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Hypersonic Waverider Test Vehicle: A Logical Next Step

Douglas J. Tincher*
Science Applications International Corporation, Huntsville, Alabama 35806
and
David W. Burnett†
McDonnell Douglas Aerospace, Huntington Beach, California 92647

Hypersonic waveriders have long been associated with extremely high lift-to-drag ratios (*L/D*) and exotic configurations with a wealth of investigation occurring from the 1950s until their fall from favor in the 1970s. Over the past few years, they have undergone a major investigative reemphasis brought about by resolution of major historical criticisms, namely poor *L/D* performance when viscous effects were included, and poor packagability. Although University of Maryland research resolved the viscous effects degradation issue with the viscous optimized hypersonic waverider family, this paper discusses modified versions of the Maryland waverider family that dramatically improve packagability making them suitable for use in many of today's and tomorrow's hypersonic missions. The paper discusses their transition from idealized shapes to one vision of near-term reality, a low-cost maneuvering hypersonic test vehicle based on a focused development and validation effort. Waverider flight demonstration is crucial to enabling high-confidence technology transfer to the wealth of supersonic/hypersonic vehicle opportunities where high aerodynamic efficiency is a fundamental requirement. The paper closes by briefly discussing the suitability of these modified waveriders for application to interplanetary missions using aerogravity-assist maneuvering.

Nomenclature

BRV = ballistic re-entry vehicle
C_D = total drag coefficient
g = unit of gravitational force
HPMaRV = high-performance MaRV
$(L/D)_v$ = viscous lift-to-drag ratio
$(L/D)_t$ = total L/D (including viscous and base drags)
$(S)_{base}$ = base area
$(S)_{plan}$ = planform area
$(S)_{wet}$ = wetted area

Introduction

FOLLOWING a period of great enthusiasm and research activity in the field of hypersonic waveriders from the 1950s until the early 1970s, they were nearly forgotten except by a few devoted advocates in industry and academia.[1-3] With the advent of the National Aero Space Plane (NASP) program, waverider activities were reinvigorated, resuming a fast development pace which has led to significant advancement in their application to "real world" systems. However, historical shortfalls such as viscous *L/D*, packagability, and off-design *L/D*, produced prejudice remaining to the present. Recent developments are felt to dispel the historical shortfalls enabling waverider technology application throughout the hypersonic flight regime. A further modification to the Maryland viscous optimized waverider is presented along with a proposed approach to mitigating leading-edge bluntness-induced *L/D* losses.

In explanation, "aerodynamic efficiency" as used in this paper represents a Küchemann view as opposed to a more conventional view of aerodynamic performance. Whereas the latter connotes high lift potential (ordinarily with little regard for drag implications), the former connotes high lift potential at minimal drag (i.e., maximum *L/D*). Also, when "high *L/D*" and "good packagability" are referenced, it is based on viscous *L/D* routinely greater than twice that of traditional hypersonic vehicles with shapes suitable for packaging off-the-shelf maneuvering re-entry vehicle (MaRV) internal components, placement on existing boosters, with *L/D* retention at off-design conditions. Also, the reader must be forewarned not to assume that all waveriders are the same. Aside from their commonalty of being designed from a known flowfield with a shock captured on the windward surface by the leading edge, there can be remarkable differences between waveriders resulting from different design methodologies.

Furthermore, because fully laminar *L/D* can be double that with a fully turbulent boundary layer, only fully turbulent *L/D* is referenced irrespective of altitude and velocity to maintain high conservatism in *L/D* predictions for continuum regime flight.

This paper is divided into sections covering advancing the reality of current waveriders, the development of a waverider flight test vehicle, anticipated experimentation, and future mission requirements for waverider *L/D*. Specifically, if this technology is to be ready for aerospace plane applications, and interplanetary missions forecasted to occur sometime in the next two decades, waverider *L/D* must be demonstrated in the relative near term. It is hoped the reader will develop a greater appreciation of the importance of advancing this unique and innovative aerodynamic design technology, leading to widespread application of this technology.

Modified Viscous Optimized Waverider

Continued waverider technology development is fueled by the need for high aerodynamic efficiency in hypersonic flight. This need is true for all supersonic/hypersonic atmospheric cruise vehicles, powered or not. The ability to fly with low drag at hypervelocity provides opportunities for extended range and maneuverability, the ability to achieve orbit with minimum propulsion or maximum payload capacity, or relaxing re-entry

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*Senior Scientist, Fluid and Propulsion Sciences Operation, 6725 Odyssey Drive. Member AIAA.

†Manager, Aero Thermal Systems Department, Advanced Product Development Division, 5301 Bolsa Avenue. Member AIAA.

environments on human occupants or cargo. As the origin and description of the Maryland viscous optimized waverider concept and Maryland AXisymmetric WAve Rider Program (MAXWARP) waverider design code have been presented on numerous occasions prior to this writing[4-6] only minor description is provided here. This section is primarily concerned with implications of Tincher and Heerdt[7] enhancements to the original Maryland waverider concept.

