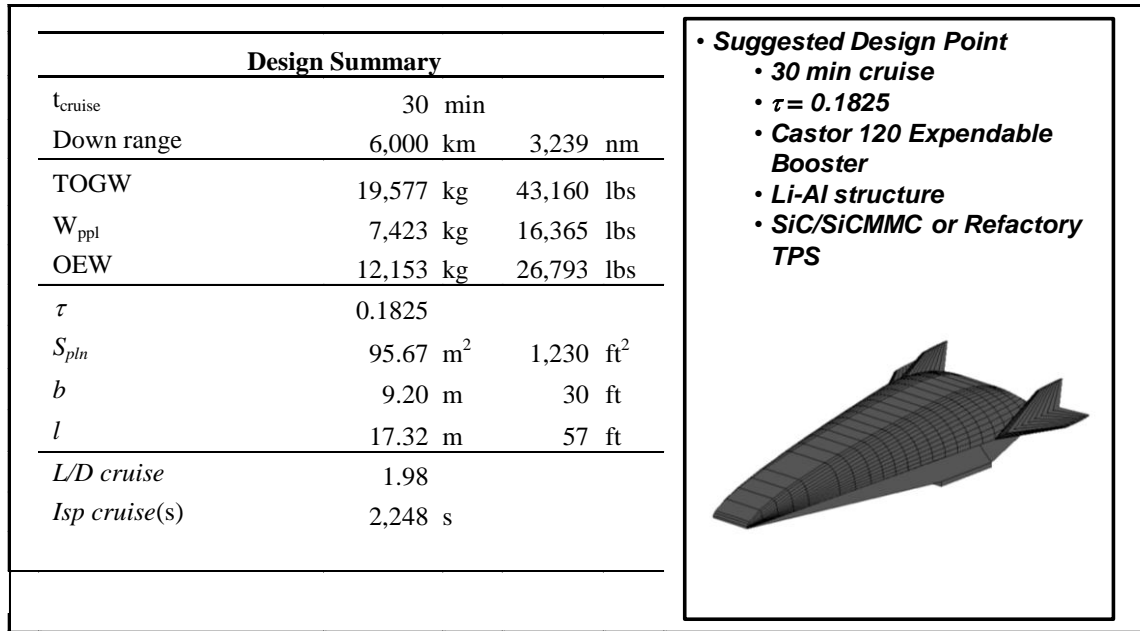


Fig. 6-34. Summary of suggested design point for the expendable booster, Mach 8, hydrogen-fuel trade.

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.

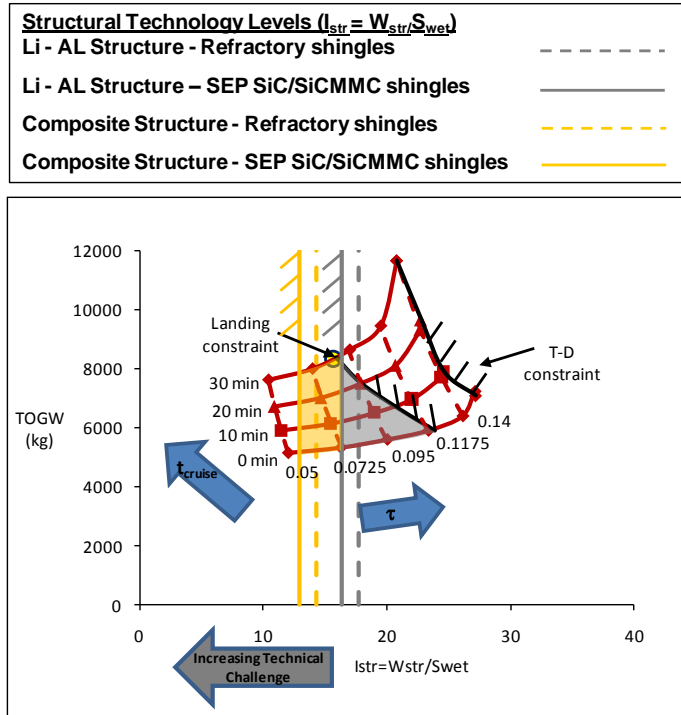


Fig. 6-35. Kerosene-fuel, Mach 6 expendable booster trade solution space.

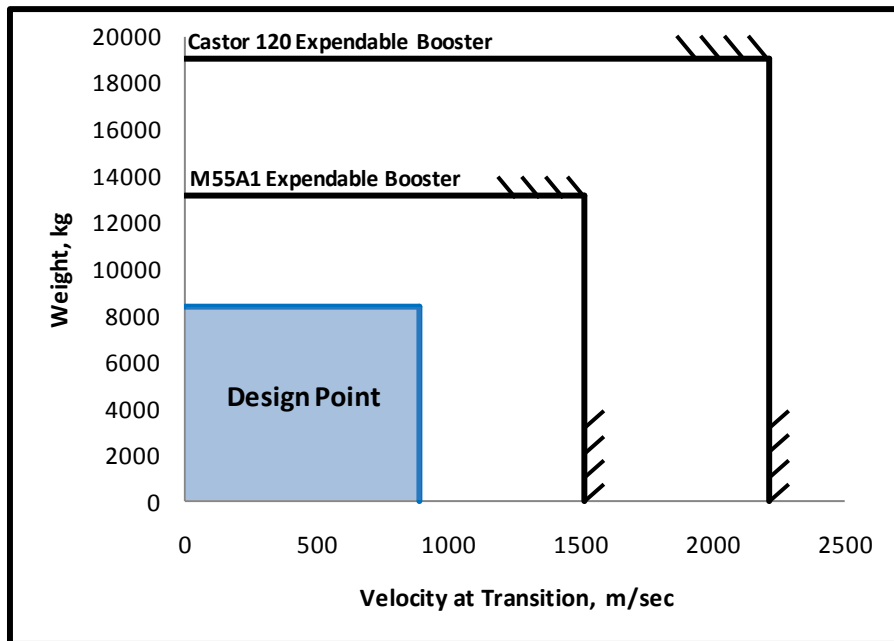


Fig. 6.36. Expendable booster constraints and suggested design point, Mach 6, kerosene-fuel trade.

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.

