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BRAZILIAN 14-X HYPERSONIC WAVERIDER SCRAMJET AEROSPACE VEHICLE DIMENSIONAL DESIGN AT MACH NUMBER 10

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Abstract. *The 14-X Hypersonic Aerospace Vehicle, VHA 14-X, designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonic, at the Institute for Advanced Studies (IEAv), is part of the continuing effort of the Department of Aerospace Science and Technology (DCTA), to develop a technological demonstrator using: i) "waverider" technology to provide lift to the aerospace vehicle, and ii) "scramjet" technology to provide hypersonic airbreathing propulsion system based on supersonic combustion. Aerospace vehicle using "waverider" technology obtains lift using the shock wave, formed during supersonic/hypersonic flight through the Earth´s atmosphere, which originates at the leading edge and it is attached to the bottom surface of the vehicle, generating a region of high pressure, resulting in high lift and low drag. Atmospheric air, pre-compressed by the shock wave, which lies between the shock wave and the leading edge of the vehicle may be used in hypersonic airbreathing propulsion system based on "scramjet" technology. Hypersonic airbreathing propulsion, that uses "scramjet" technology, offers substantial advantages to improve performance of aerospace vehicle that flies at hypersonic speeds through the Earth's atmosphere, by reducing onboard fuel. Scramjet is a fully integrated airbreathing aeronautical engine that uses the oblique/conical shock waves generated during the hypersonic flight, to promote compression and deceleration of freestream atmospheric air at the inlet of the scramjet. Fuel, at least sonic speed, may be injected into the supersonic airflow just downstream of the inlet. Right after, both oxygen from the atmosphere and on-board fuel are mixed. The Hypersonic Accelerator Vehicle, VAH, which is compound by S31 and S30 rocket engines developed by the Institute of Aeronautics and Space (IAE/DCTA) will be used to accelerate, the VHA 14-X, to the conditions pre-established to operate the "scramjet" engine, i.e. position (altitude, latitude and longitude), speed (Mach number), dynamic pressure and angle of attack. Analitic theoretical analisys and pressure measurements at pure waverider external upper and lower surfaces and scramjet power off on internal surfaces provide experimental data obtained from the experimental investigation at the T3 Hypersonic Shock Tunnel, Tunnel T3, funded by São Paulo Research Foundation (FAPESP) to design the full 2-m. long 14-X Hypersonic Mach number 10 waverider hydrogen-powered scramjet Aerospace Vehicle to atmospheric flight at 30km altitude.*

Keywords: *VHA 14-X, waverider, scramjet*

1. THE BRAZILIAN 14-X HYPERSONIC AEROSPACE VEHICLE

The 14-X Hypersonic Aerospace Vehicle (Fig. 1), named after 14-Bis developed by aviation pioneer Alberto Santos Dumont, designed at Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics (Rolim 2009; Rolim et al. 2009; 2011), at Institute for Advanced Studies (IEAv), is part of the continuing effort of the Department of Aerospace Science and Technology (DCTA) to design, to develop, to manufacture and to demonstrate, in free flight, a technology demonstrator at Mach number 10 at 30km altitude (Ricco et al., 2011; Toro et al., 2012), using: i) "waverider" technology to provide lift to the aerospace vehicle, and ii) "scramjet" technology to provide hypersonic airbreathing propulsion system based on supersonic combustion.

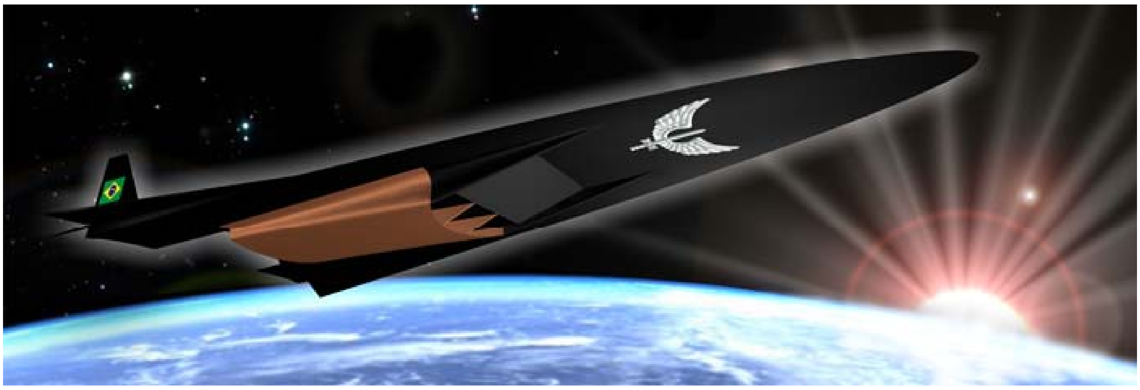

Figure 1: 14-X Hypersonic Aerospace Vehicle.

2. THE 14-X HYPERSONIC WAVERIDER AEROSPACE VEHICLE

Aerospace vehicle using waverider technology (Fig. 2) could be defined as a supersonic or a hypersonic vehicle which uses the high pressure zone on its lower surface caused by leading-edge attached shock wave to generate lift surface. Therefore, the attached shock wave in a sharp leading edge isolates the high pressure zone (lower surface) from the low pressure zone (upper surface), which inhibits the flow spillage. In general, the upper surface is aligned with the free stream hypersonic flow. Atmospheric air, pre-compressed by the leading-edge attached shock wave, which lies between the leading-edge sharp attached shock wave and lower vehicle surface may be used in hypersonic airbreathing propulsion system based on ”scramjet” technology.