In explanation, Maryland-class waveriders conform to the conventional *waverider* definition in that they are defined from a known flowfield and support their shock exclusively on the windward surface. To generate a waverider, the user need only provide a supersonic/hypersonic flowfield (typically from a body of revolution) and a continuous leading-edge shape prescribed on the flowfield shock. The waverider shape is then inversely derived from the flowfield. The windward surface is defined by piecewise tracing of flowfield streamlines from the leading edge on the shock to the vehicle base. The leeward surface is defined either by projecting the freestream velocity vector between the piecewise leading-edge locations and the vehicle base, or by piecewise prescription of two-dimensional expansion surface streamlines from the leading edge to vehicle base (used to mitigate boundary-layer growth effects or theoretically reduce lee surface pressures below freestream).

Maryland waveriders are derived using a Nelder and Mead simplex optimization process embedded in MAXWARP to iteratively seek the minima of a user-specified objective function, i.e., the Figure of Merit (FoM). The simplex requires nine numerical expressions within the FoM domain to iteratively resolve a minima. These expressions are parametric variations to the leading-edge shape. MAXWARP compares FoM results from the present iteration vs the previous iteration. For the subsequent iteration, the present iteration's best leading edge (and eight parametric variations to it) are converted to waveriders and FoM results recomputed for input to the simplex algorithm once again. These parametric variations are defined within the MAXWARP framework as "seed" leading edges, which simply translates to numerical expressions used to produce well-behaved leading-edge curves (physically reasonable) when applied to a nominal leading edge. The baseline MAXWARP FoMs are the maximum of L/D (minimum of $-L/D$), or the minimum of C_D. Approximately 100 iterations are suggested to be assured the simplex algorithm has settled on the minima of the FoM domain. Cases can be rapidly executed on a PC (or workstation) with 100 iterations requiring less than 15 min on a 486DX-33 PC.

In early studies where Tincher and Heerdt attempted to apply Maryland waveriders to doubling the L/D performance of conventional re-entry system designs,[7] geometric limitations were encountered with MAXWARP shapes. This problem occurred when shapes were sized or scaled to accommodate critical off-the-shelf internal components; their resultant lengths were incompatible with placement on the specified Minuteman II launch vehicle (MM II) booster. Conversely, if an appropriate length was specified, the resultant vehicle was too slender to accommodate the components and too wide for booster integration. MAXWARP's geometric parameters were rigorously exercised without satisfactory results, thus it is recommended the user attempt to circumvent dimensional and volumetric difficulties without employing the volumetric controls when possible. Also, though MAXWARP permits power-law and biconic body initial flowfields, the resultant waveriders do not possess significantly improved L/D nor packaging efficiency when compared to those generated from conical flowfields. Since the seed leading edges cover a reasonable progression of legitimate waverider leading-edge attributes, they remained untouched. The investigation thus centered on altering the FoM to resolve width and slenderness issues.

Given the need for coupling high L/D with good packaging characteristics, a series of systematic variations to MAXWARP's baseline FoMs were attempted, the best of which is described here. Knowing the objects to be packaged internally were designed for placement in conical frusta, "modified" FoMs stressed physical attributes of cones. Cones possess a "good" blend of L/D, packaging volume, and planform area (i.e., volumetric efficiency factor terms). Conical terms were thus factored into the maximum-L/D FoM resulting in a variety of solutions (nearly identical L/D; some improved usable volume; some not). These solutions, however, typically retained the characteristic waverider long, wide, slender profile with slenderness remaining the principal issue. This issue was resolved by substituting wetted area for planform area terms in the modified FoM since "volumetric efficiency" appears to be meaningful in this use for bodies where side and planform areas are roughly equivalent. The resultant FoM became the maximum of:

$$(L/D)_v{*}(\text{Volume})^{0.667}/(S)_{wet}$$

where $(L/D)_v$ includes pressure and friction forces, but does not include base drag. Base drag is not included in the optimization FoM since it was observed that MAXWARP attempts to balance all drag contributors. The result is that the base drag contribution is a higher percentage of the total when included in the optimization process than when it is amended in subsequent aerodynamic analysis.

In the earlier work of Tincher, the modified FoM resulted in configurations that met the strict internal and external packaging goals with $(L/D)_t$ (including base drag) greater than twice that of similarly sized traditional re-entry vehicles. Once the new FoM was employed, length (for similar useful packaging volumes) was reduced nearly 40% with approximately equal $(L/D)_t$. Geometric comparison is provided in Fig. 1, where the images have been scaled to the same length. The baseline configuration is a best-volumetric viscous optimized waverider using the maximum $(L/D)_v$ FoM. The modified configuration used identical inputs but employed the new FoM. It is easy to note the usable packaging volume increase for the same length. When sized for identical volume, the modified FoM configuration is far more compact. And there also is a significant reduction in $(S)_{base}$ leading to a significant base drag reduction for a given usable packaging volume.