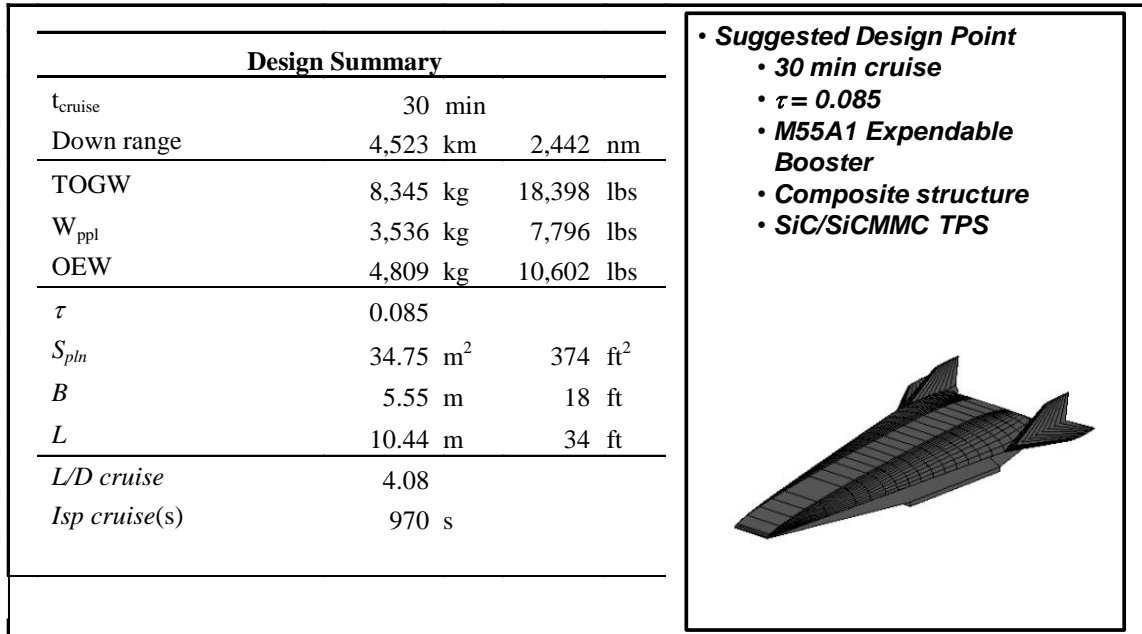


Fig. 6.37. Summary of suggested design point for the expendable booster, Mach 6 kerosene-fuel trade.

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.

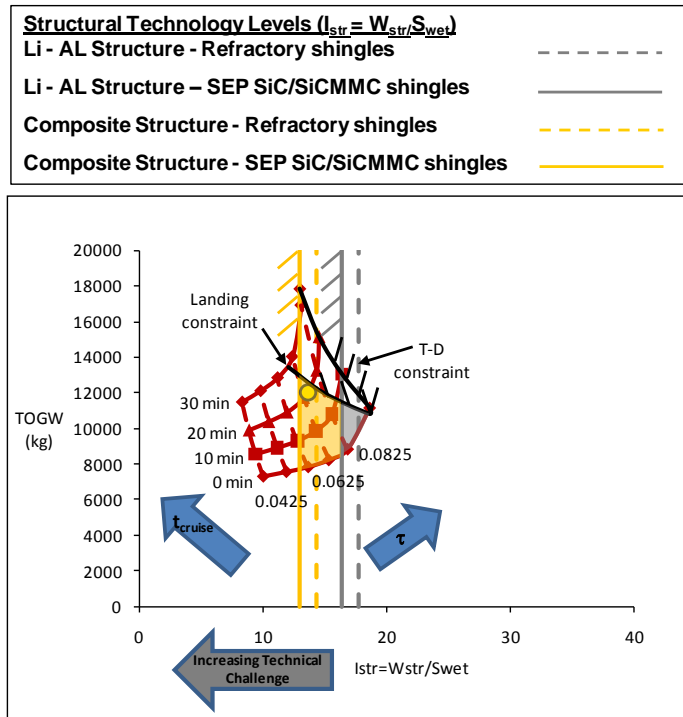


Fig. 6-38. Kerosene-fuel, Mach 8, expendable booster trade solution space.

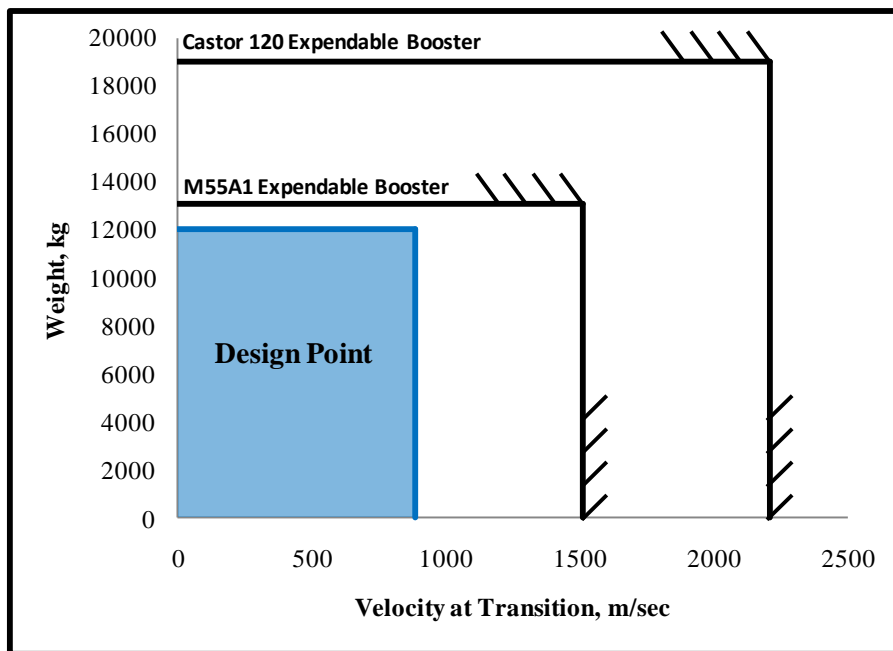


Fig. 6-39. Expendable booster constraints and suggested design point, Mach 8, kerosene-fuel trade.

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.

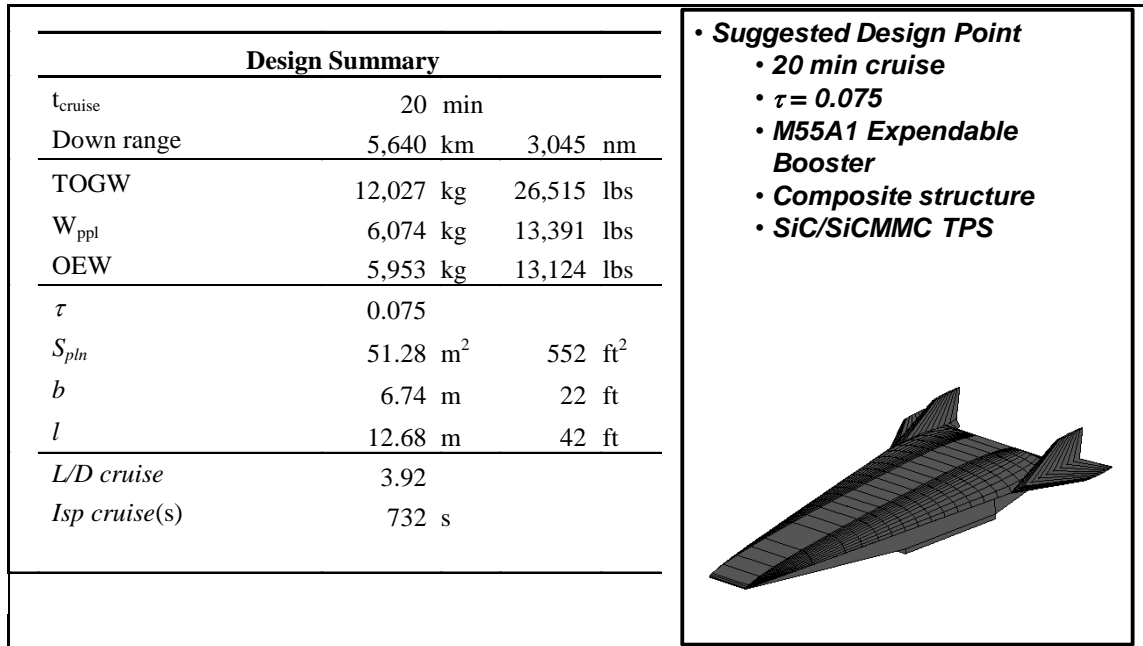


Fig. 6-40. Summary of suggested design point for the expendable booster, Mach 8, kerosene-fuel trade.