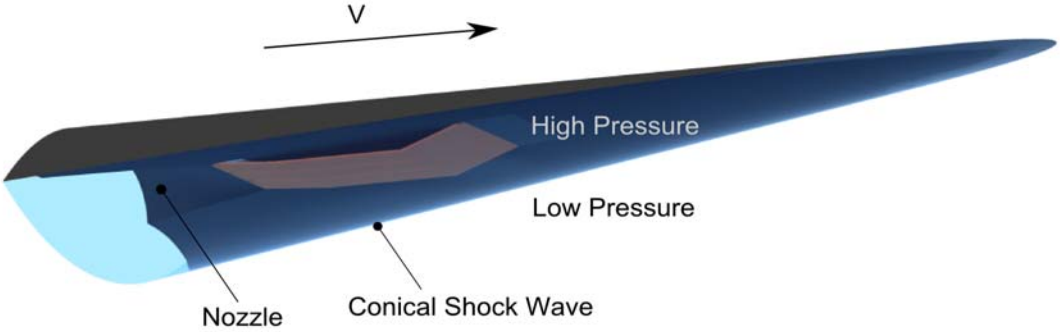

Figure 2: Waverider vehicle concept.

The VHA 14-X pure waverider (Fig. 3) surface (Rolim 2009; Rolim et al. 2009; 2011) was designed based on Rasmussen et al. (1990) concept, which is derived from a supersonic flow past a cone (Fig. 4) with the volumetric efficiency and the viscous high lift-to-drag ratio as optimization parameters. Later, Rolim (2009) and Rolim et al. (2009; 2011) added a compression and expansion ramps (Fig. 5) to the pure waverider surface in order to simulate the flow on a scramjet engine. The 14.5° deflection compression ramp is designed to capture the entire air flow compressed by the 5.5° waverider leading edge and to provide the ideal conditions for the supersonic combustion of the hydrogen, while the expansion section is assumed a 15° ramp.

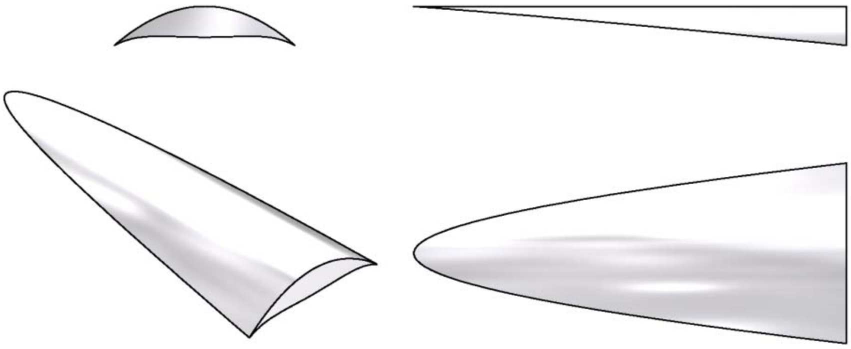

Figure 3: The 14-X pure waverider surface.

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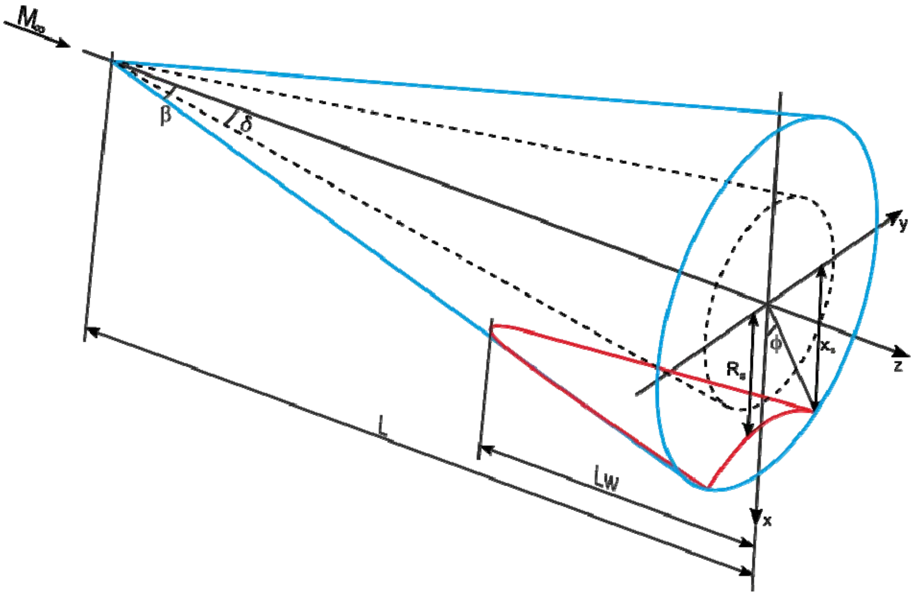

Figure 4: Schematic view of construction of the axisymmetric cone-derived waverider.

The 718.28 mm x 327.49 mm stainless steel model (Fig. 5), with 5.5° waverider leading edge, 14.5° deflection compression ramp and 15° expansion ramp was drawn by Costa (2011) and Costa et al. (2012). Seven piezoelectric pressure transducers used to obtain the pressure distribution were added on the compression surface (Fig. 6).

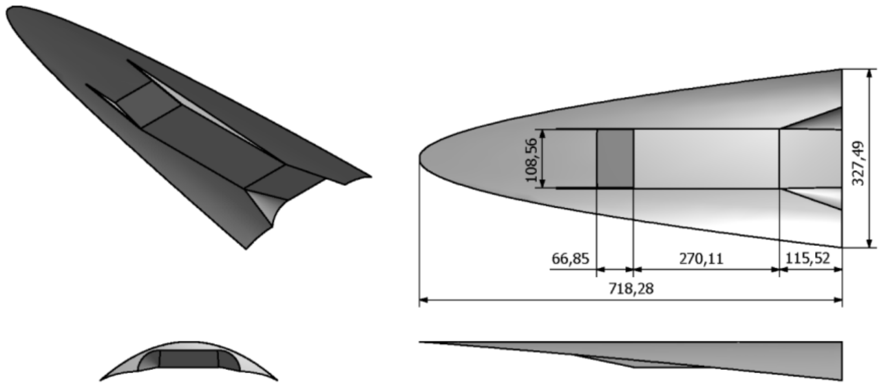

Figure 5: The 14-X waverider model main dimensions.

