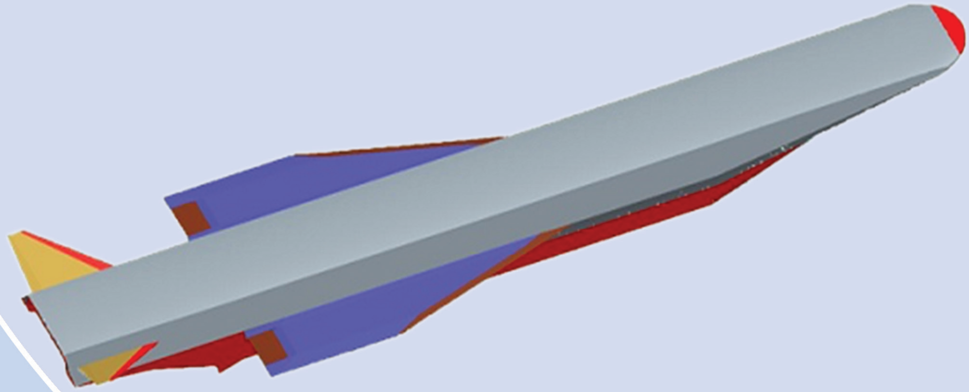

Rajaram Nagappa

Hypersonic Cruise Missiles
An Overview

National Institute of Advanced Studies
Bengaluru, India

Research Report NIAS/CSS/ISSSP/U/RR/23/2020)

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Hypersonic Cruise Missiles – an Overview

RAJARAM NAGAPPA*

Abstract

The recent flight test of the Hypersonic Technology Demonstrator Vehicle (HSTDV) by DRDO and the earlier flight test of the Advanced Technology Vehicle by ISRO has rekindled the interest in hypersonic technologies and their adaptation to practical systems in the Country. Indian interests in pursuing hypersonic technologies using both analytical and experimental approach have been around since the late 1980s. This article examines the background, the present development status including the features and outcome of HSTDV flight. The international scenario and some of the technology challenges scaling to a full fledged system are brought out.

Keywords: *Hypersonic, scramjet, Mach Number, AVATAR, CFD, TSTO, wind tunnel, thermal protection.*

INTRODUCTION

The successful flight test of DRDO's Hypersonic Technology Demonstrator Vehicle HSTDV on the morning of 07 September 2020 was extensively covered by the Indian media. The event was widely lauded and the DRDO feat was commended by the Prime Minister, Defence Minister and other important functionaries. The test is without doubt an important achievement and technological breakthrough. And the DRDO engineers and management fully deserve to be complimented. This is important as it is the first **autonomous** flight of a **scramjet** powered craft designed, developed and successfully tested by India. This paper provides an overview of hypersonic system status in the country and what further needs to be done.

HISTORICAL BACKGROUND

Diverse powerplants are available for jet powered flights and the choice depends on the speed regimes of interest. Based on this one may choose a single powerplant or a combination of powerplants based on the mission requirements. The powerplant operating regimes for hydrocarbon fuel including the overlaps is shown in figure-1.

Specific Impulse (I_{sp}) defined as the thrust produced per unit mass flow of the propellant is a figure of merit of the powerplant. Its unit – N.sec/kg in convenient engineering unit is expressed as seconds. In figure-1, all the power plants except the rocket use atmospheric air for producing thrust. The maximum operating

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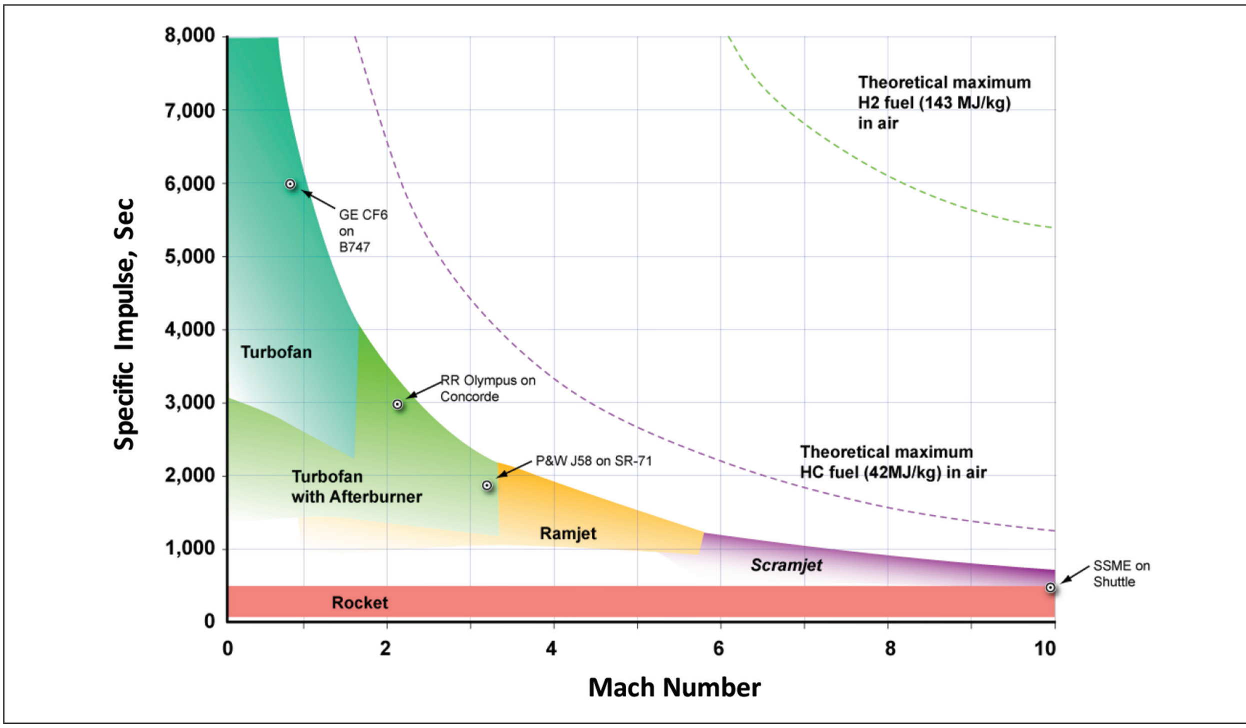

