Technology and operational sensitivity assessment for hypersonic endurance flight vehicles

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ABSTRACT

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 authors have explored the technical and operational solution space for a 30 minute cruise endurance demonstrator operating in the Mach 6 to Mach 8 speed regime. The focus of this activity has been on exploration of the available solution space through a unique screening process to assess the implication and interplay between the (a) mission, (b) baseline vehicle, and (c) operational scenarios. This study concludes that an air-launched, liquid hydrogen fuelled, 30 minute duration Mach 6 demonstrator (with 10 min Mach 8 capability) provides the largest feasible solution space of the trades examined (i.e. largest design margins, lowest technical risk) when compared to a kerosene-powered equivalent.

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NOMENCLATURE

SYMBOLS

b	span (m)
c	chord (m)
$C_{m\alpha}$	variation of aircraft pitching moment coefficient with angle-of-attack
$C_{n\beta}$	variation of aircraft yawing moment coefficient with angle-of-sideslip
D	drag (kN)
ff	fuel fraction (–)
g	acceleration due to gravity (m/s^2)
h	vehicle height, z-direction (m)
I_{sp}	specific impulse (s)
I_{str}	structural index, ratio of structural weight to wetted area (kg/m^2)
l	vehicle length, x-direction (m)
L	lift (kN)
L/D	lift to drag ratio (–)
M	Mach number (–)
MLW	Maximum Landing Weight (kg)
N_{rkt}	number of rocket motors (kN)
OEW	Operating Empty Weight (kg)
OWE	Operating Weight Empty (kg)
OWE_w	Operating Weight Empty from weight budget (kg)
OWE_v	Operating Weight Empty from volume budget (kg)
S	reference area (m^2)
S_{pln}	planform area (m^2)
S_{wet}	wetted area (m^2)
T	thrust (kN)
T/W	thrust to weight ratio (–)
t_{cruise}	cruise endurance time (min)
TOGW	Take-Off Gross Weight (kg)
T_{rkt}	total thrust from rocket motor (kN)
V_{ppl}	propellant volume (m^3)
V_{prop}	propulsion system volume (m^3)
V_{sys}	systems volume (m^3)
V_{total}	total volume (m^3)
V_{void}	void volume (m^3)
W	weight (kN)
W/S	wing loading (kg/m^2)
W_{margin}	weight margin (kg)
W_{ppl}	propellant weight (kg)
W_{prop}	propulsion system weight (kg)
W_{str}	structural weight (kg)
W_{sys}	systems weight (kg)

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GREEK SYMBOLS

τ	Küchemann slenderness parameter

ACRONYMS

AVD	Aerospace Vehicle Design Laboratory
AVDS	Aerospace Vehicle Design Synthesis
c.g.	Centre of Gravity
CL	Configuration Layout
CE	Configuration Evaluation
CG	Centre of Gravity
CTO	Chief Technology Officer
DB	Data-Base
DBS	Data-Base System
DMRJ	Dual-Mode Ram Jet (Cruise Engine)
FDL	Flight Dynamics Laboratory
FWC	Flying-Wing Configuration
HL	Horizontal Landing
HSCT	High-Speed Commercial Transport
HTO	Horizontal Take-Off
HyFAC	Hypersonic Facilities Study, See Ref. 4
KB	Knowledge-Base
KBS	Knowledge-Base System
LaRC	Langley Research Centre
Li-AL	Lithium-Aluminum Alloy
M	Managerial
MAC	McDonnell Aircraft Corporation
MDA	Multi-Disciplinary Analysis Methodology
MSTC	Multiple-Stage-To-Cruise
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NIA	National Institute of Aerospace
OWC	Oblique-Wing Configuration
PDE	Pulse Detonation Engine
PP	Parametric Process
PS	Parametric Sizing
RBCC	Rocket-Based Combined Cycle
R&D	Research and Development
RJ	Ram Jet
RKT	Rocket
S	Synthesis
SEP	Société Européenne de Propulsion
SiC/SiCMMC	Silicon Carbide/Silicon Carbide Metal Matrix Composite
SJ	Scram Jet
SSTC	Single-Stage-To-Cruise
T	Technology
TAC	Tail-Aft Configuration
TFC	Tail-First Configuration

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TJ	Turbo Jet
TO	Take-Off
TPS	Thermal Protection System
TSC	Three-Surface Configuration
TSTC	Two-Stage-To-Cruise
TSTO	Two-Stage-To-Orbit
VAB	Vehicle Analysis Branch (NASA LaRC)
VTO	Vertical Take-Off

1.0 INTRODUCTION

The research activity *Technology and Operational Sensitivity Assessment for Hypersonic Endurance Flight Vehicles* has been an effort to forecast the technology and industry capability required for a revolutionary step change in endurance time for hypersonic flight. To this end, a dedicated knowledge-harvesting (data-base and knowledge-base) approach coupled with a unique parametric analysis process has been implemented to identify and visualise the highly multi-disciplinary solution space available for a hypersonic endurance (30 min) demonstrator that employs an air-breathing propulsion system. The combined data-base, knowledge-base, and parametric process system (DB-KB-PP) establishes a best-practice product development and technology forecasting environment that integrates the key development team members, including the (1) CTO (decision maker), (2) synthesis specialist (integrator), and (3) technologist (disciplinary researcher).

The primary challenge has been to identify the multi-disciplinary mission versus flight vehicle solution space for the industry capability currently available, that might require future technology complementation. Having gained parametric insights related to the required versus the available solution space topography, it then can be determined under what conditions a practical hypersonic research testbed (research objectives, research and development time-frame, technology investment) can become a productive research instrument. Consequently, this study necessitates the use of a simulation capability able to assess and visualise the physical design drivers and sensitivities representing the coupled domains operation (mission) and design (flight vehicle).

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

2.0 MISSION REQUIREMENTS AND RESEARCH OBJECTIVES

The overall objective of this study has been to explore and visualise the technical solution space for a hypersonic endurance demonstrator. To accurately represent this type of vehicle, an array of technology and mission requirements have been assumed, see Table 1.

The broad direction specified with Table 1 translates into a large n-dimensional design trade space. Please note that the design mission outlined 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 identify feasible combinations of flight vehicle and mission scenarios. Clearly, the parametric sizing exposure will iteratively enable the designer to learn, to define and to justify a feasible baseline mission and baseline vehicle combination, see Fig. 1.