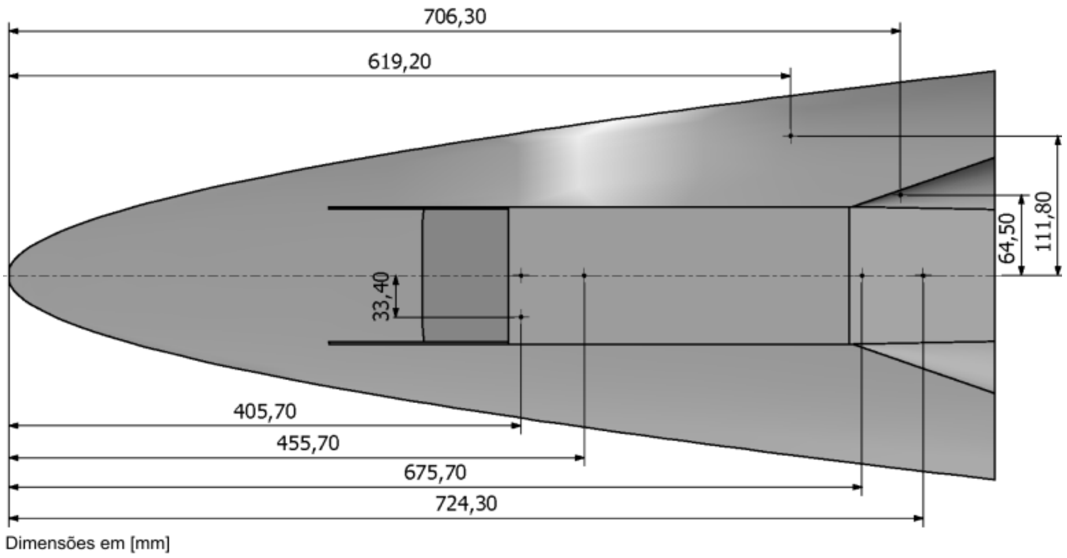

Figure 6: Location of the seven pressure transducers.

A 718.28-mm. long stainless steel "waverider" model, Fig. 7, instrumented with seven piezoelectric pressure transducers on the compression surface, had been experimental investigated (Rolim 2009; Rolim et al. 2009; 2011) on the equilibrium interface mode operation at the IEAv 0.60-m. nozzle exit diameter Hypersonic Shock Tunnel T3 (Fig. 8) at freestream Mach number from 8.9 to 10 with stagnation pressures between 2176-2938 psi and temperatures at the range of 1558-2150 K. Furthermore, the free stream conditions were such that $\mathrm{Re}_\infty = 2.25\ to\ 8.76\ 10^6\ \left(m^{-1}\right)$ and $Kn_\infty = 0.06\ to\ 0.19$.

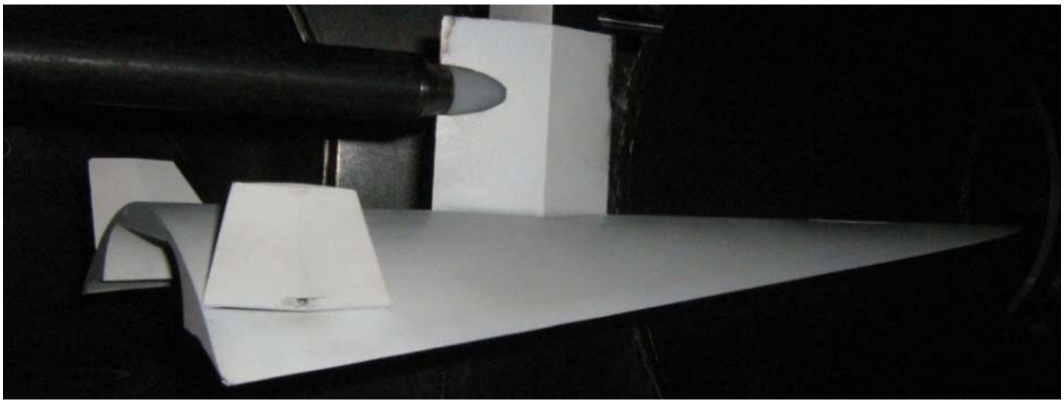

Figure 7: Instrumented "waverider" model installed at Hypersonic Shock Tunnel T3.

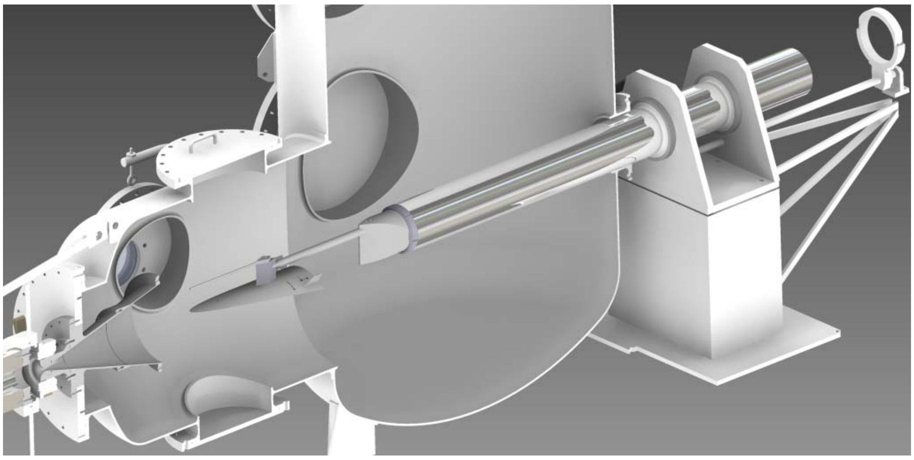

Figure 8: Instrumented "waverider" model installed at T3 Hypersonic Shock Tunnel.