Figure 1: Powerplant operating range

(*Source: https://en.wikipedia.org/wiki/Scramjet*)

regime of the turbofan engine is Mach 3; ramjet is functional between Mach 2-5.5; and supersonic combustion ramjet or scramjet engine can function up to Mach 8-10. A rocket carries its own oxidiser and can perform outside the atmosphere and higher speed regime. For weapon delivery at supersonic and hypersonic speeds, ramjet and scramjet powered missiles are the preferred systems. However, these systems have to be boosted to the threshold of the operating Mach No. to initiate and sustain the ramjet/scramjet regime of flight.

As is evident from figure-1, a combination turbofan engine and ramjet/scramjet engine could power an aircraft for speedy long distance travel. Ramjet and scramjet designs are not new – Germany's Buzz Bomb used in the second World War was ramjet propelled. Some missiles of the 1950s and 1960s like the US developed Talos and Bomarc as well as the UK developed Bloodhound missiles were based on ramjet propulsion. The Indian surface to air missile Akash and supersonic cruise missile Brahmos employ ramjet propulsion. The 1960s period also saw the commencement of testing of Scramjet engines in the US and also in Russia. Antonio Ferri of the Guggenheim Aerospace Laboratory, New York was first to put forward the scramjet (supersonic combustion ramjet) concept in 1964. Since the late 1990s renewed interest in scramjets have surfaced resulting in experimental flights in Russia, France and US. Design speeds of Mach 5-7 were targeted and ground tests were able to confirm combustor performance. Around this time the development of ballistic missiles gained ground as efficient weapon delivery system and work on ramjets and scramjets took a back seat.

In the late 80s/early 90s interest in hypersonic propulsion again picked up – the interest was towards low cost access to space with emphasis on reusable systems using combined cycle schemes shown in figure-2.

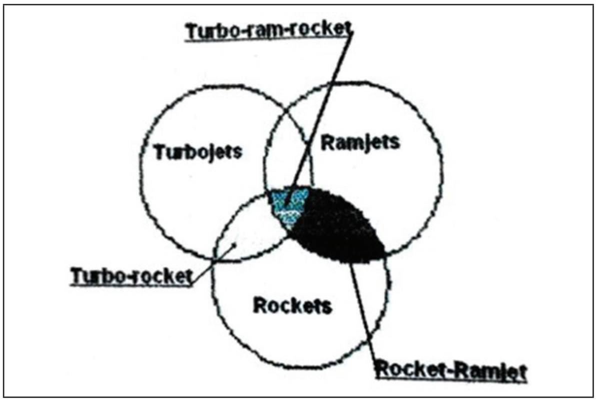

Figure 2: Combined propulsion concepts

The concepts were based on combination of gas turbine engines, ramjet/ramjet-scramjet followed by rocket propulsion to achieve orbit in single or two stage configurations. HOTOL in UK, Sanger in Germany and National Aerospace Plane (NASP) of the United States and Hyperplane of India were some of the contending designs which generated great interest and discussion. Conventional rocket based launch vehicles need to carry the oxidiser in sizeable quantities and this constitutes a significant percentage of the launch mass. The design philosophy of the hypersonic airbreathing proposals was to take advantage of atmospheric air for accelerating to near orbital speeds. The concepts therefore examined if orbital speeds could be reached with combination of turbofan+ramjet+scramjet+rocket propulsion schemes. A novel feature involved collecting air during the atmospheric phase of flight, liquefying it, separating the oxygen and storing on board for use in the subsequent rocket mode of flight. All these concepts were rather ahead of time, faced technological issues and cost overruns and did not proceed beyond the concept/development phase. However, insight into hypersonic flight, design, performance and material challenges progressed research and yielded results which could be put to use in later designs.

Early Indian Hypersonic Efforts

As stated earlier, hypersonic airbreathing concepts were studied in India, more as reducing the cost of access to space and not much as a weapon system. Concept studies were carried out at both Indian Space Research Organisation (ISRO) and Defence Research and Development Organisation (DRDO).

The ISRO concept involved Air-Augmented Rocket transitioning to Dual Mode Ramjet and then on to Rocket Propulsion. Solid propellant rocket exhausts are fuel-rich and it was felt that this mixed and combusted with atmospheric air should enhance the thrust. For demonstration, a RH-200 rocket using HTPB propellant was configured as an *Ejector-Ram-Rocket* by designing an air augmentation duct around the truncated nozzle. Once the rocket reached supersonic speeds, the ejector would perform like a ramjet intake with the ram-air mixing and combusting with the fuel rich solid propellant exhaust. Two flight tests were carried out from Satish Dhawan Space Centre in January 1993 and flight speed of M 2.3 was achieved[1]. Though the design proved the benefit of air augmentation and demonstrated an increased mission average Isp as compared to the solid propelled RH-200 rocket, the Isp was lower than that of the solid motor in the initial phase of flight. The design needed improvement by increasing the rocket exhaust

1 India Missile Chronology. NTI. 2012. "India Reports Breakthrough in Rocket Technology". Retrieved from https://media.nti.org/pdfs/india_missile_3.pdf (page 175)

pressure at which stage the project was closed. It was decided that it was preferable to directly employ Scramjet propulsion after accelerating the vehicle to required speed using an external booster. Effort at ISRO was subsequently directed at development of scramjet engines using Hydrogen fuel.