Configurations, and on- and off-design L/D results, for three modified-FoM waveriders of identical length are presented in

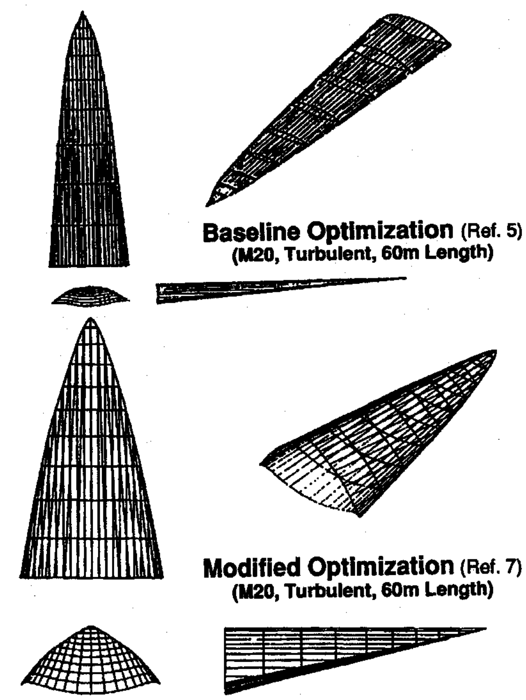
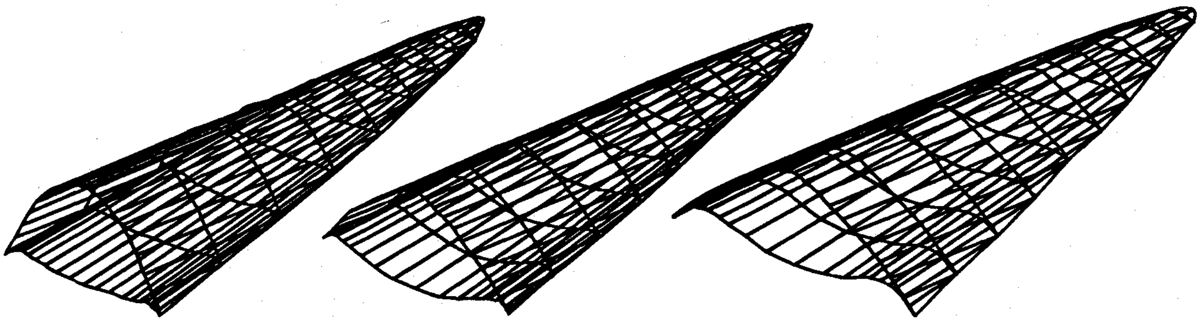


Fig. 1 Modified waveriders increase usable packaging volume without decreasing *L/D*.



Mach	Abase (ft2)	Aplan (ft2)	Awet (ft2)	Volume (ft3)
20	3.340	17.288	40.699	10.964
10	3.661	19.391	43.055	11.294
5	3.893	24.701	53.608	11.811

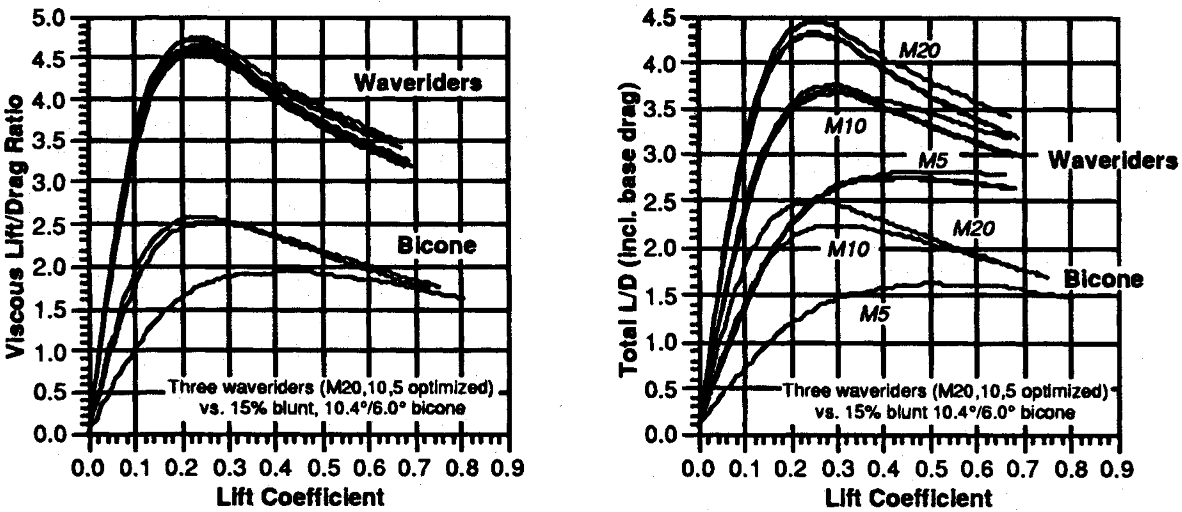


Fig. 2 Comparison of on- and off-design *L/D* for modified waveriders vs bicone.

Fig. 2. Each was optimized at unique conditions (Mach 20 at 38.1 km, Mach 10 at 25.9 km, and Mach 5 at 13.7 km, respectively) yet analyzed at its own and the other flight conditions (assuming fully turbulent boundary layers) to assess *L/D* degradation with altitude, Mach number, and angle of attack. The left plot presents viscous *L/D* for the three modified waveriders. *L/D* can be seen to be greater than twice that of traditional hypersonic vehicles typified by conical and biconic configurations. In addition, the waveriders reproduce the on-design performance of their unmodified brethren very well. The right plot presents *L/D* when base drag is amended. One must note that although hypersonic base drag is nominally small, the other drag contributors are also small, thus increasing its relative influence. However, waverider *L/D* remains double that of the conventional biconic vehicle. Similar comparison of the Mach 20 configuration with a circa-1990 Wright Research and Development Center (WRDC) high-winged Hypersonic Glide Vehicle (HGV) demonstrated identical on- and off-design viscous *L/D* performance with the waverider being only two-thirds as long as its HGV counterpart when packaged with mandated internal components.[7]

Intuitively, one can see that the "best" modified waverider cannot provide as high an *L/D* as the "best" standard Maryland waverider because of the former's trade of absolute *L/D* for packaging efficiency. However, these modified waveriders provide numerous benefits over traditional waveriders in their ability to combine high *L/D* (on- and off-design), with compactness for structural strength, and reduced base area (for the same useful packaging volume).