Schlieren photograph (Fig. 9) shows that the flow pattern around the leading edge no longer presents a bow shock as in the continuum medium, instead, near the leading edge the shock wave starting point was almost imperceptible, a main characteristic of a slip condition (Rolim 2009; Rolim et al. 2009; 2011). Furthermore, the region that follows the slip region presents shock-wave/boundary-layer interactions; the extent of the influence of this region downstream depends on the size of the subsonic portion of the boundary layer and on the strength of the shock wave. When the rate of growth of the boundary layer is large, the boundary layer and the shock wave are merged within a limited region. In this situation, the outer inviscid flow is strongly affected by the displacement thickness, which in turn substantially affects the boundary layer.

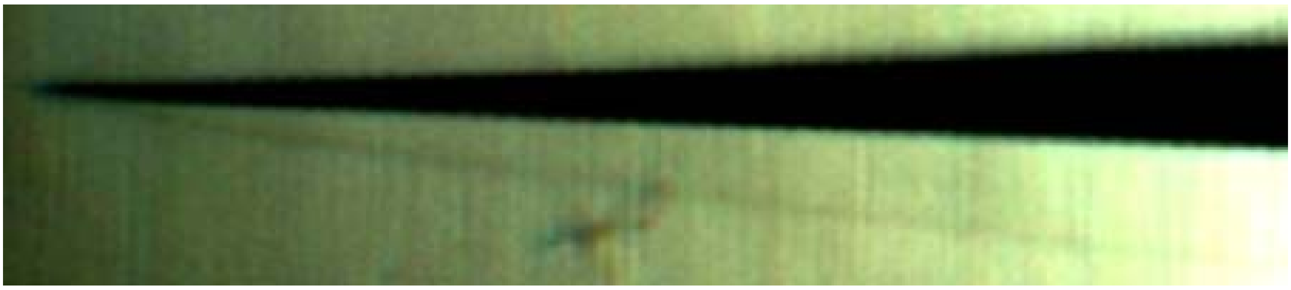

Figure 9: Mach number 10 flow past the model leading edge.

Schlieren photograph (Fig. 10) shows the oblique shock wave over the ramp, which intersects downstream the frame region. The extensions indicate a large separated region compared with the ramp length. In addition, besides the fact that the inlet shock-wave is initially curved it is possible to infer the angle of its linear portion (Rolim, 2009; Rolim et al. 2009; 2011).

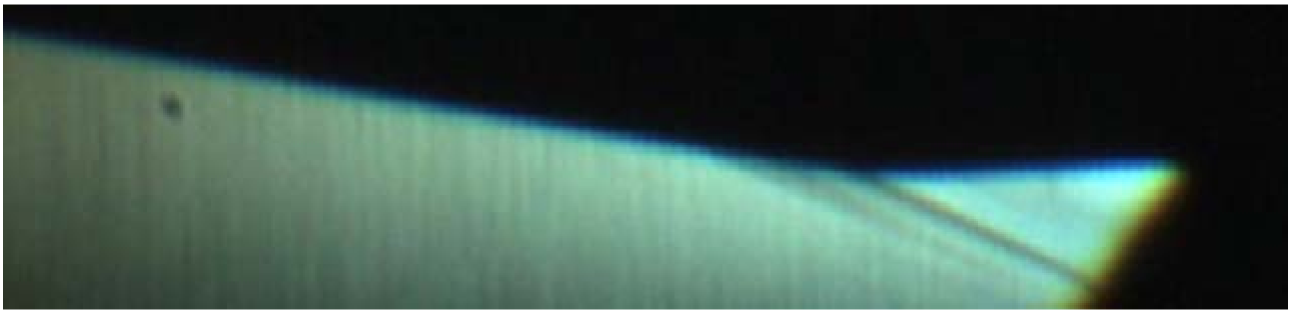

Figure 10: Mach number 8.71 flow past the inlet ramp.

3. THE 14-X HYPERSONIC SCRAMJET AEROSPACE VEHICLE

Hypersonic airbreathing propulsion, which uses supersonic combustion ramjet (scramjet) technology (Fig. 11) offers substantial advantages to improve performance of aerospace vehicle that flies at hypersonic speeds through the Earth's atmosphere, by reducing onboard fuel. As a matter of fact, at hypersonic speeds, a typical value for the specific impulse of a H_2-O_2 rocket engine is about 400s, while the specific impulse of a H_2 fueled scramjet is 2000s to 3000s. In fact, the use of atmospheric air as oxidizer allows air breathing propulsion vehicles to substantially increase payload weight. Basically, scramjet is a fully integrated airbreathing aeronautical engine that uses the oblique/conical shock waves generated during the hypersonic flight, to provide compression and deceleration of freestream atmospheric air at the inlet of the scramjet.

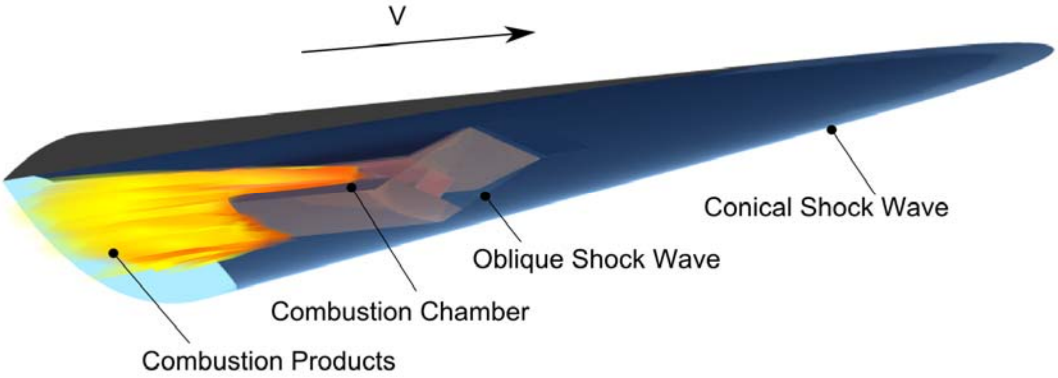

Figure 11: Scramjet hypersonic airbreathing propulsion concept.