In the late 1980s Air Commodore R Gopalaswamy of Defence Research and Development Laboratory (DRDL), Hyderabad came out with a reusable Single Stage to Orbit (SSTO) concept incorporating turbo-ram-rocket combined cycle propulsion. In a meeting of the Astronautical Society of India he proposed harnessing power from space. For building the solar collection array in space he suggested multiple sorties of the reusable craft to ferry the components to space. While the idea was technically feasible, safety issues of beaming microwave energy from space as well as the overall mission cost put the idea in cold storage. Building further on the Idea, DRDL in 1992 proposed a craft called AVATAR (Aerobic Vehicle for Transatmospheric Hypersonic Aerospace Transportation). Avatar was primarily intended to be a reusable launcher to be used either as a weapon platform or as access to space platform. The vehicle design would ensure at least a hundred re-entries into the atmosphere.

The novel feature of AVATAR was its propulsion system (engine and fuel system) using a concept called *FLOX*. According to Strickland, in *FLOX* part of the cooled air coming into the scramjet engine during the vehicle's journey in the atmosphere, is condensed into a liquid, and stored in a LOX tank. Such a SSTO starts flying with an essentially empty LOX tank, uses the rest of the cooled air during the scramjet phase, and, as it reaches the height where it cannot use air for combustion any more, switches to the condensed LOX oxidizer and to a pure rocket engine mode. AVATAR would use a turbojet engine for take-off and landing and flight to M 2.5; a dual mode ramjet-scramjet engine would be used for acceleration to M 8 in the atmosphere; during this phase atmospheric air would be collected and liquefied, oxygen separated and stored for subsequent use in the rocket mode of flight beyond M 8[2].

For space missions, AVATAR would be a two-stage to orbit (TSTO) vehicle with the first stage employing the *FLOX* concept returning to earth. A second stage going into orbit using rocket propulsion employing the inflight collected liquid oxygen and onboard carried liquid hydrogen.

As already stated these concepts were rather ahead of time; the concepts employed were technically feasible but significant R&D efforts in technologies including materials, thermal management, light weight heat exchangers were needed. In addition new test facilities, safety and reliability issues cost and other priorities put the lid on further efforts.

Current Indian Scenario

The emphasis on SSTO/TSTO approaches using airbreathing combined cycle propulsion are still of interest. The concentration at ISRO and DRDO has been on developing the technology elements and proving them through technology demonstrators in the initial phase.

Consequently, in recent years, ISRO has concentrated on the development of a supersonic

2 John K Strickland. "Current strategies towards air-breathing space launch vehicles". 2011. Space Review. Retrieved from https://www.thespacereview.com/article/1894/1

combustor and has carried out ground tests in India and Russia for design confirmation. The design confirmation was done by flying the scramjet engine at M 6 using a sounding rocket. The combustor using hydrogen as fuel was tested captively in a sounding rocket flight on 28 August 2016 for a duration of 5 seconds at M 6. The two-stage sounding rocket Advanced Technology Vehicle was used for this purpose.

The scramjet engine modules mounted on the second stage were ignited during the thrusting phase of the stage. The burn duration was restricted to 5 seconds, keeping the material functioning under the adverse thermal environment in mind. The flight test demonstrated critical technology elements like ignition of the scramjet engine, working of the air intake mechanism as well as fuel injection and flame holding at supersonic speed[3]. The schematic in figure-3 depicts the fuel injection and the flowfield in the combustor. CFD techniques were extensively employed in modelling the flowfield and the thermal regime.

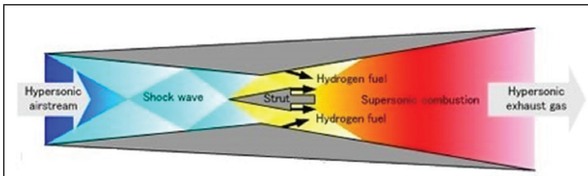

Figure 3: ISRO Scramjet combustor schematic
(Source: ISRO-Scramjet Engine TD)

Figure-4 shows the schematic of the ATV with the scramjet combustors mounted on the second stage airframe[4]. Performance details of the scramjet engine in flight are not yet available in the public domain.

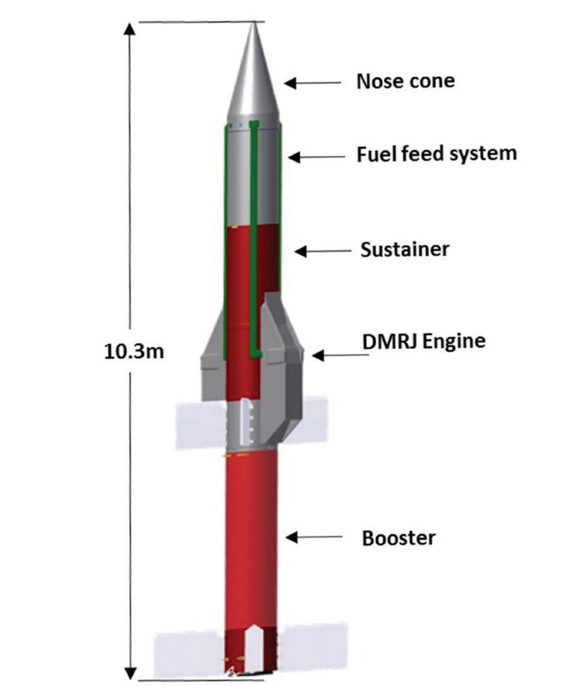

Figure 4: Scramjet engine mated with ATV
(Source: ISRO-Scramjet Engine TD)

While the ISRO scramjet is an important milestone, the test was a captive test and did not demonstrate autonomous flight.