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

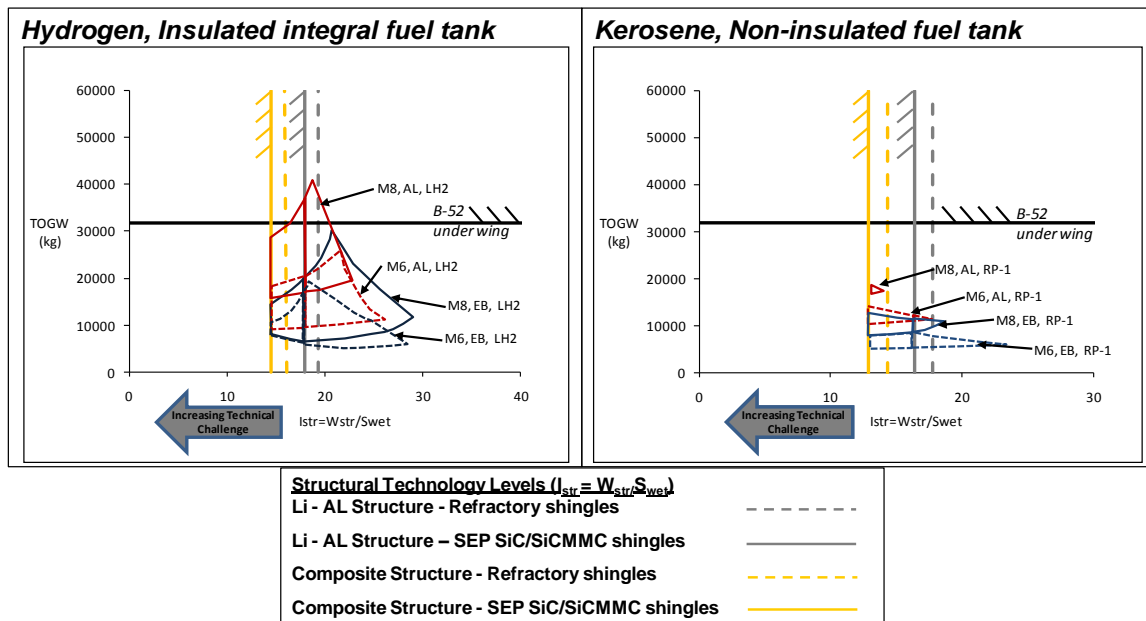


Fig. 7-1. Hydrogen-fueled vehicles allow for a larger technical solution space compared to kerosene-fueled vehicles.

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.









| | | Hydrogen | Kerosene |
|--------------------|--------|---|---|
| Air Launch | Mach 6 |  |  |
| | Mach 8 |  |  |
| Expendable booster | Mach 6 |  |  |
| | Mach 8 |  |  |

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 | |
|---------------------------|-------------------------------------|----------------------|-------------------------------------|----------------------|---|-----------------------|---|----------------------|
| <i>t_{cruise}</i> | 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_{pp1} | 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 | |
| <i>S_{pln}</i> | 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 |
| <i>L/D cruise</i> | 2.46 | | 2.31 | | 1.88 | | 1.98 | |
| <i>Isp cruise (s)</i> | 2613 s | | 2246 s | | 2600 s | | 2248 s | |
| <i>Trkt</i> | 453 kN | 102 klbs | 1015 kN | 228 klbs | | | | |
| <i>Nrkt</i> | 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 | |
|---------------------------|--------------------------|---------------------|--------------------------|---------------------|----------------------------------|---------------------|----------------------------------|---------------------|
| <i>t_{cruise}</i> | 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_{pp1} | 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 | |
| <i>S_{pln}</i> | 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 |
| <i>L/D cruise</i> | 3.79 | | 3.39 | | 4.08 | | 3.92 | |
| <i>Isp cruise (s)</i> | 943 s | | 753 s | | 970 s | | 732 s | |
| <i>Trkt</i> | 512 kN | 115 klbs | 512 kN | 115 klbs | | | | |
| <i>Nrkt</i> | 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 hydrogen scramjet testing is required, assessment results are presented with Figure 7-3:

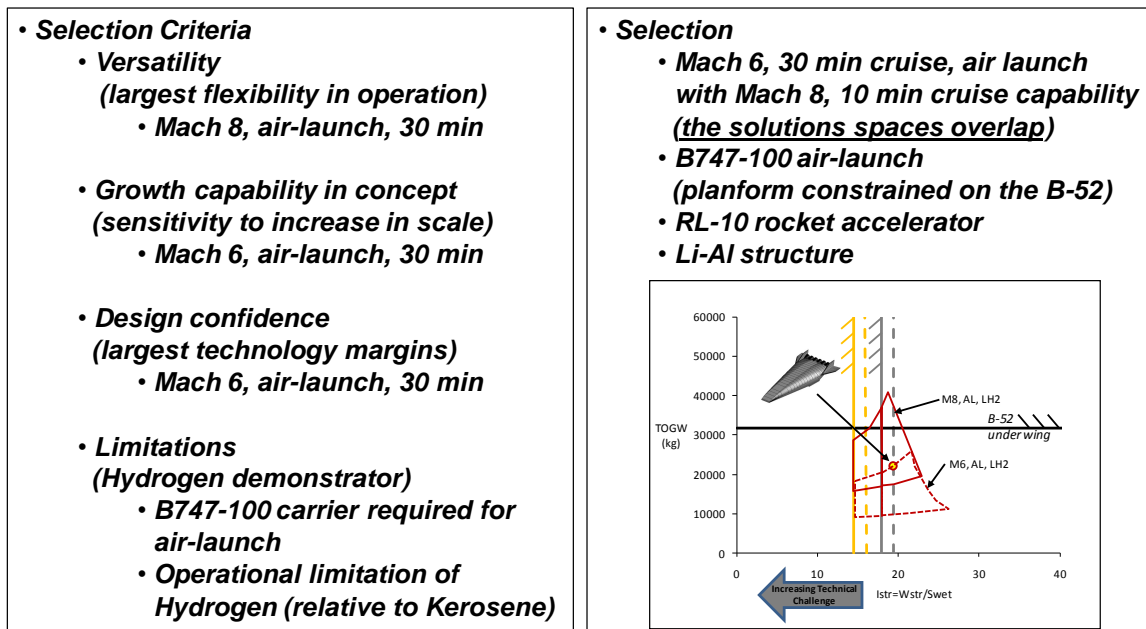


Fig. 7-3. The Mach 8 air-launched case represents the largest operational flexibility while Mach 6 air-launched has larger growth capability and design confidence. Since M6 30 min and M8 10 min solution curves overlay, it appears that the M6 30 min vehicle could perform the Mach 8 mission for 10 minutes.