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Table 1
Vehicle technology and mission requirements

Technology Requirements		Mission Requirements	
Primary Technology Goal	Scramjet Testbed	*Design Speed*	Mach 6 to 8
Reusability	Reusable	*Max Endurance*	30 Minutes
Crew	Unmanned	*Payload*	Test Instrumentation
Number of Vehicles	Minimum 3	*Fuel Selection*	Hydrogen or Kerosene
Entry into Service	Circa 2020	*Operation*	Straight-Line or Point-to-Point

Figure 1 illustrates the iterative nature of the mission and baseline vehicle selection process. The unknown-terrain of a 30 mins air-breathing demonstrator requires a modification of the traditionally utilised product development procedures, see Refs 1, 2 and 6. The best-practice AVD Laboratory screening and sizing methodology and software AVDS (Aerospace Vehicle Design Synthesis) has been the primary tool utilised to arrive at the (a) baseline mission which harmonises with (b) the baseline vehicle.

Throughout the mission-vehicle sizing phase, the sizing team actively involved key customer personnel (NASA LaRC, NIA) consisting of the three primary mindsets managerial (M), synthesis (S), and technology (T). This approach enabled to successively gain physical insights into the multi-faceted characteristic of the product. Consequently, true product understanding has been evolving whilst perturbing the parametric product solution space. Note that the mission-vehicle trading has to happen, in general, during the early parametric sizing (PS) phase, representing the essential task before a baseline objectives catalogue can be formally defined. Clearly, the traditional notion of pre-defining the mission is not feasible with a product of such novel characteristics. The screening and sizing approach becomes the enabling means to arrive at a balanced set of (a) mission requirements, and (b) baseline vehicle(s).

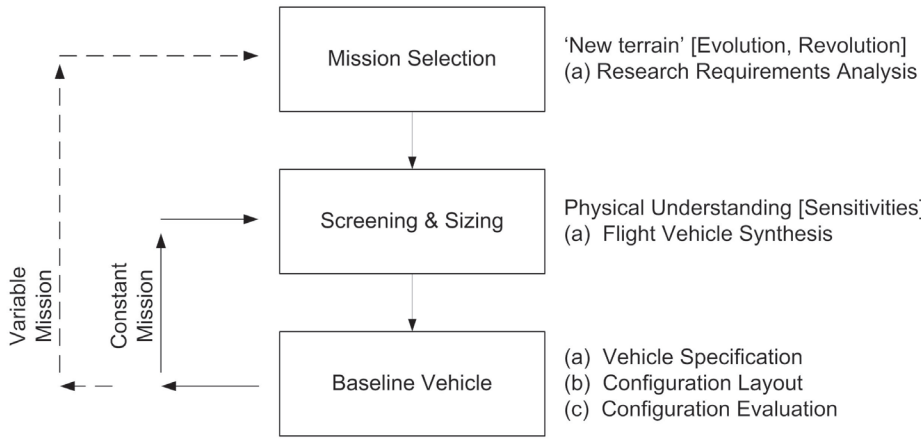


Figure 1. Iterative nature of mission and screening and baseline vehicle(s) selection process[1].

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3.0 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 adopted 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 synchronise 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 research timeframe allocated for the present activity, 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 an opportunity to evaluate past and present data, information and knowledge for its utilisation in the context of a technically demanding hypersonic demonstrator with not seen-before performance capability. Table 2 documents past-to-present high-speed test vehicle projects and programs, an experience base of relevance towards a modern hypersonic endurance testbed.

The following two sections introduce the dedicated high-speed flight vehicle sizing and conceptual design data-base (DB) and knowledge-base (KB) developed by the AVD Laboratory

Table 2
Past hypersonic demonstrator projects and programs

Start Date	End Date	Project/Program	Organization	Description
1952	1968	X-15	North American/NASA/USAF	Mach 6 to 8 rocket powered hypersonic research vehicle. 3 test vehicles, 199 flights
1957	1959	Griffon 02	Nord Aviation	manned ramjet demonstrator
1962	1971	D-21	Lockheed	Mach 4 ram-jet UAV launched from the SR-71
1964	1965	MHCV	Lockheed	*Manned Hypersonic Cruise Vehicle*, some description of a demonstrator
1967	1968	UHTV	Vought	*Universal Hypersonic Test Vehicle*, flexible and modular hypersonic test vehicle
1967	1969	X-15 Delta	North American/NASA	delta wing X-15
1969	1970	HYFAC	MAC/NASA	*HYpersonic FACilities* study, 32 rocket/air-breather configurations explored
1969	-	X-15 SERJ	Marquardt	*Super Charged Ejector RamJet* X-15
1969	-	X-15 Scram	Boeing	Scramjet X-15
1970	1972	IGV	MAC/USAF	*Incremental Growth Vehicle*
1972	-	PPD Scramjet Test Vehicle		*Propulsion Performance Demonstrator*, vertical take-off cone with four scramjets around its periphery; rocket acceleration to test speed
1975	1977	X-24C NHFRF	Lockheed/NASA	*National Hypersonic Flight Research Facility*, B-52 launched, Mach 4.8 70,000 lbs vehicle; envisioned as a X-15 type flight operation
1976	-	ASLAM	Martin	hydrocarbon fuel air-launched cruise missile
1981	-	SLRV	NASA	*Shuttle Launched Research Vehicle*, Mach 8 aerodynamic configuration demonstrator
1985	-	RSFTP	ONR/DARPA	*Ramjet/Scramjet Flight Test Program*, M 4-7 F-15 launched vehicle
1989		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		SSTO Demonstrator	Hyper Tec	RBCC hypersonic demonstrators based on HYFAC Studies
1999	-	Trailblazer	NASA Glen	modification of the NASA wing body to include RBCC and TBCC
2000	-	X-43B	NASA LaRC/NASA Dryden	reusable combined cycle demonstrator
2001	-	X-43C	NASA LaRC/NASA Dryden	hydrocarbon variant of the X-43A, RJ/SJ
2002	-	HYFLY	Boeing/DARPA	Mach 6 ramjet powered cruise missile demonstrator
2003	-	X-51A	Boeing	scramjet propulsion research vehicle
2005	-	X-43D	NASA LaRC/NASA Dryden	HYFLITE III, M 12 variant of the X-43A
2007	-	HyCAUSE	DARPA/ADST	2-stage sounding rocket for hypersonic propulsion demonstration
2009	-	Falcon HTV-3X	Lockheed/DARPA	TBCC hydrocarbon hypersonic demonstrator