Achieving TSTO capability is among ISRO future plans and as a first step, ISRO has plans to develop Hypersonic Air Breathing Vehicle with Airframe integrated system (HAVA). HAVA is a lifting body scramjet powered hypersonic vehicle which will be boosted to an altitude of 44 km by a rocket booster and then will glide down to 25 km altitude at Mach 6. The flight test objective of HAVA is demonstration of scramjet powered accelerating flight at Mach 6-7 in 250 seconds at constant dynamic pressure[5]. While the test date has not yet been indicated, it is reported

3 ISRO. 2016. "Scramjet Engine-TD". Retrieved from https://www.isro.gov.in/launcher/scramjet-engine-td

4 Retrieved from https://www.isro.gov.in/launchers/isro%E2%80%99s-scramjet-engine-technology-demonstrator-successfully-flight-tested

5 Information relating to HAVA is sourced from ISRO 2019-20 Annual Report (page 69). Retrieved from https://www.isro.gov.in/sites/default/files/flipping_book/annual_report_2019-20_english/index.html

that subsystem design is in progress and ISRO developed *Isrosene* will be used as fuel. The configuration of HAVA can be seen at figure-5.

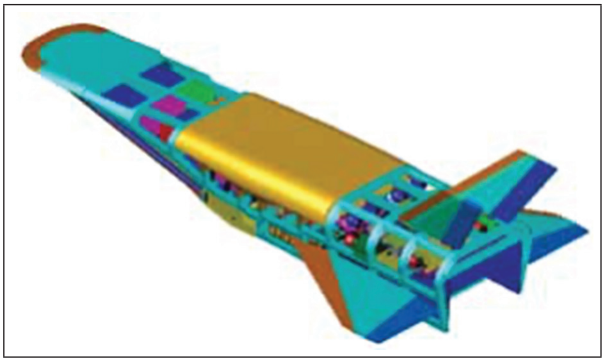

Figure 5: HAVA Configuration
(Source: ISRO Annual Report 2019-20)

In DRDO the emphasis has shifted from SSTO/TSTO concepts. Space transportation is not a primary objective for DRDO as compared to development of weapon platforms. Application of hypersonic air breathing propulsion would provide advantages of speed and low altitude flight, would delay detection by adversary sensors and provide considerably lower response time. The matter could be further complicated by adding manoeuvrability to the weapon system. The combination of speed and manoeuvrability would be helpful in penetrating enemy air defence systems.

With this objective in mind, DRDL initiated a technology demonstrator project – the Hypersonic Technology Demonstrator Vehicle (HSTDV) in early 2000. The objective was to demonstrate autonomous flight of a scramjet powered vehicle for a duration commensurate with available material technology. After design, development and ground testing of the components and the vehicle subsystems, the concept was to be proven in a free flight demonstration of the vehicle at Mach 6 under positive *thrust-minus-drag* condition. The demonstrator would be lofted to an altitude of 30 km using the Agni-1 booster and then released to continue in sustained flight as shown in figure-6.

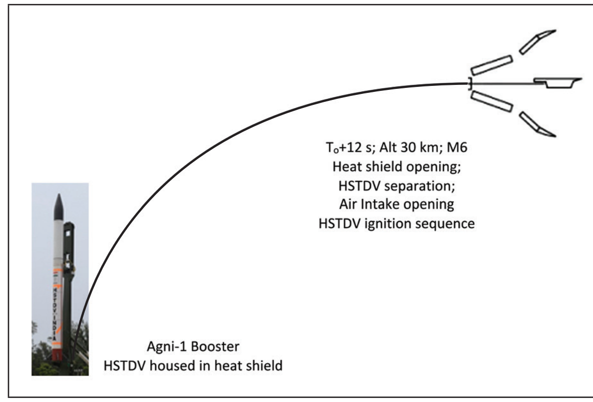

Figure 6: HSTDV flight trajectory

The realization of the Demonstrator involved design and development of the scramjet engine components, setting up of facilities for testing the subsystems and propulsion elements, wind tunnel testing, high temperature material development and CFD modelling of the internal and external flows. In a paper presented at the Aeronautical Society of India, Hyderabad Chapter organized Hypersonic Conference in 2007, the late Dr S Paneerselvam, then Project Director of HSTDV stated "hypersonic vehicle configuration has been designed by considering the aerodynamics and propulsion intensive interactions. A non-circular octagonal shape of the aerodynamic configuration has been evolved in pitch yaw roll mode satisfactory stability and control characteristics in addition to positive thrust margin. Aerodynamic characteristics of the hypersonic cruise vehicle have been estimated through wind tunnel tests. Extensive CFD analysis has been carried out for the vehicle viz., tip to end simulation considering simultaneously the external and internal flows with heat release in the combustor and heat flux evaluation on the body and the engine. The computed results are in agreement with the wind tunnel data. Strut based combustor testing has been carried out in connect-pipe mode to ascertain its performance and suitability for the vehicles. High temperature materials have been identified and characterized for the realization of airframe, engine and mechanisms"[6].

For the HSTDV mission trajectory, the Agni-1 booster experiences higher heating loads. This called for estimation of the temperatures on the missile skin, especially the fins and incorporate appropriate changes. In addition, separation of the hypersonic air breathing cruise vehicle from the launch vehicle proved to be critical due to bunching of events like stage burnout, high dynamic pressure, heat shield opening and separation sequence. Extensive simulation of stage separation needed to be carried out through CFD, considering the relative positions between the launch vehicle and the cruise vehicle to affect clean separation.

After proving the design and performance parameters of all elements of HSTDV through theoretical studies, simulation, wind tunnel and ground tests, the vehicle was successfully flight tested on 07 September 2020.

New developments related to configuration, aerodynamics, propulsion, materials and CFD were realised in meeting the HSTDV objectives. Some of these are listed below:

Scramjet Engine

- Mach Number at the engine entry was debated – literature supported deceleration to Mach 2 to 2.5. Based on CFD simulation and experimentation Mach 2.3 was selected. Air intake was accordingly designed to reduce the free stream velocity and pressure recovery.

- Both wall injection and strut based fuel injection schemes were studied. Strut based injection was found to be more efficient from mixing and performance considerations. The design however, required issues related to flow and temperature to be managed.