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.

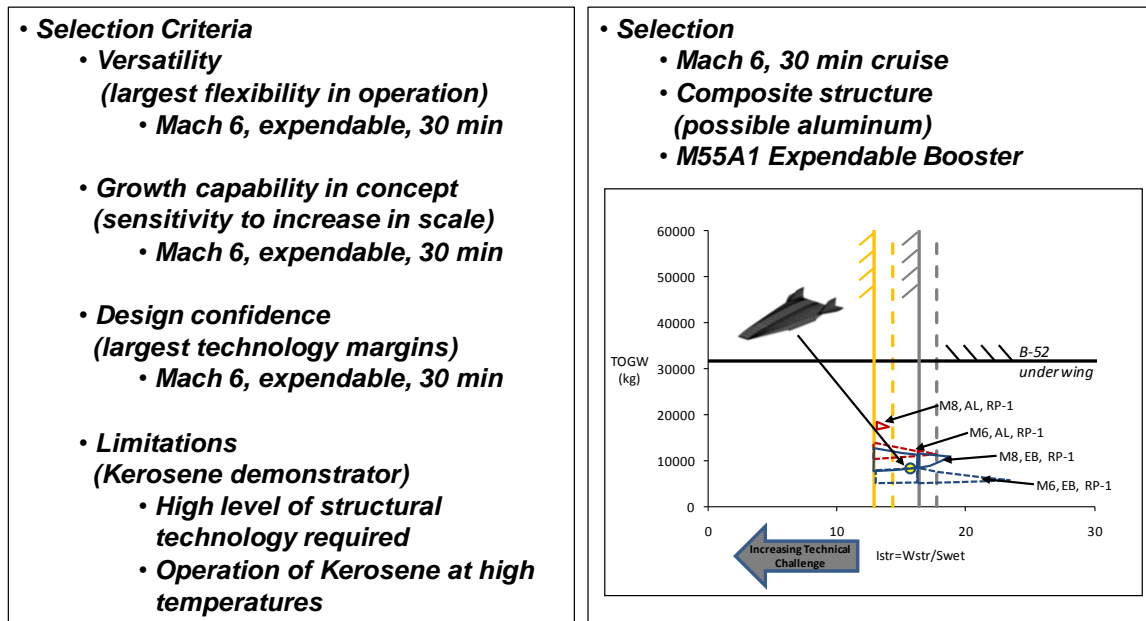


Fig. 7-4. The Mach 6 kerosene-fuel expendable booster trade is the only trade-study which allows for 30 minutes cruise endurance.

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).
- *LH₂ 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 LH₂.
- *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 LH₂ 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

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

| | |
|-----------------------------|--|
| 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., “ <i>Hypersonic Convergences</i> ,” 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 | | Applicability | | |
| Simplified geometry | | General glider and air breather configuration | | |
| Execution of method | | | | |
| Input: $S_{pln}, t, c/s, L_w, \Lambda_{LE}, \Delta, S_{\Delta}, L_c/L_w, h_c/L_c, \theta_1, h_t/L_{iso}, L_{comb}$ | | | | |
| Analysis description | | Compute minimum τ (flat top): | | |
| Compute underside geometry: | | $\tau_{min} = \frac{(h_c - h_t)(c + \frac{2}{3}s_{out})(\frac{1}{3}L_c + L_{iso} + L_{comb} + \frac{1}{3}L_{noz})}{S_{pln}^{1.5}}$ | | |
| $h_c = h_c/L_c \cdot L_c$ | | Compute height of upper surface (flat top) | | |
| $L_c = L_c/L_w \cdot L_w$ | | $h_{top} = \frac{(\tau - \tau_{min})S_{pln}^{1.5}}{\pi L_c (c + \frac{2}{3}s_{out})}$ | | |
| $\Lambda_{cowl} = \Lambda_{LE} - \Delta$ | | Compute wetted area per planform area: | | |
| $s_{out} = L_c / \tan(\Lambda_{cowl})$ | | $k_w = \frac{S_{wet}}{S_{pln}} = \frac{k_{ws} \cdot S_{\Delta} \cdot L_w + k_{wc} \cdot c \cdot L_w}{S_{pln}}$ | | |
| $S_{cowl} = c + 2 s_{out}$ | | $k_{ws} = -62.214\tau_0^3 + 29.904\tau_0^2 - 1.581\tau_0 + 2.469$ | | |
| Iterate h_t until L_{iso} convergence: | | $\tau_0 = 2/3 \cdot h_{top} / \sqrt{L_w \cdot S_{\Delta}}$ | | |
| $L_{iso} = h_t / (h_t / L_{iso})$ | | $k_{wc} = \frac{2 \sqrt{h_{top}^2 + L_w^2}}{L_w}$ | | |
| $L_{noz} = L_w - L_c - L_{iso} - L_{comb}$ | | Estimate frontal area and capture area: | | |
| Call one-dimensional stream thrust analysis at cruise condition to compute contraction ratios: | | $S_{front} = \pi S_{\Delta} h_{top} + h_{top} h_c c$ | | |
| $h_{t\ new} = \frac{h_c/L_c}{\frac{A_3 A_0 A_c}{A_4 A_3 A_0} \frac{2s_{cowl}}{s_{cowl}+c} + 1}$ | | $A_c = \frac{1}{2}(S_{cowl} + c)(h_c - h_t) + h_t S_{cowl}$ | | |
| $L_{iso\ new} = h_{t\ new} / (h_t / L_{iso})$ | | | | |
| 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 area 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.