Leading Edges

Under hypersonic flight conditions, the ideally "sharp" leading edges (which form and support the shock and constrain the resultant high pressure to the windward surface) could not possibly survive the flight times necessary for meaningful experimentation below 30.5 km altitude, or for aerogravity assist (AGA) maneuvering. Leading edge studies by Kothari and Bowcut[8] and Lewis and McRonald[9] have demonstrated "optimized" two-dimensional solutions to a hypersonic leading edge which minimizes or tailors the aerothermal loads. However, this work did not address coupling of the leading edge with the waverider flow field; thus this paper only addresses circular cross-section leading edges.

Since the waverider's shock bounds the windward surface, extending from wingtip to wingtip, the steepest pressure gradients (other than across the shock itself) are located near the wingtips. The high pressure gradient at the leading edge helps to contain the flow on the windward surface even at angle of attack.[10] Conditions at axial stations downstream and inboard of the leading edge are set by their own position with respect to the "idealized" stream surface and the properties at the leading edge.

Experimental data,[3] which form the basis for much of the waverider leading-edge treatments to date, demonstrated that flow leakage about the blunted leading edge is modestly localized to the leading edge so long as the leading-edge radius does not exceed approximately 1% of the vehicle length. However, the *L/D* implications of this traditional blunting approach are more severe than may be indicated by the pressure profiles. This can be explained by the removal of material from the wingtip. This traditional manner of blunting a waverider's leading edge (Fig. 3) disturbs the initial flow properties at the leading edge, resulting in a mismatch between the flow that the windward surface would ideally support, and the flow actually formed. Areas inboard of the wingtip attempt to form the flow as though the shock remains in its idealized placement, yet the actual shock "attachment" location (given the finite standoff distance) is now inboard of the idealized location. The resultant windward flow is no longer compatible with containment resulting in leakage from the windward to the leeward surface. The impact of leakage on *L/D* is explained by decreased windward pressures (lift reduced more than drag) coupled with increased leeward pressure (increased drag, decreased lift).

The way in which leakage occurs in the traditional blunting scheme leads to the hypothesis that leakage does not primarily occur as a result of blunting, but rather as a result of the method of blunting. It follows that an optimized leading-edge treatment is possible which can mitigate heating and erosion problems, while minimizing flow leakage-induced *L/D* degradation. To minimize flow leakage it is offered that the leading edge should be modified, adding material rather than removing it, as is also shown in Fig. 3. In this case, the configuration is split along its sharp leading edge. The leeward, or upper, surface is temporarily eliminated. A locally two-dimensional leading edge (sized by the aerothermal conditions) is fit piecewise to the outboard edge of the windward surface. Following standard waverider convention, a new upper surface is formed in a piecewise manner using freestream velocity rays, or two-dimensional expansion streamlines, which extend to the base of the waverider. The leading edge, by being relocated outward, is presumed to induce a pressure equal to or higher than the idealized leading-edge location, thus more closely reproducing the rigorous flow containment state. Through optimization within a waverider design code, it is hoped that such a leading edge will couple

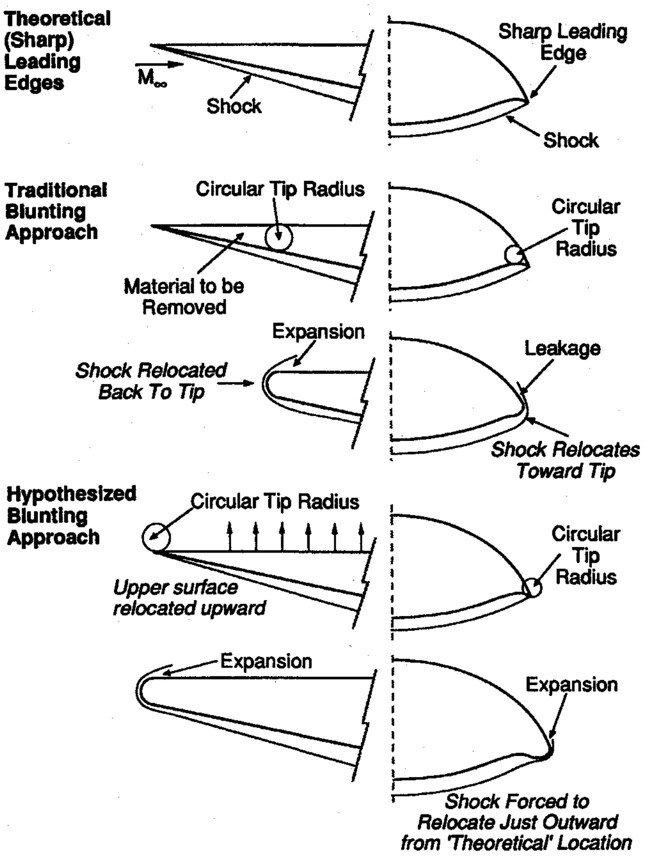


Fig. 3 Hypothesized bluntness approach intended to reduce bluntness-induced *L/D* loss.

lower leakage with the improved survivability aspects of bluntness. Continued analysis to validate this hypothetical leading-edge blunting technique is underway based on computational fluid dynamic techniques.