Fuel, at least sonic speed, may be injected into the supersonic airflow just downstream of the inlet or at the beginning of the combustion chamber. Right after, both oxygen from the atmosphere and on-board hydrogen fuel are mixed. The combination of the high energies of the fuel and of the oncoming hypersonic airflow starts the combustion at supersonic speed. Finally, the divergent exhaust nozzle at the afterbody vehicle accelerates the exhaust gases, creating thrust.

As mentioned early, atmospheric air, pre-compressed by 5.5° pure waverider leading-edge following compressed by 14.5° deflection compression ramp may be used in hypersonic airbreathing propulsion system based on ”scramjet” technology.

A 265.1-mm. long, 80-mm. wide and 35-mm. high combustion chamber (Moura, 2009), based on the numerical (Hyslop, 1998) and on the experimental (Kasal et al., 2002) works, was coupled at the lower surface of the truncated 14-X Hypersonic waverider Aerospace Vehicle between the end of the 14.5° deflection compression ramp and the beginning at the 15° expansion ramp (Fig. 12) defined by the 14-X waverider aerodynamic experimental results (Rolim, 2009; Rolim et al., 2009; 2011).

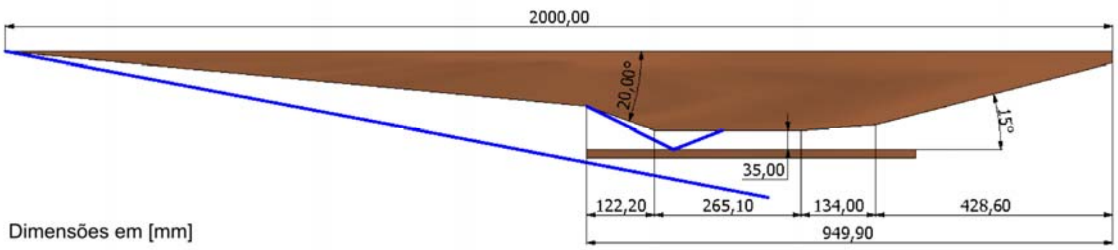

Figure 12: The 14-X waverider scramjet Mach number 10 model main dimensions.

The T3 Hypersonic Shock Tunnel, which has 0.60-m. diameter by 1.40-m. long test section, which does not allow accommodating model bigger as the full scale (2-m. long by 0.83-m. wingspan) 14-X waverider scramjet Mach number 10 model (Fig. 12).

Therefore, only one nacelle of the combustion chamber of the 14-X waverider scramjet model (Fig. 13) truncated before the 14.5° deflection compression ramp was designed. The 5.5° waverider leading edge surface of the truncated model was aligned with the free stream hypersonic flow, so that there is not conical shock wave generated by the 5.5° waverider leading edge.

Therefore, the truncated 14-X waverider scramjet model (Fig.14) was designed by Costa (2011) and Costa et al. (2012) and instrumented to experimentally investigate at the T3 Hypersonic Shock Tunnel (Fig. 15). In this configuration only the boundary layer will be established at the 5.5° waverider leading edge surface during the experimental runs. Quartz windows were designed to obtain schlieren photographs during the supersonic combustion runs.

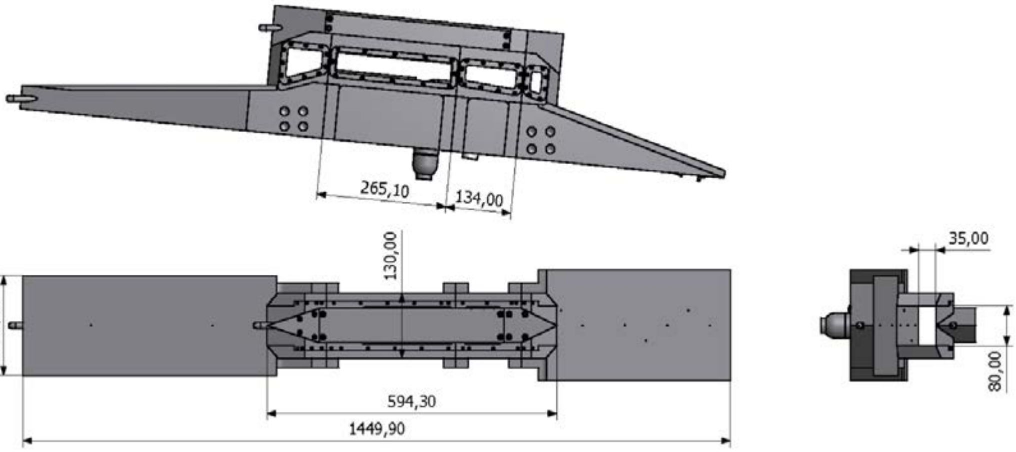

Figure 13: The truncated 14-X waverider scramjet model main dimensions.