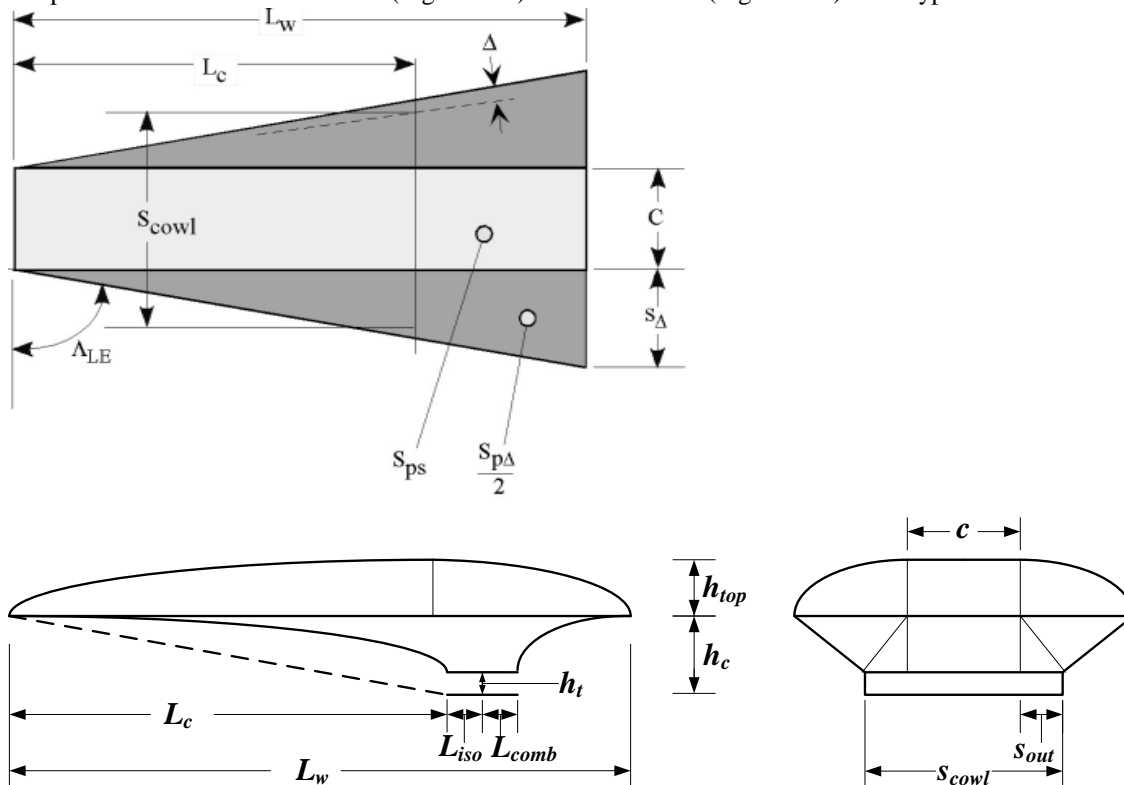
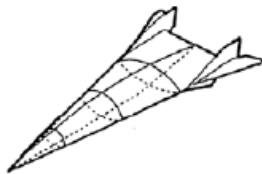


Fig. A-1. Volume parameterization of a hypersonic air-breather.



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

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

| Method overview | | | | |
|--|---------------------|---|--|---------------|
| Discipline | Design phase | Method title | Categorization | Author |
| Propulsion | Sizing | Hypersonic cruiser trajectory | Numerical | HYFAC |
| Reference: Czysz, P.A., "Hypersonic Convergence," Air Force Research Laboratory, Wright Patterson Air Force Base, AFRL-VA-WP-TR-2004-3114, 2004. | | | | |
| Brief description | | | | |
| <p>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.</p> | | | | |
| Assumptions | | | Applicability | |
| <p>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.</p> | | | <p>Air-breathing hypersonic or supersonic cruisers or first-stage launchers.</p> | |
| Execution of method | | | | |
| Input | | | | |
| Trajectory, C_{D0} , L' , T/Tsl , n_{max} , I_{sp} at each step | | | | |
| Analysis description | | | | |
| <p>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).</p> <p>Each segment is then integrated based on constant, altitude, velocity, or dynamic pressure.</p> <p>The total fuel fraction is then summed for weight and volume convergence.</p> <p>The largest thrust-to-weight ratio is used for engine weight estimation.</p> | | | | |
| Output: WR , $(T/W)_{TO}$ | | | | |
| Experience | | | | |
| Accuracy | | General comments | | |
| Depends on aero and propulsion system accuracy | | 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. | | |

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).

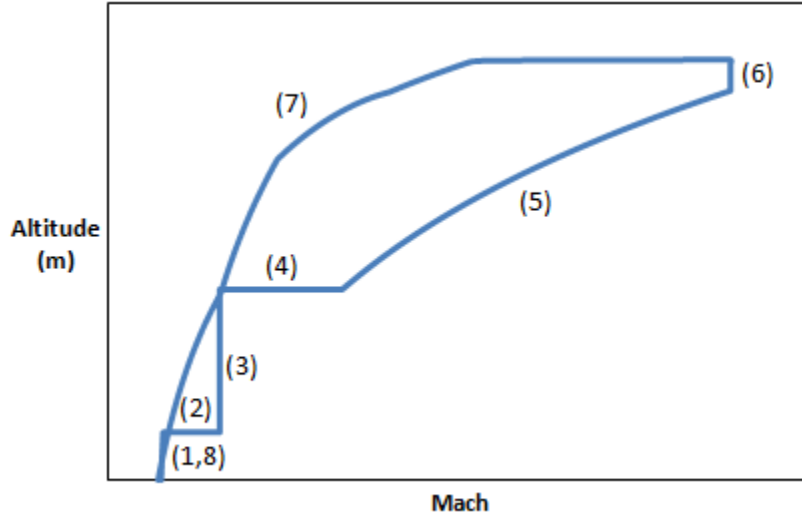


Fig. A-3. Assumed trajectory of the hypersonic cruiser.

At each integration step (i) (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:

$$\begin{aligned}\dot{E}_i &= V_i \cdot n_{\text{max}} \\ \Delta t &= \frac{E_i - E_{i-1}}{\dot{E}_i} \\ \Delta R &= V_i \cdot \Delta t \\ \frac{\Delta W_i}{TOGW} &= -\Delta T \frac{T/W}{I_{SP}}\end{aligned}$$

Then,

$$\begin{aligned}t_{i+1} &= t_i + \Delta t \\ R_{i+1} &= R_i + \Delta R \\ \frac{W_{i+1}}{TOGW} &= \frac{W_i}{TOGW} + \frac{\Delta W_i}{TOGW}\end{aligned}$$

3. Weight and Balance

Empty Weight and Volume Formulation

Table A-4. Convergence Empty Weight Estimation Method

| Method overview | | | | |
|--|-------------------|---|----------------|-------------------|
| Discipline | Design phase | Method title | Categorization | Author |
| Weight estimation | Parametric sizing | Convergence empty-weight estimation | Empirical | Coleman/ Czysz |
| Reference: Dissertation | | | | |
| 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. | | | | |
| Assumptions Wing area is not constant | | Applicability Any aircraft or launcher configuration. Applicability depends on the methods used for the structural, propulsion, and systems weight. | | |
| Execution of method | | | | |
| Input: $WR, T/W, W_{pay}, W_{crew}, V_{pay}, V_{crew}$ | | | | |
| Analysis description Solve the following system for S_{pln} and OWE : Weight budget: $OWE = \frac{W_{str} + C_{sys} + W_{oper} + (T/W)_{\max} WR / E_{TW} (W_{pay} + W_{crew})}{\frac{1}{1+\mu_a} - f_{sys} - (T/W)_{\max} WR / E_{TW}} + W_{pay}$ Volume budget: $OWE = \frac{\tau \cdot S_{pln}^{1.5} (1 - k_{vw} - k_{vs}) - V_{fix} - V_{pay} - V_{crew}}{\frac{WR-1}{\rho_{fuel}} + k_{ve} (T/W)_{\max} WR}$ Use the additional methods for $W_{str}, W_{sys}, f_{sys}, W_{oper}$ and E_{TW} | | | | |
| Output: $OEW, TOGW, OWE, S_{pln}$ | | | | |
| Experience | | | | |