- Fuel injection and mixing were experimentally studied and improved mixing was possible in the presence of stage II struts.

- Use of ethylene was preferred as it provided a better equivalence ratio and higher thrust. This was essential to obtain a positive $T - D$ with margins

- The HSTDV faces a hostile thermal environment both externally due to aerodynamic heating and internally due to the combustion process. Active cooling was not an option for the Demonstrator and hence materials for the airframe, injector struts and combustion chamber had to be carefully chosen. In some cases, special thermal coatings had to be developed.

- Wind tunnels at DRDL, IISc and NAL could be used for limited tests and characterising isolated intake performance. Facility for hot test of the engine in connected pipe mode had been set up at DRDL. However, for open jet tests to characterise the engine in

6 S. Paneerselvam. 2007. "Progress On The Design And Development Of Hydrocarbon Fuelled Scramjet Engine Integrated Vehicle Towards Demonstrating Hypersonic Autonomous Flight". Paper presented in International Conference on High Speed Transatmospheric Air & Space Transportation. 29 - 30 June 2007. Hyderabad. Retrieved from: http://www.aesihyd.com/hypersonic_conference/contents/Souvenir_June_2007.pdf

flight simulated conditions, TsAGI facilities in Russia had to be used.

Boost system

Though Agni-1 is a proven and qualified stage, adaptation for HSTDV required some changes essentially from aero-thermal considerations. The other challenge was the mission management of a number of critical events sequenced in quick succession. The heat shield separation, air intake opening, ejection of the cruise vehicle and initiation of scramjet were all critical.

The Flight Article

Some particulars of the HSTDV have appeared in the media based on interviews and other information. Based on this the flight article characteristics are summarised below[7]:

HSTDV Particulars

- Length: 5.6m
- Mass: 1000 kg
- Cross section: Octagonal with rectangular shaped air intake
- Materials: Titanium alloy, Aluminium alloy, Niobium and Nimonic alloys

Other features include twin parallel fences in the forebody to reduce spillage; part span flaps at the trailing edge of the wings for roll control; and a deflectable nozzle cowl. The HSTDV configuration is shown in figures 7 and 8[8,9].

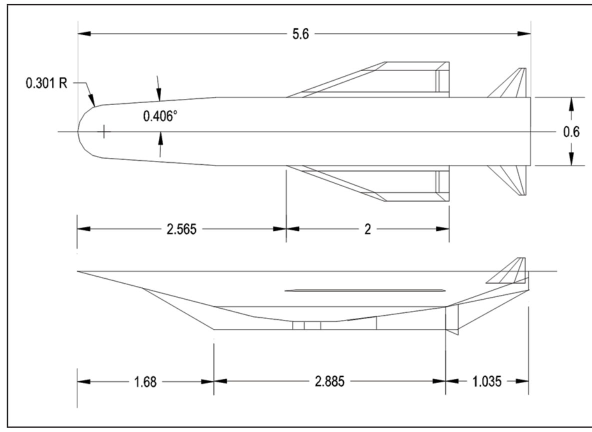

Figure 7: HSTDV Configuration
Source: Conference Paper

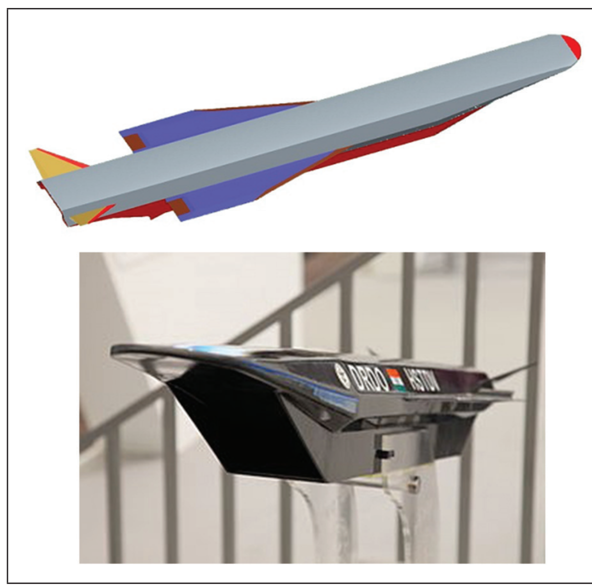

Figure 8: HSTDV Flight Configuration
Source: PIB Press Release 08.09.2020

7 Cloudfront.net (no date). Hypersonic Technology Demonstrator Vehicle. Retrieved from https://db0nus869y26v.cloudfront.net/en/Hypersonic_Technology_Demonstrator_Vehicle?rev=1589060076292 (accessed 15 September 2020)

8 KPJ Reddy. "Hypersonic Flight and Ground Test Activities in India". 2007. 16th Australasian Fluid Mechanics Conference. Gold Coast. Australia. Retrieved from Reddy_afmc_16_07.pdf (accessed 15 September 2020)

9 Ministry of Defence. 2020. "DRDO successfully flight tests Hypersonic Technology Demonstrator Vehicle". Press Information Bureau. Retrieved from https://www.pib.gov.in/PressReleasePage.aspx?PRID=1651956

The integrated vehicle was first tested on 12 June 2019 from Dr Abdul Kalam Launch Complex at Wheeler Island. It is understood that this flight was partially successful. The current flight test was conducted on 07 September 2020 and was a complete success. According to the press release carried on DRDO website, "The hypersonic combustion sustained and the cruise vehicle continued on its desired flight path at a velocity of six times the speed of sound i.e., nearly 02 km/second for more than 20 seconds. The critical events like fuel injection and auto ignition of scramjet demonstrated technological maturity. The scramjet engine performed in a text book manner"[10].