Flight Test Vehicle Development

The development of an unmanned maneuvering hypersonic flight test vehicle based on the above discussions is possible in the near term. A waverider program should not be construed as a replacement for an existing technology or flight test project, but rather a near-term technology augmenting focus. As an example, a vehicle was designed at McDonnell Douglas[7] to accommodate all instrumentation; guidance, navigation, and control; avionics; and controls necessary for maneuvering re-entry flight under conditions well beyond those necessary to meet the objectives of the NASA Generic Hypersonics Research Program (GHRP) High Velocity Research Envelope (HVRE) shown in Fig. 4. By leveraging Department of Defense (DoD) re-entry system hardware and software experience, and with judicious relaxation of the MIL-SPECs for flight articles, it is felt that such a system could be built at relatively low expense by a re-entry system integrator. In a robust program approach, present-day technology can be applied with minimal risk limited to the uncertainties remaining following an analytical and experimental validation phase. If greater risk for higher technology payoff can be tolerated, then exotic thermal protection materials and/or systems can be applied in early flights.

As with any flight system, aerothermal validation of the vehicle and its performance is mandatory. Current heatshield, transpiration cooling, and aerodynamic flap control technologies can be readily applied to this vehicle, although their effectiveness must be assessed with detailed analysis. Rigorous analytical validation of the vehicle (including leading edges and control scheme) should take best advantage of methodological advancements brought about by such programs as the NASP and aeroassist flight experiment (AFE). As shown in Fig. 5, ground testing could be accommodated in industry and government wind tunnels (e.g., NASA Ames Research Center (ARC) or Langley Research Center (LaRC), Calspan HST, NSWC, Arnold Engineering Development Center, or Wright Research Development Center, although compromises may be required depending on vehicle size, Mach number, and enthalpy. If the flight articles are constructed small enough for full-scale wind-tunnel testing (laminar boundary layer), flight uncertainties in aerodynamics and control can be minimized. Larger flight vehicles (length $\geq$ 2.5 m), which provide the opportunity to study natural transition and turbulence, demand test and/or specimen compromise. Scaling to substantially larger sizes, as determined

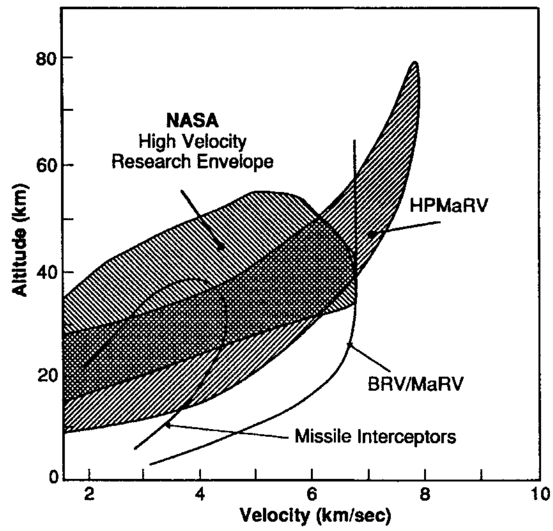


Fig. 4 Flight envelope similarity between defense programs compared to HVRE.

by mission requirements, may present a challenge to the design process as is discussed by Lewis and McRonald.[9]

With a focus on flight demonstration/validation, we propose the development of a viscous optimized waverider-based hypersonic flight test vehicle. This waverider should stress operation throughout the High Velocity Research Envelope (HVRE) shown in Fig. 6. It would thus have immediate application to the science and technology objectives of NASA's GHRP providing strong relevance to present and future needs. The utility of such a flight test vehicle for a range of atmospheric, hypersonic flow (continuum and rarefied), and flight dynamics measurements is significant. Critical issues, desirable attributes, and proposed analyses and assumptions must be identified and issues resolved. Other options include using the waverider shape as the aeroshell for other flight test experiment options. Thus, these data could be complementary to other aeroshell design and evaluation programs such as the AFE by providing information regarding high *L/D* vehicles.

Launch options for a waverider test vehicle are plentiful. They are primarily dependent on the size of the vehicle which, in turn, is an explicit function of the scope and size of instruments to be placed in the vehicle. Sized as a primary payload to a Pegasus (air-launch) or Minuteman (ground-launch) boosters, or with small expendable deployer system-like tether deployment from a Space Shuttle Orbiter or a Delta II second stage as is described by Burnett,[11] the vehicle could easily accommodate all instruments necessary to meet the above-stated objectives since the vehicle could be greater than 2 m in length.