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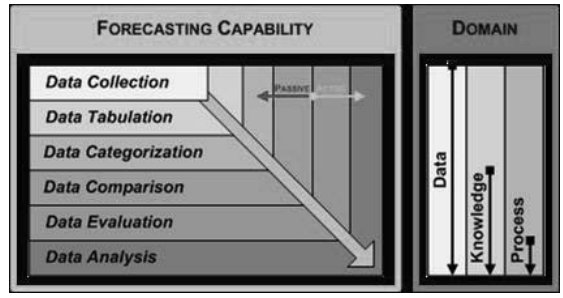


Figure 2. Dedicated AVD Laboratory Flight Vehicle DB and organization scheme.

over more than two decades and its adaptation for the present research undertaking. The primary flight vehicle research and design work has been directly benefitting from this rich and organised DB and KB foundation.

3.1 Hypersonic flight vehicle Data-Base (DB)

The first step in efficiently utilising existing high-speed aircraft design knowledge has been a systematic literature survey, which in itself has been an ongoing effort throughout the current research period. Source for accessing normal and radical design data, information and knowledge has 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 utilised, see Fig. 2. This DB-software handles disciplinary and inter-disciplinary literature relevant for conceptual design (methodologies, flight mechanics, aerodynamics, etc.), interview-protocols, flight vehicle case study data and information (descriptive-, historical-, numerical information on conventional and unconventional flight vehicle configurations), simulation and flight test information, etc. The top-level requirement for the utilisation of the hypersonic flight vehicle DB has been simplicity in construction, maintenance, and operation, to comply with the time constraints usually dictated by industry-typical sizing and conceptual design studies.

A detailed description of the DB is beyond the scope of the present discussion; for more information see Ref. 2. The flight vehicle design DB 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 utilising design data and information has been opened up by proceeding as follows:

- availability of a *reference list* containing meaningful entries (DB)
- availability of these references as a *hardcopy* on the table (DB)
- utilisation of time to *absorb* the data and information (DB)
- *review, select, classify, subtract, and document* the data and information provided (DB)
- *extraction, combination and utilisation* of data and 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

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design data and information. The research goal, to develop an air-breathing hypersonic demonstrator, requires accounting for as many design-related interactions as necessary due to the geometrically highly blended nature of hypersonic flight vehicles. The aircraft design disciplines identified relevant and the representative case studies of design ingenuity selected, see Table 2, 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. The following four DB sections have been updated and utilised for the current study: (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).

The knowledge-base (KB) step five has been organised outside the DB. Clearly, it is the process of knowledge extraction, knowledge compilation, and the generation of parametric knowledge guidelines into an organised and concise format available 'at the fingertips' for problem solving activities. For this purpose, a simplified knowledge-base (KB) has been utilised as detailed in the following sub-chapter.

3.2 Hypersonic flight vehicle Knowledge-Base (KB)

The dedicated aircraft conceptual design knowledge-base (KB), as advanced and utilised for the present research undertaking, has to be considered an early development-version of a fully integrated design knowledge-based system (KBS). Without reiterating the capability of exemplary KBSs, the KB system utilised here is a 'manual' system in contrast to the 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 recognised as being one of the most problematic areas of KB and KBS development. Clearly, it is the knowledge collecting, knowledge management and knowledge utilisation 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 flight vehicle conceptual design KB has been, to make relevant past-to-present normal and radical design knowledge effortlessly available. The particular strength of the system manifests in that it enables the user to advance the understanding in a highly focused thus accelerated mode with respect to the variety of high-speed aircraft and launch vehicle configurations by identifying flight vehicle configuration commonalties and peculiarities. This feature has been empowered by placing particular emphasis on consistently grouped flight vehicle configuration-specific design knowledge. As a result, vehicle sizing and conceptual design aspects, like for example longitudinal stability, can be compared for the range of flight vehicle 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 and (b) lateral/directional motion. Each motion is subdivided into:

- Flight Character: design constraining flight conditions: trim, control, stability, etc.
- Aerodynamic Character: stability and control derivatives, etc.
- Flow Character: flow phenomena: tuck, pitch-up, non-linearity, etc.
- Additional Grounds: landing gear location, geometry limitations, c.g. range, etc.

Figure 3 overviews the lessons-learned section as described above. These sections clearly emphasise physical understanding and design related decision-making for relevant high-speed flight vehicle case studies of conventional and unconventional configuration, see Ref. 3.

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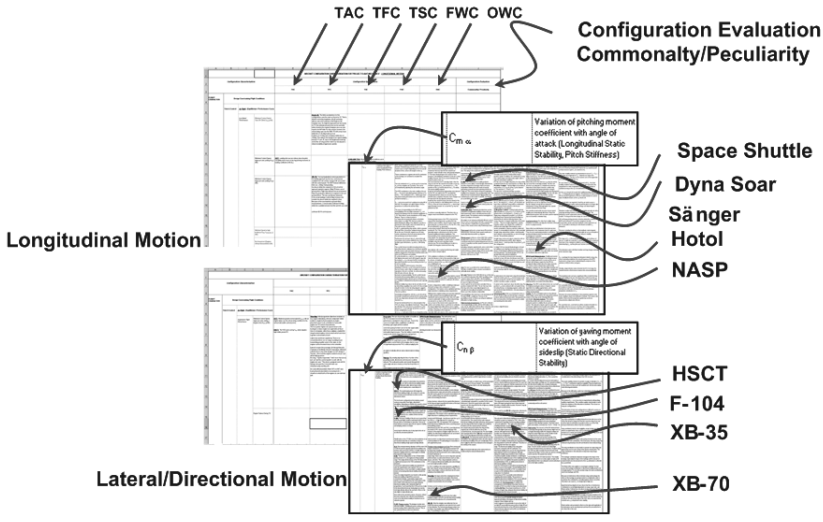


Figure 3. Design lessons-learned of selected flight vehicle design case-studies.