The successful flight test, especially the fulfilment of the laid out test objectives is truly a significant achievement for DRDO. The test adds to the confidence in the design and conduct of the experiments, wind tunnel and other ground tests, the aero-thermal data, material choice and use of CFD as a tool for involved flow modelling. Having said that, the obvious question will be what is the next step and how to prepare for it. The answer will be to use the lessons and experience gained in HSTDV realisation and develop additional technologies required for deriving a vehicle system of an appropriate range and payload capabilities. From this consideration, it is worthwhile to examine the international status in hypersonic cruise missiles.

International Hypersonic Cruise Missile Scenario

Russia and US are leading in the development of hypersonic cruise missiles. China has done some R&D and is reported to have carried out a flight test. France had an early start in the development of scramjet engines. Other countries including Japan, UK, France and India have carried out research and development in hypersonic airbreathing vehicles. In the initial years the US carried out a few short duration tests under the X-43 and X-51 series – these helped in advancing the technology but did not result in operational system. These tests are summarised in table-1 below.

Vehicle	Test date	Scramjet burn time	Max speed	Remarks
X-43A Hyper-X	02 /06/2001	0	NA	Booster failure.
	27/03/2004	11 s	M 6.8	Mission objectives met
	16/11/2004	10 s	M 9.6	Hydrogen used as fuel. Mission objectives met
X-51A Wave-rider	26/05/2010	143 s	M 4.9	Planned burn was for 240 s. Hot gases from scramjet leaking on to the vehicle from a damaged seal resulted in early flight termination
	13/06/2 011	10 s	M 5	Scramjet ignition using ethylene but failed during transition to JP7.
	14/08/2012	NA	NA	Faulty control surface. Vehicle lost control after separation from booster
	01/05/2013	240	M 5.1	Mission goals met

Table 1: US Scramjet Tests

10 ibid

The Russian hypersonic missile **Tsirkon** is being developed for anti-ship role. It is a scramjet powered hypersonic cruise missile expected to reach speeds of Mach 5-6 and a range of 600 to 1000 km. The missile is expected to be difficult to intercept because of its speed and manoeuvring capability. The missile is adapted for launch using Onyx and Calibre compatible 3C14 launch platforms and will be capable of launch from surface ships and submarines and is expected to be deployed aboard Kirov class destroyers by 2022. The missile uses *Decilin-M* special fuel and employs a new metal alloy capable of withstanding high temperatures. The missile is manoeuvrable during its final approach. From the limited information available, the missile length is estimated at 8 to 11 m, warhead weight of 300 kg to 400 kg and peak altitude along the trajectory at 30 km to 40 km[11]. Artist's rendering of Tsirkon missile is shown in figure-9.

Figure 9:Tsirkon missile

In the US, the Air Force and Navy are backing the development of Hypersonic Air Breathing Weapon Concept (HAWC). Independent development contract are being pursued by Lockheed Martin and Raytheon. Both firms have completed air carriage trials and are expected to start actual flight trials this year. Details of HAWC range and other technical details are not publicly available. Artist's conception of the missile is shown in figure 10.

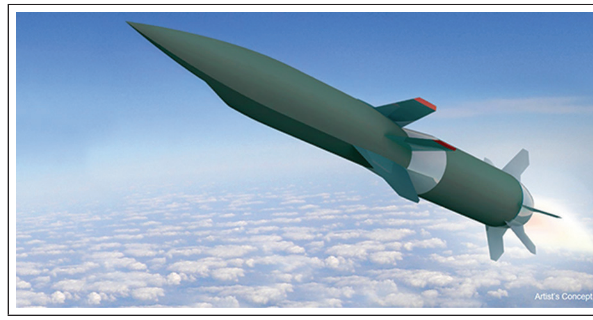

Figure 10: US HAWC

(Source: Aviation Week and Space Technology)

China's main emphasis was on the development of hypersonic glide vehicle, where they have made adequate headway with the DF-ZF system[12]. They have however, also been working on hypersonic cruise vehicle called Starry Sky-2 (or Xing Kong2) based on waverider principle[13]. In a flight test done on 03 August 2018, China claimed the vehicle reached Mach 5.5-6 at an altitude of 30 km. The vehicle flight lasted more than 400 seconds during which the vehicle executed manoeuvres[14] (at Mach 5.5 for flight of 400 seconds the range covered would be nearly 700 km). According to a news item in the South China Morning Post, "the aircraft was carried into space by a multistage rocket before separating

11 Jill Hruby. "Russia's new nuclear delivery systems". 2019. Nuclear Threat Initiative. Retrieved from https://media.nti.org/pdfs/NTI-Hruby_FINAL.PDF

12 Hypersonic Glide Vehicle is another hypersonic weapon concept being actively pursued by China, Russia and the US. In this a maneuverable body is boosted to the edge of atmosphere and allowed to glide to the target at hypersonic speeds ranging from Mach 10-20. The glide body is maneuverable in both cross range and down range during the hypersonic descent.

13 In a waverider design the bow shock is attached to the leading edge at the design point and providing in the process, maximum lift to drag ratio. The attached shock wave also prevents flow spillage from lower to upper surface at the design point by creating an effective compression lifting surface.

14 Xinkong-2/Starry Sky 2. Global Security. 2020. Retrieved from https://www.globalsecurity.org/wmd/world/china/xingkong-2.htm

and relying on its own power". Quoting the Chinese Academy of Aerospace Aerodynamics, the news story further stated "on completion of the 'hugely successful' flight, the aircraft landed in a designated target zone[15]". The system could be weaponised by 2023.

In addition, China has developed a Mach 6+ scramjet engine test bed – Lingyun-1 to research hypersonic cruise missile technologies including thermal resistant materials and components[16]. The prototype of the vehicle is shown in figure 11.