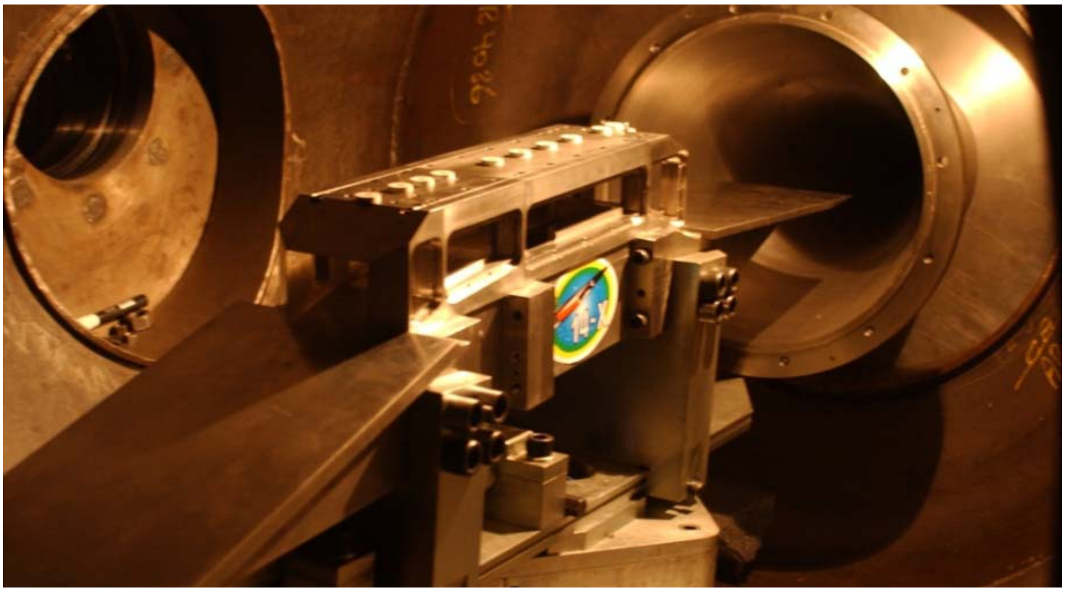

Figure 14: Instrumented truncated 14-X waverider scramjet model installed at the T3 Hypersonic Shock Tunnel.

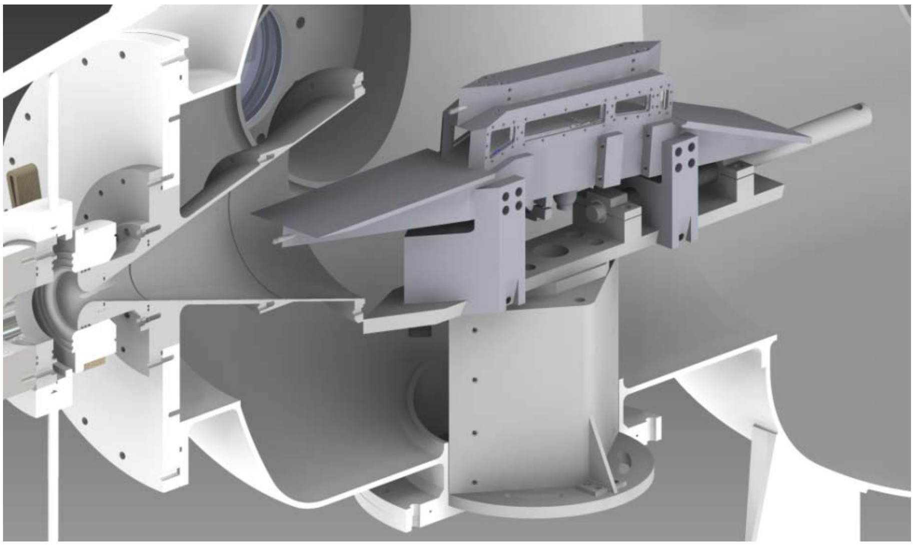

Figure 15: Instrumented truncated 14-X waverider scramjet model installed at the T3 Hypersonic Shock Tunnel.

Schlieren photograph, Fig. 16, shows the 19.85° oblique shock wave established at the manufactured 13.6° (designed 14.5°) deflection compression ramp as one may expect.

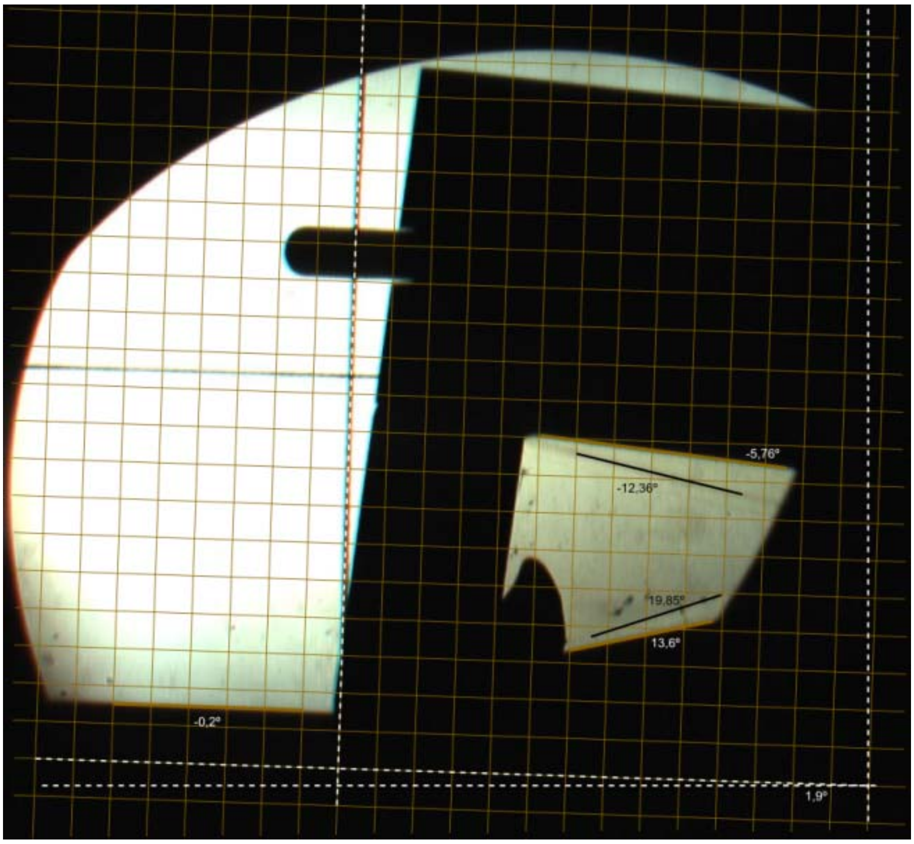

Figure 16: Mach number 7 flow past the model leading edge aligned if the horizontal.