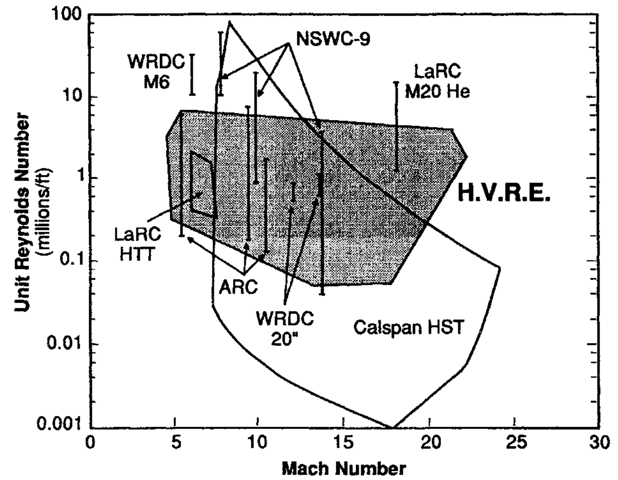


Fig. 5 Current wind tunnel facilities cover a majority of the required altitude/velocity test conditions.

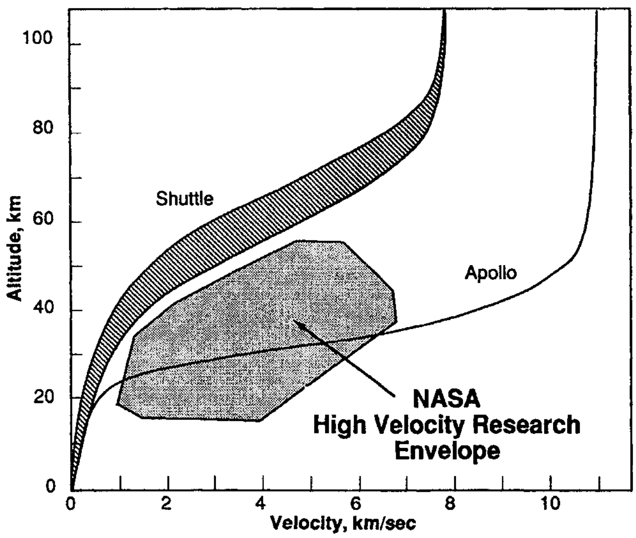


Fig. 6 HVRE bounds a velocity/altitude range more stressing than for Shuttle or Apollo.

Flight Experimentation

There are a wealth of flight measurements which can and must be made to characterize general hypersonic flow phenomena and the flow on and about the waverider vehicle. In nearly all cases, however, additional advancement is required in instrumentation technology and miniaturization to ensure instrument survival and make them compatible with placement in a relatively small vehicle. A parachute recovery system similar to that designed for MaRV programs could be employed to ensure vehicle recovery for postflight visual inspection and potential reuse of high-cost internal components.

Since the leeward surface of the hypersonic waverider is aligned with the freestream velocity vector, flow over this surface behaves two dimensionally making it ideal for performing boundary-layer measurements in flight. If the vehicle is long enough, instruments can bound natural transition regions. Measurements at a relative angle of incidence can be accommodated by employing the control system. Or, measurements can be obtained on the windward surface for the investigation of more severe aerothermal conditions.

Surface and flowfield measurements (Fig. 7) can be obtained similar to those proposed for the AFE[12] or similar hypersonic test bed.[13] Intrusive probes could be located within the airframe until such time that they are exposed to the flow during specific flight phases. Provision for probe jettison or retraction must be designed into such a system to minimize adverse effects on subsequent measurements or compromise of the mission due to thermal loads transferred through and about an exposed probe. A primary nonintrusive emphasis can provide increased knowledge of the boundary-layer behavior because nonintrusive techniques represent the optimal means for directly measuring flowfield and turbulence quantities in flight,[14] but it is clear a substantial effort would be required to select and develop the most reasonable technique, and integrate the instruments to the flight vehicle. Given the upper surface orientation flexibility coupled with optical window developments by the U.S. Army and Strategic Defense Initiative Organization, a window should be capable of surviving the flight. Mean and fluctuating flowfield diagnostics data could be gathered using, for example laser-induced fluorescence, laser Doppler velocimetry, Rayleigh scattering, Raman spectroscopy, or electron beam techniques if sufficient power and device efficiency can be attained. Flowfield penetration depth, given internal laser placement, is relatively small thus decreasing power requirements. Such systems must first be demonstrated on the ground under simulated flight vibration, pressure, density, and temperature conditions while being packagable to the flight system.

A waverider flight test vehicle can be designed, using carbon-carbon leading edges, to survive flight through the HVRE so long as the nosetip is protected using existing active cooling

Flow Field Diagnostics

Intrusive/Surface Mount
- Temperature Probes; T_T, T_T'
- Pressure Probes; P_p, P_p'
- Hot Film Gages; (ρu), $(\rho u)'$
- Sample Probes; c, c'
- Skin Friction Gages; c_f

Nonintrusive
- Electron Beam; ρ, ρ'
- Laser Doppler Velocimeter; u, u'
- Laser Induced Fluorescence; ρ, ρ', T, T'
- Raman Spectroscopy; c, c', T, T', u, u'
- Rayleigh Scattering; ρ, ρ', T, T', u, u'

Fig. 7 A variety of flow-field diagnostic techniques can be assessed for obtaining a mean and fluctuating hypersonic boundary layer and shock layer characteristics.

technology such as water transpiration. Therefore, early flights can be accomplished without the need for exotic thermal protection systems. The thermal environment provides an excellent opportunity for testing leading-edge heatpipe technology in flight. Heatpipe and conducting plate technologies have advanced since Nonweiler proposed them as a means of transporting thermal energy from waverider leading edges.[15] As heatpipe technology further advances, an externally passive system is envisioned to replace the transpirationally cooled nosetip permitting boundary-layer measurements with minimal adverse vehicle influence on the flowfield.