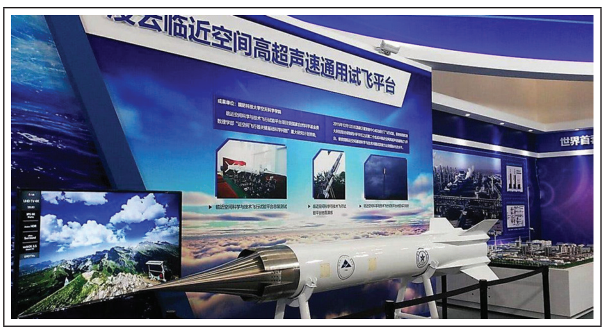

Figure 11: Lingyun-1 Vehicle prototype displayed at National Science and Technology Expo
(Source: CRS Report 45811)

The way ahead for India

The successful flight test of HSTDV has confirmed the approach adopted for the design and realization of the vehicle as well as the conceptualization and execution of the Mission. In the process design practices, performance assessment and technology elements have been developed, reviewed and applied. Important gains of HSTDV can be listed as:

- Cruise vehicle configuration including forebody, mid-section housing the propulsion unit and aft body.
- Internal and external flow field modelling using procured and in house developed CFD codes.
- Wind tunnel studies, validation of CFD results and prediction using CFD for non-wind tunnel simulation conditions.
- Mapping of external and internal thermal regimes leading to selection/development of materials and thermal protection systems.
- Sequencing of mission critical events – achievement of cruise vehicle injection conditions, stabilization, separation, air intake function and initiation of scramjet combustion.
- Fuel injection schemes for efficient mixing and combustion and adopting the strut based injection scheme.
- Mission management including navigation and control, instrumentation to check health and performance parameters, handling and safety issues.

In this flight, HSTDV would have covered a distance of about 40 km in the hypersonic regime of flight. For an operational system obviously, the range will have to be much larger. To achieve Mach 6 hypersonic flight over a distance of 1000 km a flight time of 550 seconds would be needed. Accounting for drag, a flight time of 600 seconds will have to be accounted for. The technologies developed for HSTDV will be applicable and in addition, the design will have to account for challenges associated with much longer operation time, associated technology solutions and mission specific issues.

15 Liu Zhen. "China's hypersonic aircraft, Starry Sky-2, could be used to carry nuclear missiles at six times the speed of sound". 6 August 2019. South China Morning Post. Retrieved from https://www.scmp.com/news/china/diplomacy-defence/article/2158524/chinas-hypersonic-aircraft-starry-sky-2-could-be-used

16 Hypersonic Weapons: Background and issues for Congress. 2020. CRS Report Number R45811. Page 14-15. Retrieved from https://fas.org/sgp/crs/weapons/R45811.pdf

It is assumed here that the operational system to be developed will be for an offensive surface-to-surface role, though hypersonic systems can be deployed for other applications like interception, surveillance and access to space. It is felt however, the following issues will need to be addressed:

1. **High temperature issues:** The thermal regimes encountered in hypersonic flight are extremely high and their management is and will be a challenge. The stagnation temperature at an altitude of 30 km for a vehicle travelling at Mach 5-6 will be in the range of 1000-1500º C. The high temperatures associated with hypersonic flight is not the same over the entire airframe. It is more pronounced at the nose and at the leading edge of aerodynamic surfaces. A first-hand feel of the nominal temperatures experienced by different parts of a hypersonic vehicle can be seen in figure 12.

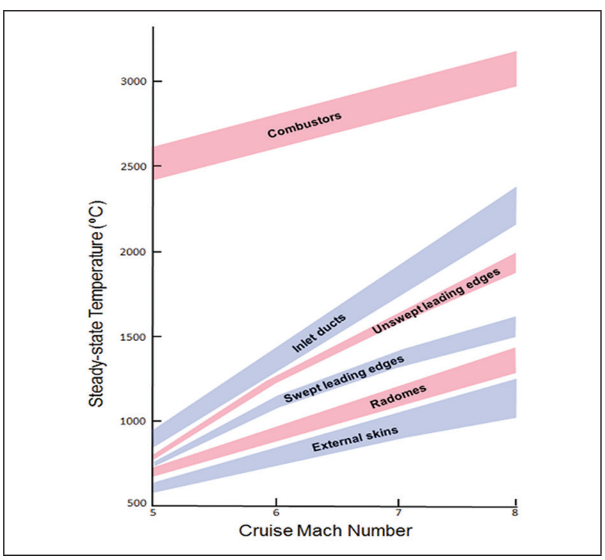

Figure 12: Nominal Air Frame Temperatures vs M No.
(Source: Hypersonic Air Power[17])

The temperature profile dictates the material selection, material development choices and thermal management requirements including active cooling of subsystems. Complimenting this, figure-13 shows different materials based on their heat capacity. The figure outlines the specific strength (ratio of yield strength to density) against temperature. In India fair capability exists in respect of aluminium alloys, titanium alloys, steel varieties and nickel alloys. In terms of composites similarly familiarity and capability is available with glass and carbon reinforced polymers, carbon-carbon composites. Some capability has been developed with regard to SiC/SiC and C/SiC composites. The first assessment is that India has developed or has the capability to develop many of the aerospace materials usable in high temperature applications shown in figure-13. The quantity demand for such exotic materials is rather limited and the development in many instances has not translated to industrial levels. Keeping the lead-time in scaling up and creation of facilities, it is advantageous to categorise the materials needed, list the existing and needed capacity and evolve a plan of action for material realisation.