4. THE 14-X HYPERSONIC WAVERIDER SCRAMJET ANALYTICAL THEORETICAL ANALISYS

The 2-m. long 14-X Hypersonic Mach number 10 Aerospace Vehicle (Fig. 17) has been designed to flight at 30km altitude at Mach number 10 for the first time, in Brazil, based on waverider (Rolim 2009; Rolim et al. 2009; 2011) and scramjet engine (Moura, 2009) experimental data as well as on the one-dimensional theoretical analysis, based on compressible flow (Anderson, 2003) and Prandtl-Meyer expansion flow (Anderson, 2003) theories applied to the external and internal surfaces and to the internal and external expansion surfaces, respectively.

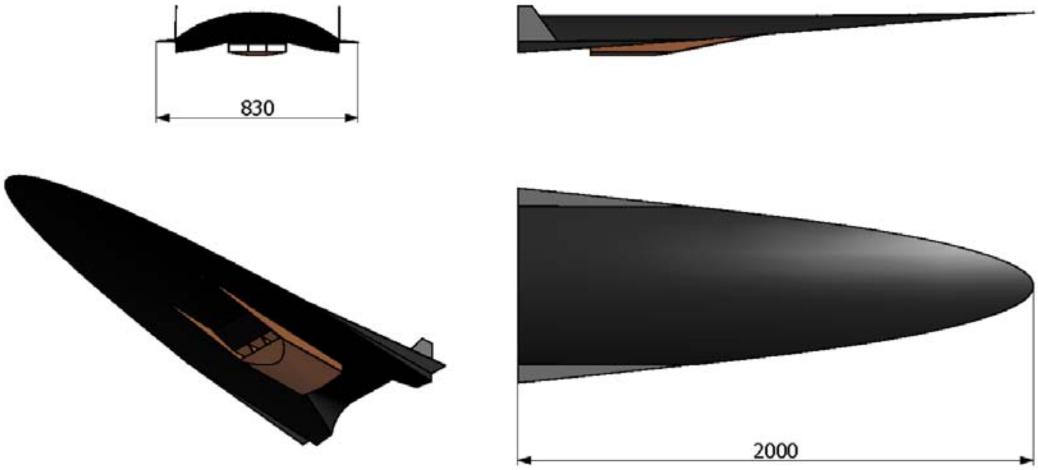

Figure 17: Dimensional for the 14-X Hypersonic Aerospace Vehicle.

The Brazilian Hypersonic Accelerator Vehicle which is composed by two-stage, unguided, rail launched, solid rocket engines will be used to accelerate the 14-X Hypersonic Aerospace Vehicle to the predetermined conditions of the scramjet operation (Fig. 18), i.e., position (altitude, latitude and longitude), speed (Mach number), dynamic pressure and angle of attack from the Alcântara Launch Center.

The 14-X Hypersonic Aerospace Vehicle will separate, at 30km altitude, from the rocket engine 2nd stage of the Hypersonic Accelerator Vehicle. The scramjet will be operational for about 4-5 seconds in upward flight of the 14-X Hypersonic Aerospace Vehicle. After scramjet engine demonstration is completed, the 14-X Hypersonic Aerospace Vehicle will follow the ballistic flight. After reaching the apogee, the 14-X Hypersonic Aerospace Vehicle will follow the descending flight to splash into the Atlantic Ocean. Both Hypersonic Accelerator Vehicle and 14-X Hypersonic Vehicle will not be recovered.

The Alcântara Launch Center (CLA) is a satellite launching base of the Brazilian Space Agency (AEB), located at the Latitude 2° 18' S Longitude 44° 22' W, on Brazil's northern Atlantic coast, outside São Luis city (capital of Maranhão State).

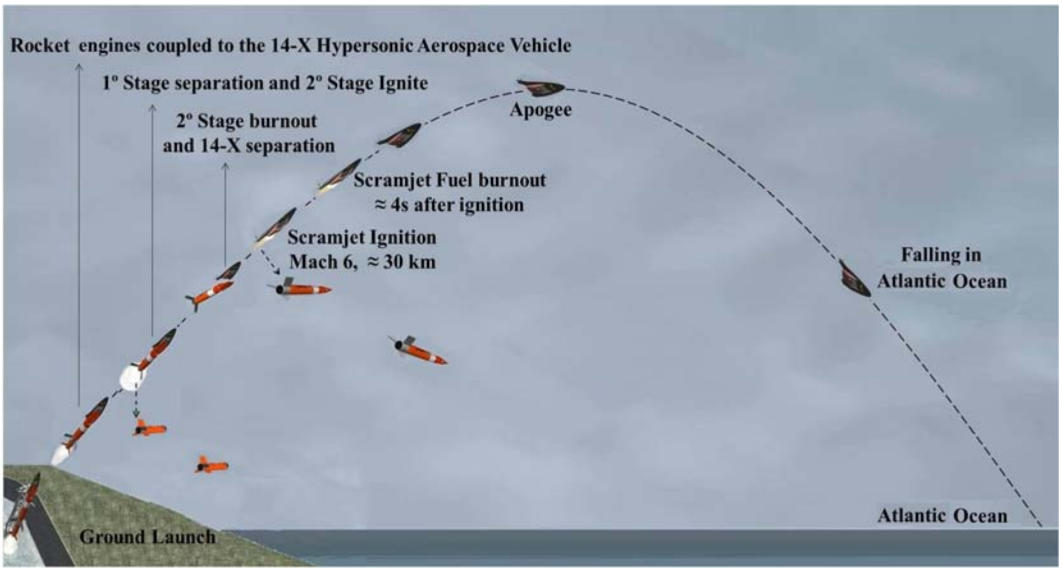

Figure 18: VAH and 14-X VHA in ballistic trajectory.

Internal configuration of the 14-X Hypersonic Aerospace Vehicle is being studied, (Fig. 19) to determine the structural dimensions and materials considering the dynamic pressure and the aerodynamic heating during the ballistic trajectory (Fig. 18).