| 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:

$$W_{sys} = C_{sys} + f_{sys}W_{dry}$$

$$0.16 \leq f_{sys} \leq 0.24 \text{ ton/ton}$$

$$C_{sys} = C_{un} + f_{mnd}N_{crew}$$

$$1.9 \leq C_{un} \leq 2.1 \text{ ton}$$

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

$$W_{cprv} = f_{cprv}N_{crew}$$

$$0.45 \leq f_{crew} \leq 0.50 \text{ ton/person}$$

$$W_{eng} = \frac{TW_oWR}{E_{TW}} (W_{dry} + W_{pay} + W_{crew})$$

$$4.0 \leq E_{TW} \leq 25 \text{ kg thrust/kg weight}$$

Additional volumetric relationships:

$$V_{pay} = W_{pay}/\rho_{pay}$$

$$48 \leq \rho_{pay} \leq 130 \text{ kg/m}^3$$

$$V_{crew} = N_{crew}(V_{pcrv} + k_{crew})$$

$$0.9 \leq k_{crew} \leq 2.0 \text{ m}^3/\text{person}$$

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

$$V_{void} = k_{vv}V_{tot}$$

$$0.10 \leq k_{vv} \leq 0.20 \text{ m}^3/\text{m}^3$$

$$V_{crew} = N_{crew}(V_{pcrv} + k_{crew})$$

$$0.9 \leq k_{crew} \leq 2.0 \text{ m}^3/\text{person}$$

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

$$V_{sys} = V_{fix} + k_{vs}V_{tot}$$

$$0.02 \leq k_{vs} \leq 0.04 \text{ m}^3/\text{m}^3$$

$$V_{fix} = V_{un} + f_{crew}N_{crew}$$

$$5.0 \leq V_{un} \leq 7.0 \text{ m}^3$$

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

$$V_{eng} = k_{ve}(T/W)_{\max}W_RW_{OE}$$

$$0.25 \leq k_{ve} \leq 0.75; \text{ m}^3/\text{ton thrust}$$

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

4. Structural weight

Table A-5. Structural Index Estimation Method

| Method overview | | | | |
|---|---------------------|--|--|---------------|
| Discipline | Design phase | Method title | Categorization | Author |
| Structure | Sizing | Structural index | Empirical | Czysz |
| <p>Reference: Czysz, P.A., “<i>Hypersonic Convergence</i>,” Volume 1, Air Force Research Laboratory, Wright Patterson Air Force Base, AFRL-VA-WP-TR-2004-3114, 2004.</p> | | | | |
| <p>Brief description</p> <p>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).</p> | | | | |
| <p>Assumptions</p> <p>Blended-body or wing-body hypersonic cruiser or launch vehicle Integrated thermal projection and structural sandwich</p> | | | <p>Applicability</p> <p>Both passive and actively cooled structures Hypersonic cruisers and launch vehicles</p> | |
| Execution of method | | | | |
| <p>Input: $\tau, S_{pln}, S_{wet}, OEW$</p> | | | | |
| <p>Analysis description</p> <p>Compute structural weight and structural index required for a given τ, S_{pln}, S_{wet}, and OEW:</p> $W_{str} = I_{str} \cdot S_{wet} = K_{str} \cdot S_{pln}^{0.138} \cdot OEW$ | | | | |
| <p>Output: W_{str}, I_{str}</p> | | | | |
| Experience | | | | |
| <p>Accuracy</p> <p>Has worked well for a variety of hypersonic cruisers projects at MAC Proves valid for the Sanger II</p> | | <p>General comments</p> <p>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.</p> | | |

Further description:

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

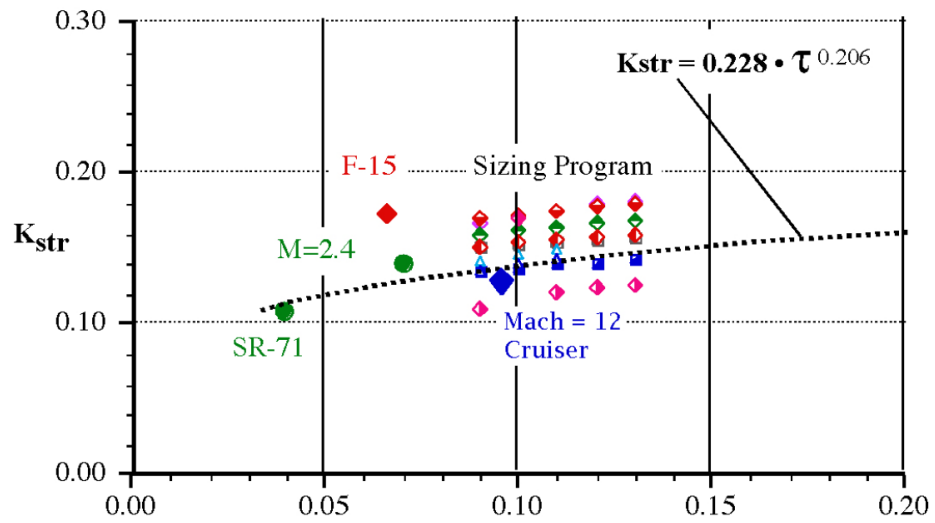


Fig. A-4. Structural index prediction description.

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 | 74.63 kg/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

$C_{Lmax} = 0.50$ (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

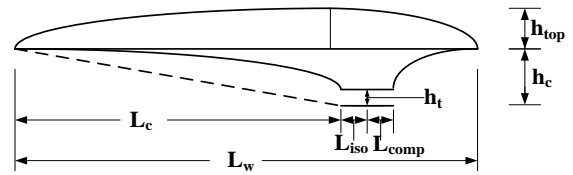
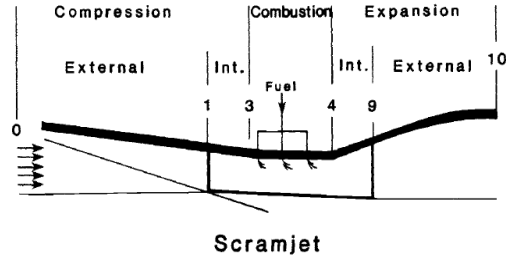
| | RL-10A-5, P&W | Vulcain, SEP |
|--|---------------------|--------------|
| E_{TW} – Engine thrust-to-weight ratio | 46.12 | 61.36 |
| ISP _{vac} – Vacuum ISP | 373.0 s | 440 |
| T_{vac} – Vacuum thrust | 64.7 kN (14,500 lb) | 1015 kN (lb) |
| ϵ – Nozzle-expansion ratio | 4.0 | 45.0 |
| P_c – combustion-chamber 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_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 0.01 |
| $\left(\frac{C_f A_w}{A_3}\right)_b$ | 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_{Lmax} .