As new higher-temperature heatshield materials are developed for manned and unmanned systems, they can exceed the ability of ground test facilities to replicate the environment they must survive. The waverider vehicle should be designed to accommodate new heatshield panels in part or in their entirety (depending on material thermal growth and reaction mismatches). Designed-in flexibility would permit heatshield testing under hypersonic conditions in high heating (windward surface placement at high angle of attack) and/or low heating (leeward surface or windward surface at low-to-negative angle of attack) conditions. As wall catalysis plays an important role in high altitude, ultrahigh velocity flight, the coupling of the measurements described previously (or those proposed for the AFE) with waverider flight permits direct measurements under the wider variety of flight conditions made possible by high *L/D* flight.

Air data sensor technology is thought to be relatively advanced although improvements are envisioned as programs such as NASP force advancement of the state-of-the-art. Test vehicles of the 2.5+ m length class can become the focal point for the latest developments in hypersonic air data sensor systems to enable flight demonstration prior to their application to critical manned and unmanned systems. This is especially important for long-duration flight since time of flight typically stresses the ability of the system to provide continuous accurate information. High-accuracy measurements through the mesosphere would provide valuable insight to the density variations in this altitude band as well as provide a stressing demonstration/validation environment for these systems.

As the gathering of atmospheric data in the mesosphere is of particular significance, a number of data collection opportunities are made available with a high *L/D* test vehicle. Data can be gathered over extended ranges and time periods at constant altitude because of low waverider drag. This has been seen in recent Maryland research[16] where it was shown that whereas *L/D* is substantially diminished as a result of transitioning from continuum to rarefied regime flight, the drag coefficient merely doubles over an altitude range where density falls by nearly four orders of magnitude. Direct-simulation Monte Carlo (DSMC) calculations at NASA LaRC by Rault[17] have confirmed that although *L/D* is diminished at high altitude, the waverider remains superior to the other configurations addressed.

Measurement strategies are envisioned to consist of continuum regime flight coupled with pull-up maneuvers inducing an arcing glide through the altitude band of interest (taking best advantage of waverider *L/D* to maximize time within that band). The waverider would gradually return to continuum flight where the maneuver could be repeated as needed. If measurements are required at low-to-zero velocity, a primary (or secondary) mission can be flown where a rapid pull-up maneuver is initiated lower in the atmosphere to remove all velocity at a given altitude. A parachute would then deployed and data collected as the vehicle drops to Earth. The parachute can be retained or jettisoned to enable additional data collection or subsequent maneuvering to the vehicle recovery location.

AGA: Long-Term Need for Waverider *L/D*

Beyond the design of Earth-borne aerospace planes, one of the foremost projected needs for waverider *L/D* is to enable fast far-planet exploration using AGA maneuvering.[18–22] While remote exploration of the Sun, Uranus, Neptune, and Pluto are of enormous scientific value, trip times, particularly to Pluto, are prohibitively large and launch opportunities are limited using classical Jupiter gravity-assist techniques. AGA maneuvering, as developed by Randolph and McRonald of the Jet Propulsion Laboratory, appears to hold great promise of significantly reducing trip times and launch energy while increasing launch opportunities by taking advantage of gravity and atmospheric effects during encounter of intermediate planets. To minimize drag losses during a planetary encounter, such AGA vehicles are critically dependent on the ability to realistically produce waverider-class *L/D* with a realistic shape and structure. Since the references go into substantive detail as to the mechanics and benefits of AGA, this technique is only briefly explained here to relate it to the generation of practical waverider shapes.

In AGA maneuvering, the vehicle follows much the same flight path as in a traditional gravity-assist mode except the vehicle encounters the planet's atmosphere (within the continuum, ~30–50 km equivalent Earth altitude) during the pass (Fig. 8). The vehicle performs a roll maneuver to orient the lift vector toward the planet center, increasing the turning angle thereby dramatically increasing the spacecraft velocity during the encounter while promoting departure angle flexibility. JPL and Maryland research[6,9,19] have shown the potential benefits of employing AGA given small atmospheric drag losses for the moderate lift required.

Special attention must be afforded to the thermal protection scheme necessary for planetary encounters. In a systems context, the trajectories will be tailored based on available and projected thermal protection technology limits (active and passive techniques). Recognizing that the vehicle is not intended to be any more reusable than other planetary exploration vehicles, ablation shape change can be tolerated to the state where *L/D* is seriously compromised. As an example, in the circumstance of Earth return or Mars aerocapture, the waverider need not