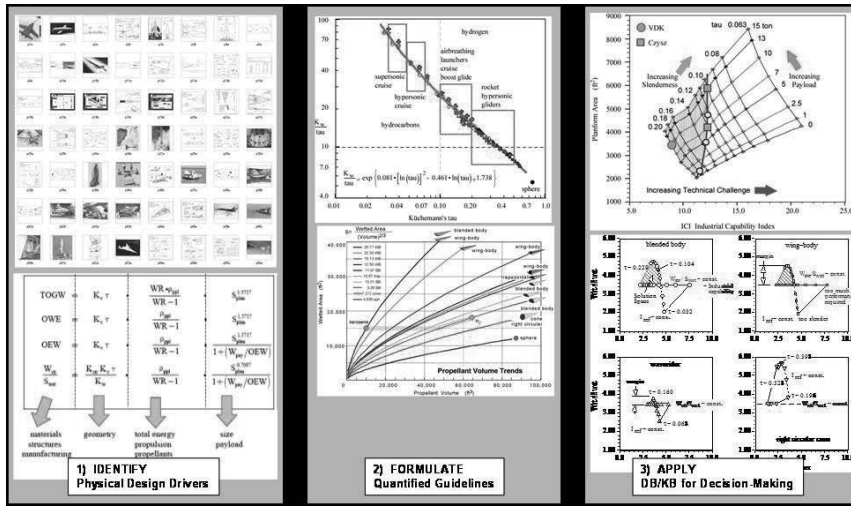


Figure 4. KB development steps resulting in numerical knowledge design guidelines.

Figure 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 the correct continuum of the pertinent design characteristic in contrast to the narrow exposure of typical point-design characteristics. Overall, the 'living-character' of both, the DB and KB, is ensured by permitting unconstrained data and knowledge entries as gained during the iterative design life-cycle, see Fig. 1.

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Table 3
Top-level trade-space concepts and configurations, categories and options

Concept/Configuration	Categories	Total Trade Options	Selected Trades
Mission Concept	Mach Number and Duration	design Mach 6	design Mach 6
		design Mach 8	design Mach 8
		design Mach 12	
		test duration	0 – 30 min
	Test Range Options	point-to-point	point-to-point
		fly-back	fly-back
Staging Configuration	SSTC	integrated booster, propellant and oxidizer tanks	
	TSTC	air launch	air launch
		expendable booster	expendable booster
		oxidizer drop tanks	
	MSTC	any combination of TSTC	
Operations Concept	Launch	horizontal TO	
		vertical TO	
	Recovery	HL	
Hardware Concept	Lift & Volume Supply	lifting body	lifting body
		wing body	
	Propulsion Concept: (Accelerator Engine)	RKT	RKT
		TJ	
		RBCC	
		PDE	
	Propulsion Concept: (Cruise Engine)	SJ	
		dual mode RJ/SJ	dual mode RJ/SJ
		RKT	
	Fuel Selection	hydrogen	hydrogen
		methane	
		kerosene	kerosene
	Primary & Secondary Controls	aerodynamic	
		mix	mix

4.0 OVERALL TRADE SPACE AND PROJECT-FOCUS REDUCED TRADE SPACE

The challenge of designing a 30 minute hypersonic endurance demonstrator is embodied in the fundamentally unknown vehicle solution space and solution topography. Based on the best hypersonic testbed DB/KB understanding available at the outset, it is required to define an initial or 'start' trade-space by taking relevant constraints and requirements into account, see Table 3.

It has been anticipated from the outset that the initially comprehensive trade-space, with associated constraints and requirements, will naturally mature thus reduce during the configuration exploration phase. The initial configuration exploration phase is responsible to correctly identify the two primary solution-space topographies of significance: (a) the required and available solution space area based on presently available industry capability, and (b) the expanded required and available solution space area requiring prospective future technologies. Dependent on the establishment of overall project objectives (performance requirements, research objectives, operational robustness, low-cost and risk demonstrator, etc.), the physical understanding generated throughout the initial solution-space exploration phase directly contributes towards the refinement of the initial trade-space scope.

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Clearly, key is the early identification of the correct trade-space and anticipated technology combinations complementing the industry capability available. In order to accomplish such, the industry best-practice generic and parametric flight vehicle sizing methodology AVDS has been employed to numerically explore the multi-disciplinary solution space topographies from which a feasible baseline design will be selected in a follow-on step. The utilisation of the combined DB, KB and parametric design synthesis methodology AVDS does provide such insights within the time assigned.

The process of rectifying thus reducing the theoretical trade-space available and required 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 and technology alternatives. (c) Harmonise pre-selected trades with the customer's (NASA VAB) research objectives.

Table 3 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 would be executed, the total number of trades would exceed 90,000 cases.

Applying the DB and KB lessons-learned and further harmonising the research objects with the customer NASA VAB, these activities further reduced and focused the trade-space as follows:

- ***Mission Concepts***: Mach 6 and Mach 8 design trades are given priority; point to point and fly-back options are explored. The Mach 12 design trades have been eliminated due to excessive technology requirements and flight vehicle design implications.
- ***Staging Configurations and Operational Concepts***: The HyFAC study, see Ref. 4, 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 only.
- ***Hardware Concepts***: Alternative vehicle concepts have been grouped as follows:
  - ***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, see Refs 4, 5, and 6.
  - ***Off-the-Shelf Accelerator Rocket***: the off-the-shelf rocket motor (low risk item) is selected to accelerate the ramjet to start Mach number.
  - ***Dual-Mode Ramjet Cruise Engine***: the dual mode ramjet (DMRJ) is a scramjet engine that has been selected to allow for testing of both modes (ramjet and scramjet) with a single vehicle.
  - ***Fuel selection limited to liquid hydrogen and kerosene:*** the fuel selection is determined by the operational vehicle envisioned. For prospective reusable TSTC launch vehicles, hydrogen is the most likely choice. Kerosene appears to be an operationally practical option for a military hypersonic point-to-point vehicle. Consequently, both fuel options (hydrogen and kerosene) are explored throughout the trade volume.

The above reasoning is logically reducing the overall trade-space, as introduced with Table 3, to ten primary trade studies, each consisting of a constant test vehicle concept (lifting body, dual mode ramjet/scramjet, horizontal landing) with varying (a) design Mach number, (b) endurance, (c) launch concept, and (d) fuel choice. The reduced trade-space resulting into ten distinct sizing studies is introduced with Table 4 and Fig. 5.