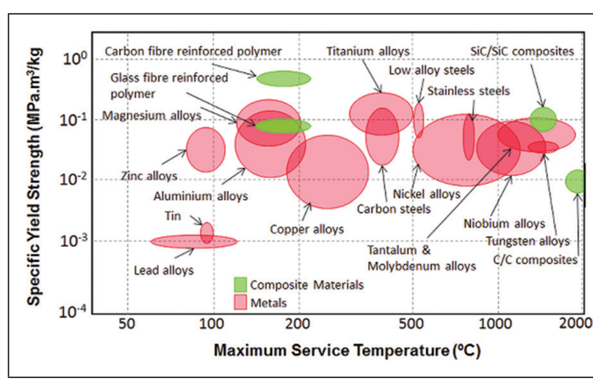

Figure 13: Material selection guide[18]

2. **Propulsion:** Though other schemes like rocket propulsion and combined cycle

17 Travis Hallen and Michael Spencer. "Hypersonic Air Power". Air Power Development Centre, Australia. Page-13.
18 Ibid. page-14.

propulsion are available for reaching/sustaining hypersonic speeds, for this study, the selected candidate is scramjet propulsion. That means the cruise vehicle will be boosted, just as in the case of HSTDV to hypersonic speed and the desired altitude at which time the scramjet propulsion will kick in. The airframe and the propulsion system has to be a highly integrated system with the forebody aiding the air compression and the aftbody aiding the post-combustion expansion. While adequate background design information – both analytical and experimental – is available for design of intakes, some trade-off between altitude of operation and engine performance will have to be accounted for. Hypersonic vehicles work with small difference in the engine thrust and vehicle drag. The vehicle drag is proportional to the air density and M^2. This means for the same Mach Number, lesser thrust is required to overcome the vehicle drag with increase in altitude. A higher altitude of operation also favours lower structural loads. However, the scramjet engine requires a certain mass flow rate of oxygen to be maintained for optimum combustion and at higher altitudes will have to fly faster for this purpose. Hypersonic vehicles therefore have to operate within a corridor where the upper bound is constrained by condition required for producing positive thrust and the lower bound constrained by dynamic pressure and heating loads with resultant impact on the structure. Typically for Mach 5 flight the lower and upper bounds are 12 km and 33 km respectively; and for Mach 6 the bounds happen to be 17 km and 38 km respectively. This substantiates the reason why a combination of Mach 6 and 30 km altitude is preferred for scramjet operation.

Some additional research relating to scramjet fuel is needed. Endothermic fuels will need to be developed and characterised. Russia uses a special fuel called Decilin-M and the US is reported to be using JP-10.

3. **Manoeuvrability:** As a weapon system, Hypersonic cruise missiles derive advantage if they are manoeuvrable along both down range and cross range. At hypersonic speeds, manoeuvring is a major challenge. Aerodynamic control surfaces have to be chosen to be effective over a speed range (at least in both hypersonic and supersonic speed regimes). Hypersonic speeds and agility are contradictory requirements and design compromises/trade-offs would be needed to work out a practical design.

4. **Avionics:** Onboard avionics has to cater to diverse requirements like a) mission related computations, b) trajectory related steering and control functions, c) monitoring the output of sensors and functional employment of sensors and d) communication with command and control networks. These requirements are common for all airborne weapon systems but tends to be more complicated and challenging for hypersonic vehicles. Thermal and vibration levels are expected to be quite intimidating. In addition to the vehicle thermal management, the heat dissipation by the electronics will also require proper cooling and management functions. The adequacy of presently available components, devices, conformal coatings and adhesives has to be checked and modified/new systems developed to meet the requirements[19].

5. **Facilities:** Wind tunnel, shock tunnel and open jet facilities would be required

19 JR Wilson. "The electronics design challenges of hypersonic flight". 2020. Military Aerospace Electronics. May 22, 2020. Retrieved from https://www.militaryaerospace.com/print/content/14176531

to simulate the flow conditions and get a measure of the aerodynamic and propulsion characteristics. In addition facilities would be required to measure material mechanical and thermal properties at elevated temperatures and measure material response to high heat flux. Some facilities are available in India and an assessment as to creation of new facilities needs to be taken.

A missile stage would be the obvious choice to boost the cruise vehicle to about 30 km altitude and release it after attaining Mach 6. If like the Russian Tsirkon and the US HAWC weapon systems, an aircraft could be used, it will provide the advantage of reducing the missile booster performance demand on the one hand and also provide a significant advantage of stand-off distance. This can be decided based on the mass of the long distance cruise vehicle and booster and availability of suitable aircraft in our fleet.

In addition, policy issues will need to be addressed. These will relate to the vehicle mission and payload. Consideration whether the warhead should be conventional HE or strategic or maintain a level of ambiguity will need addressing in the operational phase. Likely constraints related to the platforms on/from which the hypersonic vehicle will be deployed will have a say on the weapon and mission design. Obviously, a set of experts will need to put their heads together and draw out the detailed specification, performance and mission requirement document.

Conclusion

The successful flight of India's hypersonic technology demonstrator HSTDV on September 07, 2020 ushered in a new frontier of high speed flight with its attendant advantages and technological challenges for India. The international scenario shows that progress has been made in US, Russia and China hypersonic weapon technologies involving boost-glide and scramjet based propulsion. It is very appropriate for India to now concentrate on the development of a fullfledged hypersonic vehicle. Some technology requirements and issues outlined in this paper are difficult and challenging but can be addressed by our R&D establishments. DRDO in addition to leading the development project can benefit from partnering with the academic, R&D laboratories and industry for early realisation of the prototype.

The development and operationalisation of a hypersonic cruise missile will be a significant force multiplier for India. For exercising true deterrence capability India will have to decide whether the missile will be nuclear capable or carry conventional weapons or maintain like some other countries a degree of ambiguity. India will also have to study measures for early detection of incoming hypersonic weapons and plan defensive/counter measures. These will be technically demanding, will need long lead times and expensive.

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11. **Abstract:**
The recent flight test of the Hypersonic Technology Demonstrator Vehicle (HSTDV) by DRDO and the earlier flight test of the Advanced Technology Vehicle by ISRO has rekindled the interest in hypersonic technologies and their adaptation to practical systems in the Country. Indian interests in pursuing hypersonic technologies using both analytical and experimental approach have been around since the late 1980s. This article examines the background, the present development status including the features and outcome of HSTDV flight. The international scenario and some of the technology challenges scaling to a full fledged system are brought out.

12. **Keywords:**
Hypersonic, Scramjet, Mach Number, AVATAR, CFD, TSTO, Wind tunnel, Thermal protection

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