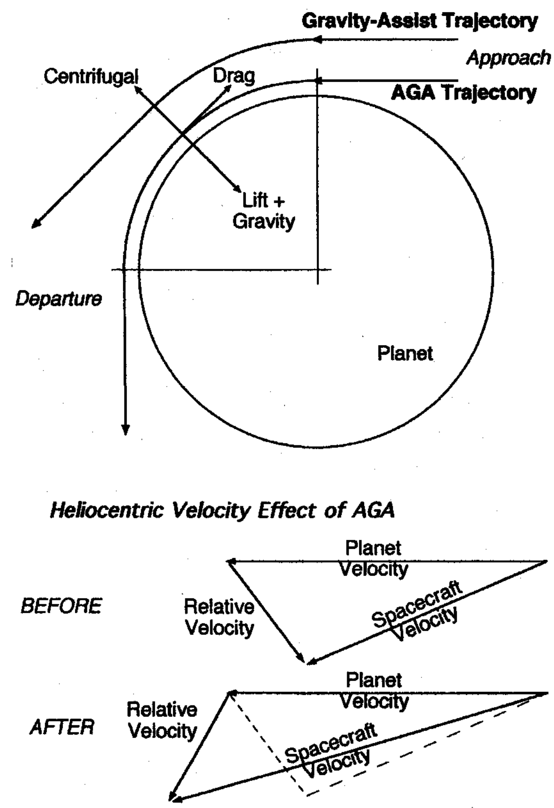


Fig. 8 Diagram of an AGA maneuver as compared to a conventional gravity-assist maneuver.

retain more *L/D* capability than would be necessary for low-*L/D* aerobraking as was shown in NASA's AFE program.[12]

Near-planet exploration under the direction of the reconstituted space exploration initiative (SEI) program offers the potential for cooperatively demonstrating AGA in missions to Mars commencing near the end of this decade. Minimizing transit times and energy requirements are high mission priorities based on human and launch economy factors. The Randolph AGA references cite that a Mars mission using a Venus aeropass would substantially reduce the required launch energy (as compared to current transportation options). Similarly, if the conventional transportation option trip time is acceptable, the velocity increase available through a Venus aeropass would reduce the Earth-departure energy requirement. Aerocapture would complete the AGA trip to Mars leaving it free to deploy landers or probes, or to be used as a lander itself by employing a pull-up stall maneuver with parachute deployment or reaction rockets used to mitigate landing loads. In addition to the positive influence on SEI program functionality and economics, use of AGA in a Mars mission can provide necessary confidence for AGA use in interplanetary missions.

Waveriders of the Maryland family have been shown capable of providing *L/D* sufficient to enable AGA maneuvering. However, with unmanned missions reasonably approaching lateral accelerations of 25 *g* to minimize mission flight time, attention must be paid to the design of a compact, minimum-weight structure capable of carrying and protecting cargo (as were discussed in previous sections). This is where these modified waveriders are expected to provide aeroshells better suited than their nominal waverider counterparts for surviving the maneuver loads.

What must occur prior to a commitment to AGA missions, though, is a waverider flight demonstration at Earth. As stated earlier, the flight envelope of choice is most accurately represented by the NASA GHRP HVRE. Flight in this domain provides for high dynamic pressure, hypersonic flight to stress airframe, heatshield, guidance, and controls technologies prior to AGA validation testing, and ultimately, AGA interplanetary missions.

Conclusion

Waveriders are not a figment of 1950s fantasy transplanted in the 1990s. This technology has progressed enormously since its inception, with the principal historical criticisms resolved, particularly in the past few years. Waveriders have progressed to the point where they deserve devoted attention. They can serve as a key enabling technology to a number of hypersonic research activities. A waverider-based hypersonic flight test vehicle is the logical next step toward this goal.

A waverider flight test vehicle is a logical step to achieving the hypersonic science and technology ambitions of NASA's GHRP. Successful completion of initial flight testing opens the possibility for widespread waverider application to many hypersonic missions including NASA's SEI and other interplanetary mission initiatives. Data regarding hardware performance in flight can then be made readily available to the user community at low risk and low relative cost for a dedicated or shared flight. Hypersonic fluid dynamics and flight dynamics data would be available throughout the HVRE and beyond, flying in a high *L/D* or moderate *L/D* orientation. Initial tests can be performed at low relative cost by primarily using off-the-shelf MaRV components and thermal protection system elements.

Nowhere is the need for waverider technology more apparent than in AGA maneuvering missions to the Sun and far planets. There appears to be adequate time to conduct feasibility design studies to further advance and rigorously validate the design concepts prior to technology cutoff dates based on gravity-assist mission strategies. It is urged that an analysis and testing program be initiated rapidly. To miss this opportunity would undoubtedly have a detrimental impact on interplanetary missions, and a commensurate impact on waverider progress.

The waverider state-of-the-art has progressed far under the leadership of academia. Recent progress in transitioning waveriders from idealized, theoretical shapes to "real" vehicles has placed waverider technology at the next threshold in their development. Without a waverider program, waveriders will likely remain a topic of enthusiastic investigation but progress will likely be slow, particularly without the resources available with program status.

NASA's hypersonic flight test priorities and budgets should strongly reflect recent waverider advancement and readiness levels. The GHRP budget for waverider technology should be set sufficient to initiate a significant study, with ultimate cost potentially shared by interested industry and academic partners and end users. NASA's research center personnel could readily apply their hypersonic methods to this topic to establish an official government baseline to provide a focus to activities, particularly related to feasibility and projected cost. This would also be of value to meeting U.S. aeronautics and space technology objectives, and fluid dynamic and flight dynamics research and education goals.

Drawing on existing defense technology can minimize startup costs for a flight test demonstrator. NASP and AFE analysis and materials developments can be directly applied to this vehicle. With flight demonstration of the waverider concept there will be no remaining roadblock to the infusion of this technology to future hypersonic vehicle designs.

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Gerald T. Chrusciel
Associate Editor