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 | CDO | 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_FUEL1 | 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 | 74.63 kg/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

$C_{Lmax} = 0.50$ (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

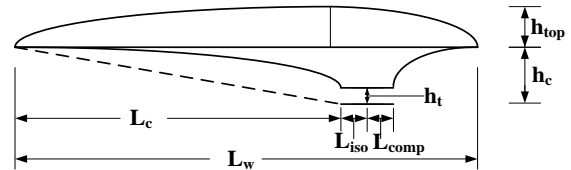
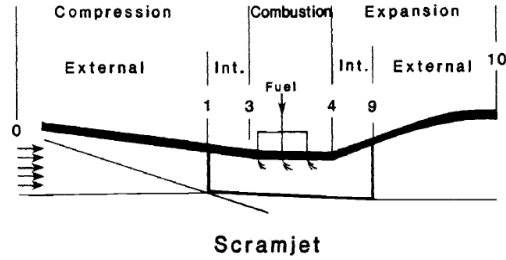
| | RL-10A-5, P&W | Vulcain, SEP |
|--|---------------------|--------------|
| E_{TW} – Engine thrust-to-weight ratio | 46.12 | 61.36 |
| ISP_{vac} – Vacuum ISP | 373.0 s | 440 |
| T_{vac} – Vacuum thrust | 64.7 kN (14,500 lb) | 1015 kN (lb) |
| ϵ – Nozzle-expansion ratio | 4.0 | 45.0 |
| P_c – combustion-chamber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

Dual-mode ram-scrumjet

The dual-mode ram-scrumjet 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 |
|--|----------|
| H_{pr} (kJ/kg) | 119954.0 |
| f (stoichiometric) | 0.0291 |
| V_{fx}/V_3 | 0.50 |
| V_f/V_3 | 0.50 |
| η_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 0.01 |
| $\left(\frac{C_f A_w}{A_3}\right)_b$ | 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 (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_{Lmax} .

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 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 | 0.15 |
| | 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 | CDO | 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_FUEL1 | 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 |
| | <i>T/W</i> rocket | TW_TJ_MAX | 2.5297 |
| | <i>T/W</i> 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.

Geometry

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

Aerodynamics

$C_{Lmax} = 0.50$ (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-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

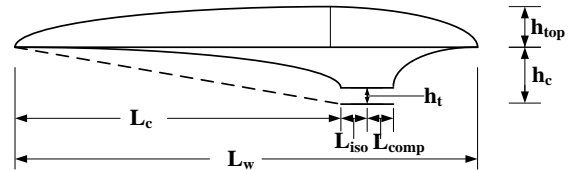
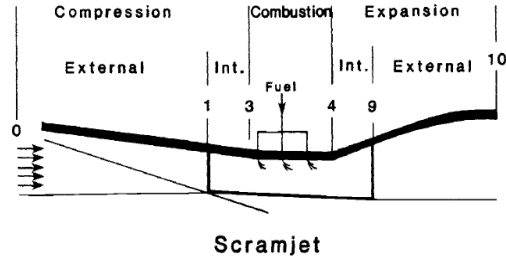
| | Merlin , Space X |
|--|---------------------|
| E_{TW} – Engine thrust-to-weight ratio | 96.0 |
| ISP_{vac} – Vacuum ISP | 304.0 s |
| T_{vac} – Vacuum thrust | 512.0 kN (115.0 lb) |
| ϵ – Nozzle-expansion ratio | 14.0 |
| P_c – combustion-chamber pressure | 60.69 atm |
| O/F – oxidizer-to-fuel ratio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

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-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_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 0.01 |
| $\left(\frac{C_f A_w}{A_3}\right)_b$ | 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) | 0.000075 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_{Lmax} .

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_FUEL1 | 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

$C_{Lmax} = 0.50$ (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

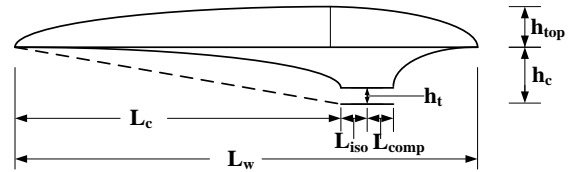
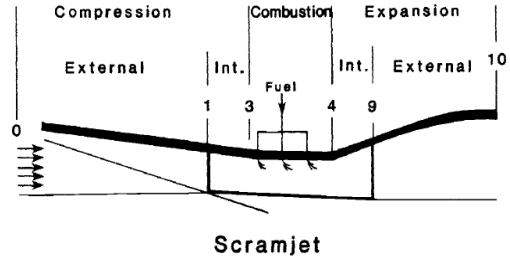
| | Merlin, Space X |
|--|---------------------|
| E_{TW} – Engine thrust-to-weight ratio | 96.0 |
| ISP_{vac} – Vacuum ISP | 304.0 s |
| T_{vac} – Vacuum thrust | 512.0 kN (115.0 lb) |
| ϵ – Nozzle-expansion ratio | 14.0 |
| P_c – combustion-chamber pressure | 60.69 atm |
| O/F – oxidizer-to-fuel ratio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

Dual-mode ram-scrumjet

The dual-mode ram-scrumjet 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 |
|--|---------|
| H_{pr} (kJ/kg) | 43380.0 |
| f (stoichiometric) | 0.0680 |
| V_{fx}/V_3 | 0.50 |
| V_f/V_3 | 0.50 |
| η_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 0.01 |
| $\left(\frac{C_f A_w}{A_3}\right)_b$ | 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) | 0.000075 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_{Lmax} .

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 | 74.63 kg/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

$C_{Lmax} = 0.50$ (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

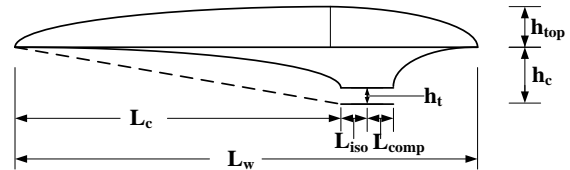
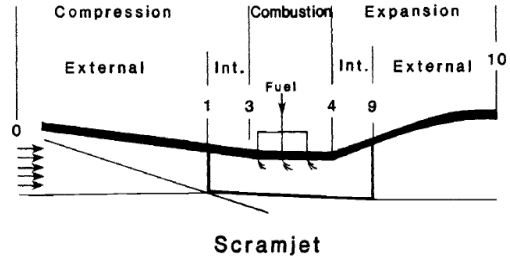
| | Merlin, Space X |
|--|---------------------|
| E_{TW} – Engine thrust-to-weight ratio | 96.0 |
| ISP_{vac} – Vacuum ISP | 304.0 s |
| T_{vac} – Vacuum thrust | 512.0 kN (115.0 lb) |
| ϵ – Nozzle-expansion ratio | 14.0 |
| P_c – combustion-chamber pressure | 60.69 atm |
| O/F – oxidizer-to-fuel ratio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

Dual-mode ram-scrumjet

The dual-mode ram-scrumjet 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_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 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-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_{Lmax} .