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Table 4
Summary of design trades executed

	Mission				Staging Configuration		Operations Concept		Hardware Concept		
	Atmospheric			*Test Range Options*	*TSTC*		*Launch*		*Fuel Selection*		
trade #	design Mach 6	design Mach 8	test duration	point-to-point	air launch	expendable booster	HTO	VTO	hydrogen	kerosene	dual fuel
1	x		0 - 30 min	x	x		x		x		
2		x	0 - 30 min	x	x		x		x		
3	x		0 - 30 min	x	x		x			x	
4		x	0 - 30 min	x	x		x			x	
5	x		0 - 30 min	x	x		x				x
6		x	0 - 30 min	x	x		x				x
7	x		0 - 30 min	x		x		x	x		
8		x	0 - 30 min	x		x		x	x		
9	x		0 - 30 min	x		x		x		x	
10		x	0 - 30 min	x		x		x		x	

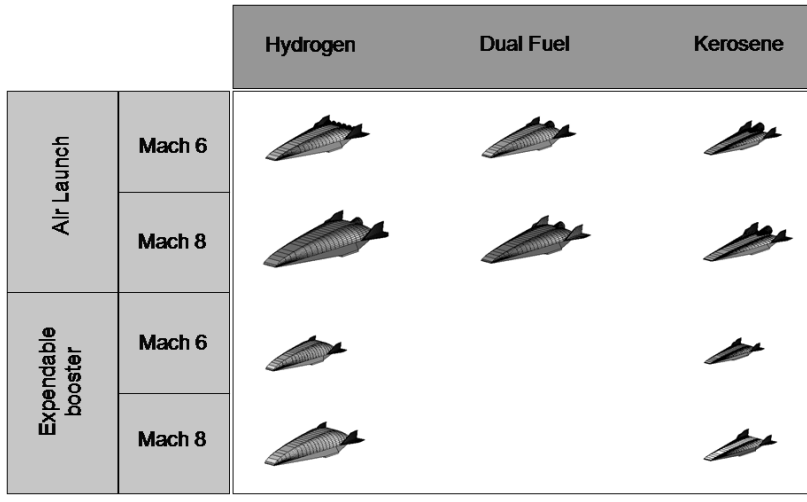


Figure 5. Reduced trade-space converged flight vehicles comparison.

5.0 PARAMETRIC SIZING AND SOLUTION SPACE SCREENING

For each of the ten individual trade studies, design sweeps result in families of converged flight vehicles which identify the total flight vehicle system design solution space which is visualised accordingly. The AVD Laboratory parametric sizing program AVD^{sizing} is a 'best practice' sizing approach that has been developed over a decade through a thorough review of parametric sizing processes and methods from the 1960s to the present-day for subsonic to hypersonic and reusable space access vehicles, see Refs 6 and 7. With this framework in place, the available solution space is identified considering both technical and operational constraints.

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5.1 AVD Sizing process summary

AVD^{sizing} is a constant mission sizing process capable of first-order or 'highest-in-importance' solution space screening of a wide variety of conventional and unconventional vehicle configurations. Solution space screening implies the tasks of identification and visualisation of design interactions and trends of converged thus feasible total flight vehicles.

This screening activity is conducted with the multi-disciplinary parametric design synthesis methodology AVD^{sizing} which 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 Refs 4 and 8. 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 Refs 9 and 10. 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. Fig. 6 visualises the top level sizing process implemented.

At the heart of the process is the weight and balance budget. The results from the geometry, performance constraint and trajectory modules (weight ratio, required *T/W* ratio, and vehicle geometry) are provided to a weight and 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 and volume available equal weight and volume required.

5.2 Description of solution space visualisation

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

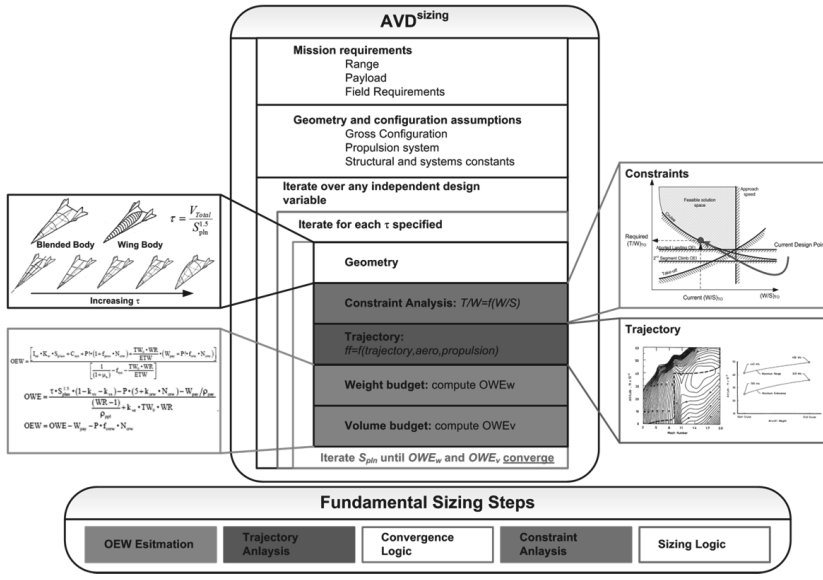


Figure 6. AVD^{sizing} methodology visualized via Nassi-Schneidermann structogram.

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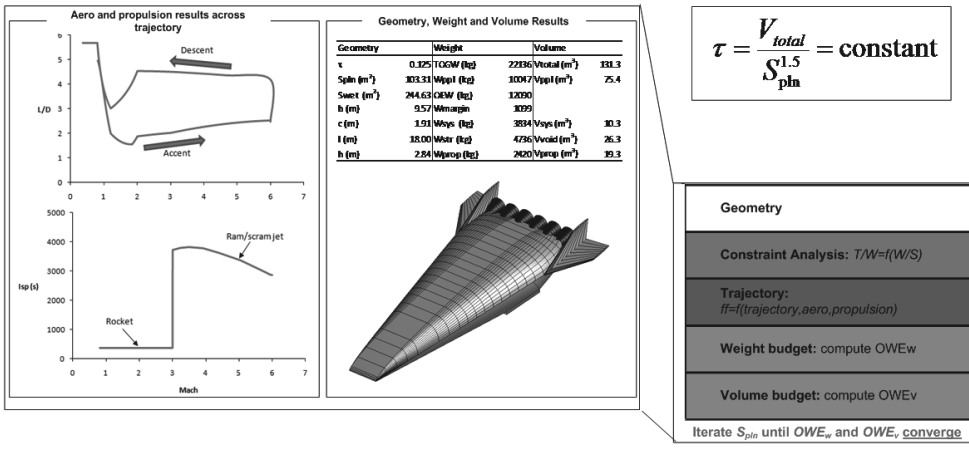


Figure 7. Each design point represents a converged complete hypersonic vehicle.