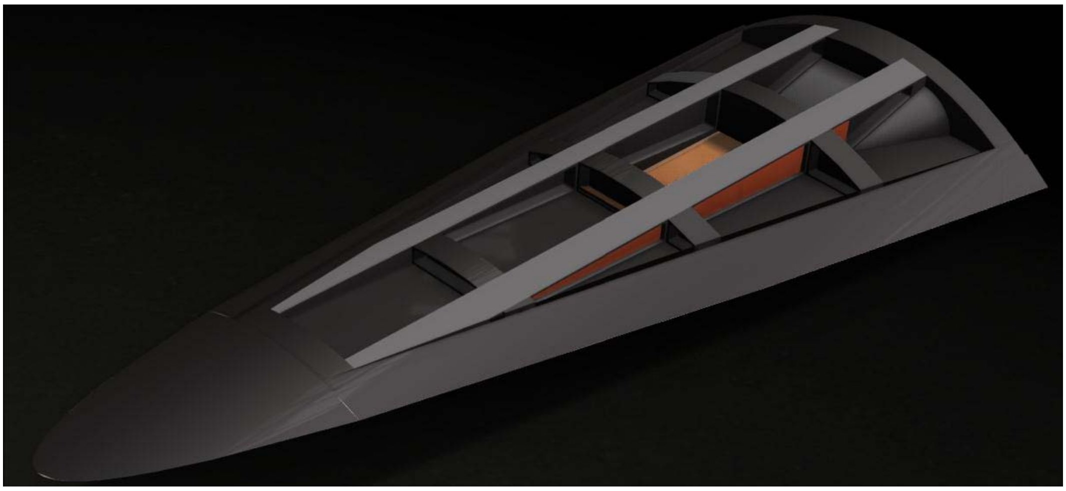

Figure 19: 14-X waverider scramjet internal configuration.

As mentioned early, the VHA 14-X requires a VAH to deliver it to the scramjet engine test condition. In order to use the S31 and S30 unguided, rail launched, solid rocket engines, which are developed and manufactured by the Institute of Aeronautics and Space (IAE/DCTA) for the first Atmospheric flight as planned for 14-X captive scramjet-unpowered Mach number 7. In order to use the S31 and S30 motors at Mach 7 Structural and Thermal Analysis have been developed for the 2-m. long 14-X hypersonic Mach number 7 (Fig. 17) using the one-dimensional Analytical theoretical Analysis, based on compressible flow (Anderson, 2003) and Prandtl-Meyer expansion flow (Anderson, 2003) theories applied (Fig. 20) to the external and internal surfaces and to the internal and external expansion surfaces, respectively.

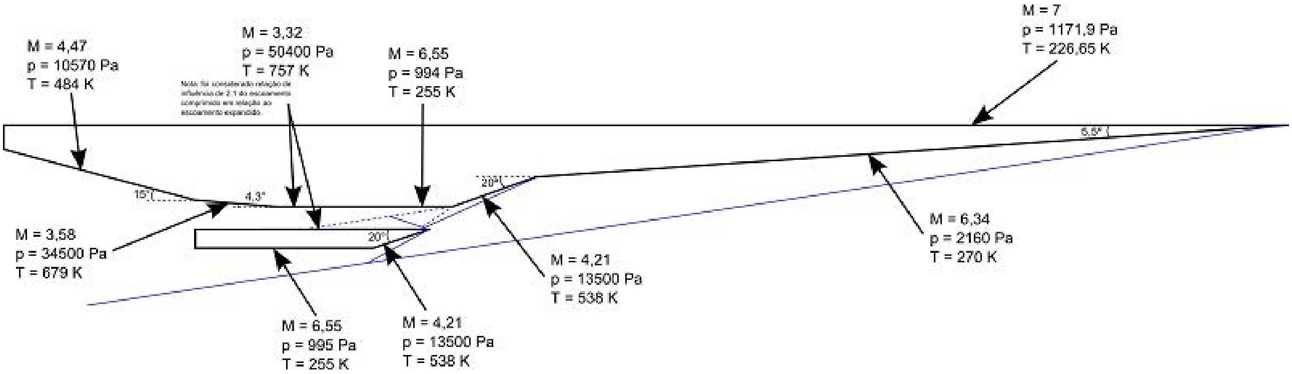

Figure 20: 14-X Hypersonic Aerospace Vehicle Analytic Theoretical Analysis at Mach 7.

5. CONCLUSION

The primary objective of this work is to present the dimensional design of the 14-X Hypersonic Aerospace Vehicle, designed as an option of a new generation of scientific aerospace vehicle to replace not in a too distant future the conventional multi-stage rocket-powered vehicles, which have flown hypersonically, carrying their own propellant (solid and/or liquid, oxidizer along with fuel) to propel payloads and astronauts to Earth’s orbit.

Experimental investigations at the Hypersonic Shock Tunnels along with non-intrusive diagnostic techniques, Computational Fluid Dynamics (CFD) codes as well as Theoretical Analysis have been used to design the 14-X Hypersonic waverider scramjet Aerospace Vehicle.

Experimental data of the waverider and scramjet configurations obtained with the T3 Hypersonic Shock Tunnel have been used to compare with the CFD codes at the IEAv.

Also, the internal configuration (volume) of the 14-X Hypersonic waverider scramjet Aerospace Vehicle have been designed and specified, based on the on-board equipment’s such as instrumentation, fuel tank, telemetry and data acquisition system, which some are specified to monitor the combustion during the flight of the 14-X Hypersonic waverider scramjet Aerospace Vehicle.

Several activities are just started after the previous dimensional design of the 14-X Hypersonic waverider scramjet Aerospace Vehicle as materials for the internal structure and Thermal Protection System, aerodynamic heating, thermal and structural analyses, interstage adapter system used to couple the 14-X Hypersonic Aerospace Vehicle and the Hypersonic Accelerator Vehicle and optimized trajectory.

6. ACKNOWLEDGEMENTS

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