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 |
| Trajectory summary | Weight ratio | WR_TJ | 0.48596 |
| | 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 | 74.63 kg/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

$C_{Lmax} = 0.50$ (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

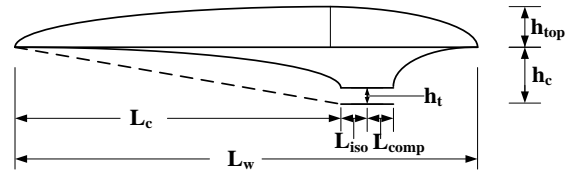
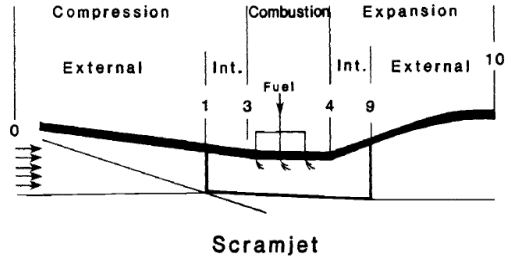
| | Merlin, Space X |
|--|---------------------|
| E_{TW} – Engine thrust-to-weight ratio | 96.0 |
| ISP_{vac} – Vacuum ISP | 304.0 s |
| T_{vac} – Vacuum thrust | 512.0 kN (115.0 lb) |
| ϵ – Nozzle-expansion ratio | 14.0 |
| P_c – combustion-chamber pressure | 60.69 atm |
| O/F – oxidizer-to-fuel ratio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

Dual-mode ram-scrumjet

The dual-mode ram-scrumjet 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_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 0.01 |
| $\left(\frac{C_f A_w}{A_3}\right)_b$ | 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_{Lmax} .

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 |
| Trajectory summary | Weight ratio | WR_TJ | 0.46921 |
| | 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 |
| | <i>T/W</i> rocket | TW_TJ_MAX | 2.03595 |
| | <i>T/W</i> 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

$$C_{L_{\max}} = 0.50 \text{ (FDL-7)}^{[11]}$$

Hyfac database, MAC circa 1970^[3]

Spatular corrections from Pike

Structure and thermal protection

Structural shape factor K_{str} from MAC^[6]

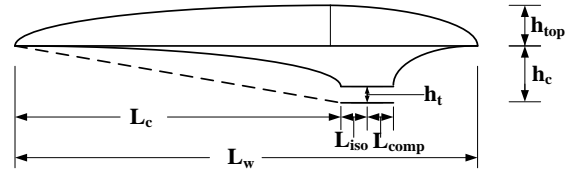
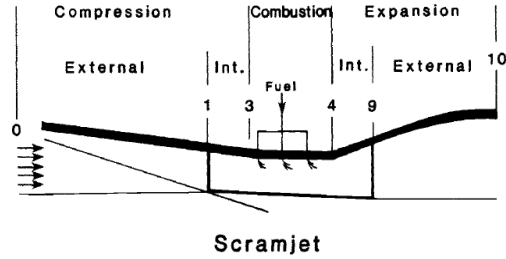
Propulsion

Dual-mode ram-scrumjet

The dual-mode ram-scrumjet 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_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 0.01 |
| $\left(\frac{C_f A_w}{A_3}\right)_b$ | 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 |



Weight, volume, and balance

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 |

Performance

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

The required approach speed was computed from the assumed C_{Lmax} .

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

$$C_{L_{max}} = 0.50 \text{ (FDL-7)}^{[11]}$$

HyFAC database, MAC circa 1970^[3]

Spatular corrections from Pike

Structure and thermal protection

Structural shape factor K_{str} from MAC^[6]

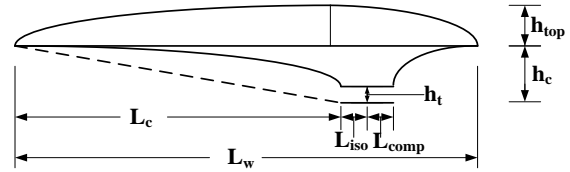
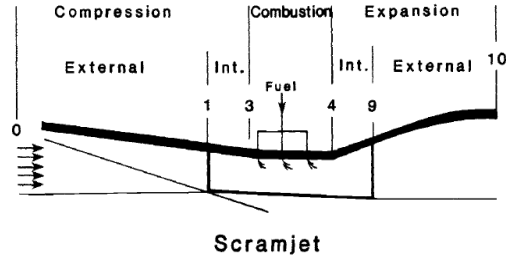
Propulsion

Dual-mode ram-scrumjet

The dual-mode ram-scrumjet 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_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 0.01 |
| $\left(\frac{C_f A_w}{A_3}\right)_b$ | 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_{Lmax} .

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

$C_{Lmax} = 0.50$ (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]

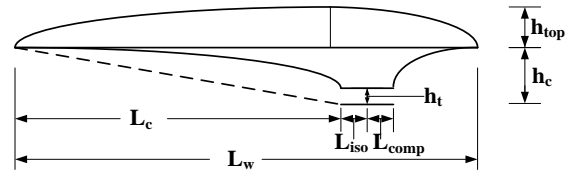
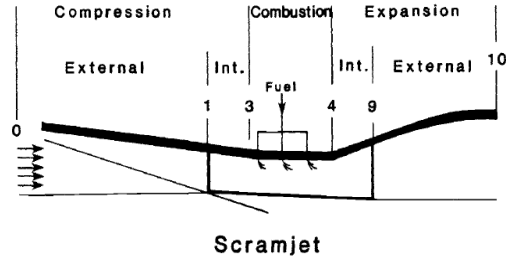
Propulsion

Dual-mode ram-scrumjet

The dual-mode ram-scrumjet 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_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 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_{Lmax} .

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 <i>q</i> 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

$$C_{L_{\max}} = 0.50 \text{ (FDL-7)}^{[11]}$$

Hyfac database, MAC circa 1970^[3]

Spatular corrections from Pike

Structure and thermal protection

Structural shape factor K_{str} from MAC^[6]

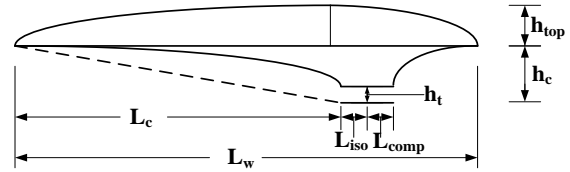
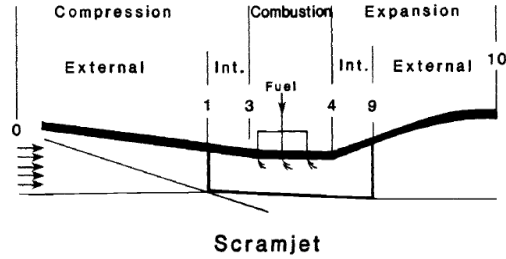
Propulsion

Dual-mode ram-scrumjet

The dual-mode ram-scrumjet 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_l | 0.95 |
| η_b | 0.90 |
| $\left(\frac{C_f A_w}{2 A_3}\right)_c$ | 0.01 |
| $\left(\frac{C_f A_w}{A_3}\right)_b$ | 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_{Lmax} .

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 |
| | <i>T/W</i> rocket | TW_TJ_MAX | 0 |
| | <i>T/W</i> scramjet | TW_SC_MAX | 0.94606 |
| | Wing loading | WS | 234.5592 |

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