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 Fig. 7.

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 Fig. 8. The structural index, I_{str}, is a metric of the structural efficiency of the concept, and is defined as structural weight per unit wetted area. This parameter will be further discussed when addressing the description of the solution space constraints.

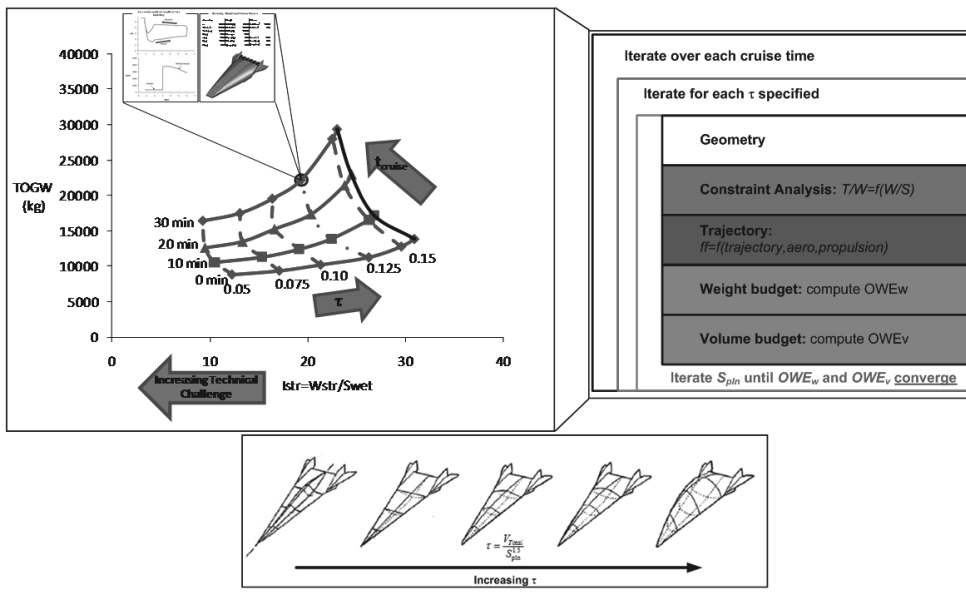


Figure 8. Solution space plot of TOGW and I_{str} for varying vehicle slenderness and cruise time.

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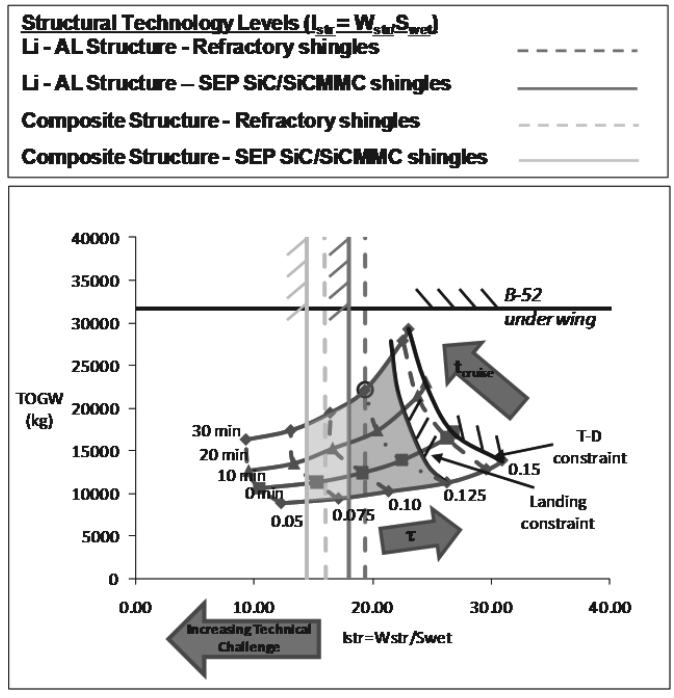


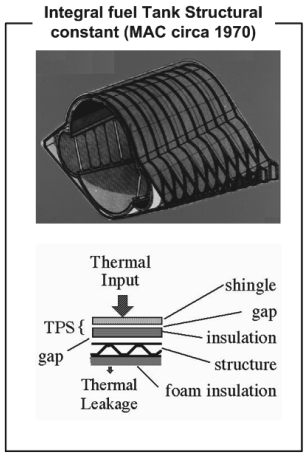
Figure 9. Landing and *T-D* constraints imposed on the solution space. For the Mach 6 demonstrator, the landing constraint is more constraining than *T-D*. Superposition of structural indices provides the final constraint to determine the technical solution space.

5.3 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 Fig. 9. 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 Fig. 9. In addition, the figure shows 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. Figure 10 documents the structural indices utilised to derive the technology solution space boundaries pertinent to the flight mission.

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-launch carrier vehicle are the B747-100SCA and B-52H; both

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Break-down of industrial capability index

Integral Hydrogen Fuel tank

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

Integral Kerosene fuel tank

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

Figure 10. Definition of structural capability indices used for this study[8].

options have been explored as possibilities. The B-52H employs an under wing mount constrained by: (a) the maximum load of the pylon, and (b) the geometric boundaries between the fuselage and inboard engine, the test vehicle wing and engine exhaust plum. The X-24C was intended to be the largest vehicle to possibly fit under the B-52H wing mount. Therefore, the X-24C's TOGW, length and width represent a guide for the maximum capability of the B-52H air-launcher for this investigation, see Fig. 11.

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 Fig. 12(a).

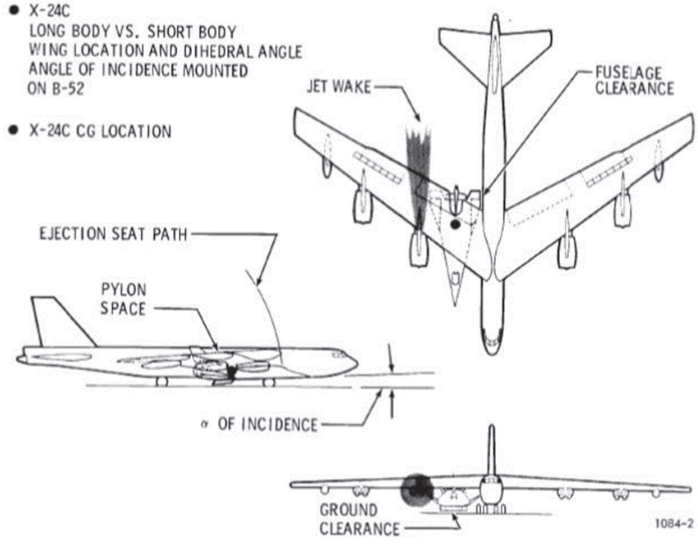


Figure 11. B-52H under-wing mount geometric constraints[11].

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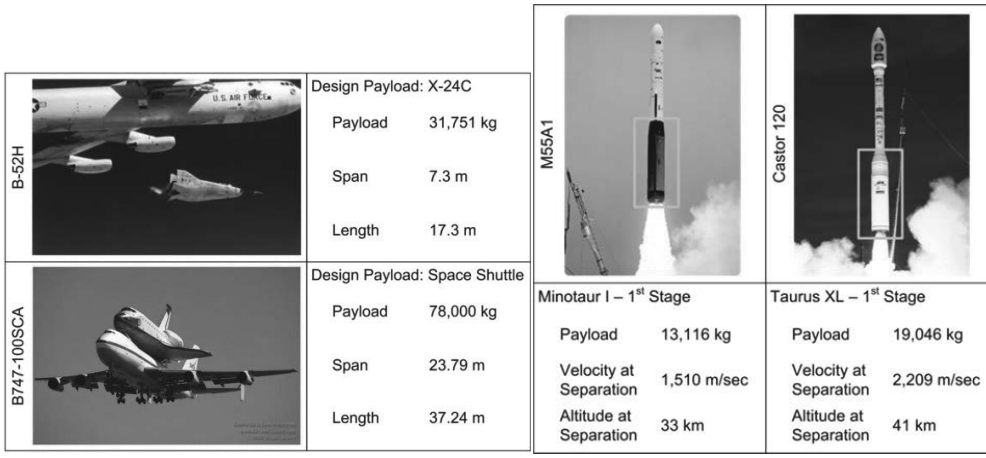


Figure 12. Summary of constraints: (a) B747-SCA and B-52H[11,12]; (b) Minotaur I and Taurus XL 1st stage[13].

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 Fig. 12(b). 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.

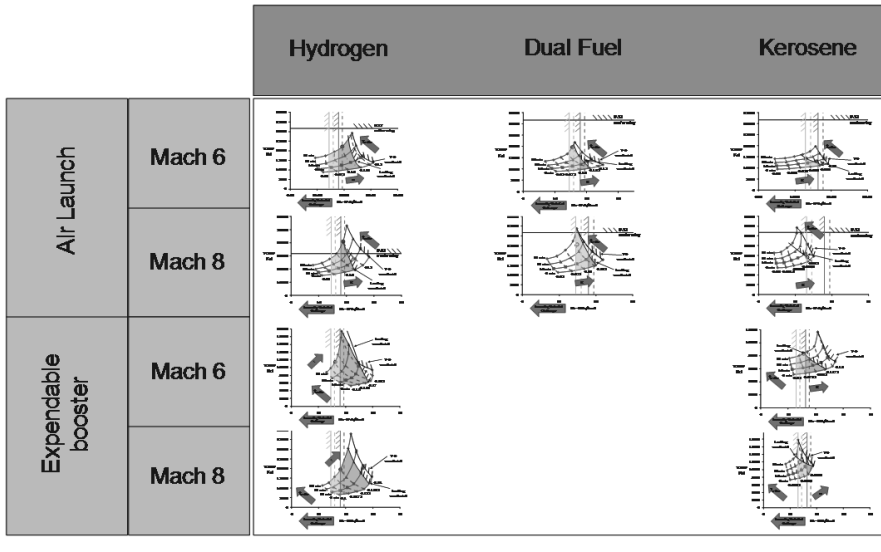


Figure 13. Relative comparison of solution spaces for each design trade explored.

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5.3 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 visualised relative to each other with Fig. 13.

For each trade, the cruise time will be increased from 0 min to 30 min in increments of 10 min while vehicle slenderness is varied, generating the distinct solution space carpet plot. Since Fig. 13 compares discrete flight vehicle types (launch method, Mach number, fuel), note that the ten identified and visualised 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.

6.0 SOLUTION SPACE COMPARISON AND BASELINE FLIGHT VEHICLE 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 industry capability. Required technology development efforts would primarily focus on scramjet engine requirements for a (a) hydrogen-based, and/or a (b) 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

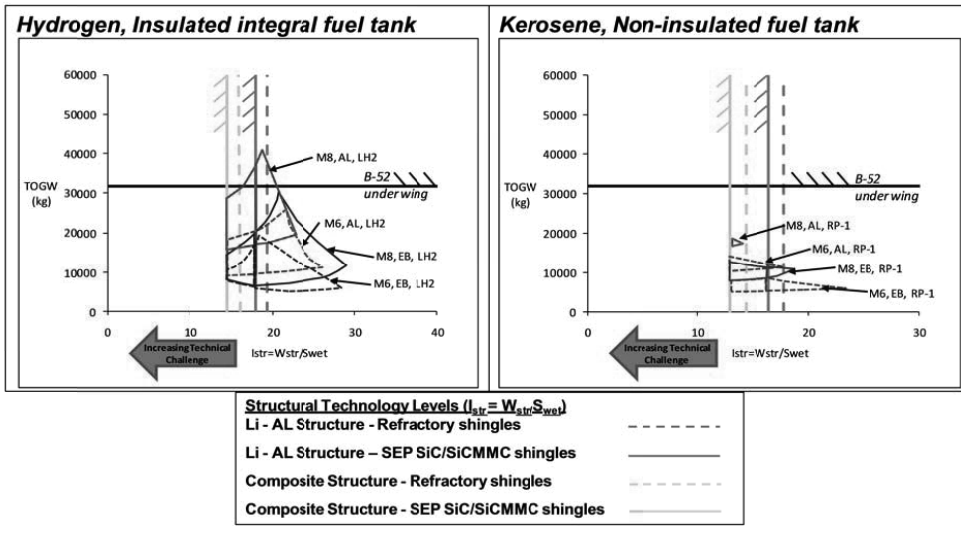


Figure 14. Hydrogen-fuelled and kerosene-fueled vehicles solution space comparison.

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been demonstrated. Clearly, parametric sizing utilises the first principles or 'highest-in-importance' mindset and tools to answer how changes within the mission, operational scenario and overall research objectives thus technology influence the design 'hardware' requirements, thus the decision-making process. The recommendations and conclusions of the solution space trade analysis follow.

6.1 Solution space screening

6.1.1 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 Fig. 14. Comparing kerosene vehicles relative to hydrogen vehicles, the kerosene designs show larger sensitivity to landing constraints due to increased vehicle density (which increases wing loading) and the requirement for a lighter structure to compensate for reduced fuel I_{sp} values. Comparing hydrogen vehicles relative to kerosene vehicles, the trade-off between fuel weight density and energy density characteristics yields a higher total system benefit for hydrogen.

6.1.2 Mission-level summary

In order to explore the hypersonic design relationships at mission level, Fig. 14 compares 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 centres 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 that each 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 mins cruise mission. For the kerosene-based demonstrators, only the M = 6 Expendable Booster trade offers a feasible 30 mins endurance solution. The remaining trades do not present feasible solutions for the 30 mins 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.

6.2 Design point comparison

The following discussion reviews the converged baseline vehicle design points selected from the hypersonic flight vehicle design solution space screening activity. For more information regarding the demonstrator selection for individual hydrogen- and kerosene-fuel trades, please refer to the earlier sections. Referring back to Fig. 5, when eliminating the dual-fuel options, the figure presents the short-list overview of prospective baseline vehicle configuration-, speed- and fuel combinations. Table 5 and Table 6 are summarising the general 'parametric' design characteristics for the feasible baseline vehicle options utilising either hydrogen or kerosene fuel.

6.3 Baseline vehicle election

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

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Table 5
Design Characteristics for Hydrogen-Based Suggested Vehicle Selection

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

Table 6
Design Characteristics for Kerosene-Based Suggested Vehicle Selection

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

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:

- *Versatility*: Which vehicle represents the largest flexibility of its operational capability?
- *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?
- *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?
- *Limitations*: Which vehicle has any perceived limitations that would hinder development?

If hydrogen scramjet testing is required:
Observing that the Mach 6, 30 mins vehicle can perform the Mach 8 mission for 10 mins, this scenario provides a compromise which allows for both, the endurance and speed requirements to be accomplished at a lower risk option compared to the Mach 8, 30 mins vehicle. Assuming that the technology level permits this, 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:
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 mins vehicle as the only viable technical option for the kerosene scramjets. Furthermore, it is important to note that the Mach 6, 30 mins solution overlays with the Mach 8, 0 mins cruise time solution. Based on information stemming from the DB, KB and the constraints adopted, it is assumed that the Mach 6, 30 mins research vehicle can accelerate to Mach 8, but it will not have sufficient fuel for 30 mins but instead 10 mins cruise endurance.

6.4 Recommendations for the CTO

Beyond the two primary recommendations communicated (suggested baseline vehicles), there are decisions that cannot be made solely based on technical feasibility. For this study, two such factors are fuel choice (hydrogen or kerosene) and launch arrangement (air-launch or vertical take-off). To this end, several design lessons have been learned and translated in an effort to aid the CTO (decision maker) in making informed decisions.

6.4.1 Fuel choice

Hydrogen fuel allows for a larger technical solution space relative to the kerosene option. The increased size of the feasible solution space translates into a design with comparatively less risk. That being said, both hydrogen and kerosene provide technically feasible solutions. The dual fuel option marginally decreases the vehicle size, relative to the 30 min hydrogen variant. The cost associated with the added complexity of storing two fuels onboard outweighs its performance benefit. This option does not buy itself onto the vehicle. As such, the selection of scramjet fuel (hydrogen or kerosene) is not driven by technical feasibility of the demonstrator testbed alone, but also by requirements specified by the operational aircraft. An analysis of perspective customers and funding agencies should be employed to decide which fuel choice should be chosen.

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6.4.2 Launch arrangement

Air-launch from the B-52 is limited due to under-wing geometry (planform) constraints rather than under-wing load limitations. Landing constraints, driven by the abort mission, tend to constrain the solution space; thisleads to larger values of required planform area to meet this requirement (assuming equal high-lift system technology levels). If the landing constraint ($MLW = TOGW$) were to be relaxed, the size of the vehicle would decrease; this is at the expense of vehicle recoverability. If this constraint is retained, the B747-100SCA can be used to increase the feasible design space (larger geometric and weight capabilities). This comes at the expense the operability of the vehicle; there are two B747-100SCA vehicles in existence thereby constraining the anticipated flight rate of the demonstrator fleet. Off-the-shelf accelerator rocket motors are available for the vertical take-off launch arrangement, thereby reducing overall development program costs and initial program risks. This benefit is offset by the decreased availability of launch sites for the demonstrator. Launch arrangement should be based on flight rate requirement, take-off location, and associated operating cost.

The breadth and scope of the study has been a top-down view of the interplay between technology requirements and operational considerations aimed at the development of a hypersonic endurance demonstrator within a given timeframe. To this end, the solution space for this type of vehicle has been visualised from the perspective of the synthesis specialist (integrator), using the best available knowledge from the technologist (disciplinary researcher), and recommendations have been drawn to directly aid the CTO (decision maker).

7.0 CONCLUSION SUMMARY

A parametric sizing study has been performed to develop a program strategy (1) for research and development (RandD), and (2) for the procurement of a next-generation hypersonic air-breathing endurance demonstrator. The design process utilised emphasises three distinct steps (a) data-base, (b) knowledge-base, (c) parametric process. This sequence is the catalyst enabling the synthesis specialist to apply disciplinary data and knowledge in a truly multidisciplinary setting. In the context of the present research undertaking, the authors have utilised a unique parametric sizing (PS) tool to measure sensitivities and classical figures-of-merit for the CTO (decision maker), synthesis specialist (integrator), and technologist (disciplinary researcher). The systematic approach presented has applied screening and sizing to iteratively harmonise the relationships amongst: (a) mission selection, and (b) baseline vehicle(s) characterisation. The above outlined process arrives at a physics-based justification package able to characterise the suggested baseline hypersonic vehicle designs, as well as to provide rational recommendations for non-technically driven design decisions.

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