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Research and Design for Hypersonic Aircraft

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Research and design for hypersonic aircraft

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This paper presents a short account of some problems that arise in the practical achievement of hypersonic flight, and it reviews some possible solutions. It is in no way a complete account, but it presents, among other things; (*a*) some well established methodology, which was produced too late to influence hypersonic design during the mid 1960s, and is now in some danger of being left in the archives; and (*b*) some revised proposals on how the essential needs of component design and vehicle integration can be realistically achieved.

Glossary of terms

α, δ	angle of attack or flow deflection
γ	ratio of specific heats
ζ	shock angle
η	efficiency
A_{cap}	intake capture area
AOTV	aerodynamically assisted OTV
CCV	control configured vehicle
C_L	coefficient of lift force
C_D	coefficient of drag force
C_{D0}	coefficient of drag at zero lift
C_f	coefficient of skin friction
D	aerodynamic drag force (incl. friction)
D_P	aerodynamic drag due to pressure only
f_1, f_2	functions of Mach number in figures 8, 13 and 15
HST	hypersonic transport (aircraft)
H_{tot}	total (freestream) enthalpy
H_w	wall enthalpy
l_f	forebody length
L	aerodynamic lift force
L/D	lift-to-drag ratio
M	local Mach number
M_∞	flight Mach number
NASP	National Aerospaceplane (American project)
OTV	orbital transfer vehicle
p	local static pressure
p_b	base pressure
p_∞	ambient static pressure
q	kinetic pressure

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$\dot{q}$ heat transfer rate
SSTO single-stage-to-orbit (aircraft)
T thrust
T_{∞} ambient static temperature
T_{LE} leading edge temperature
TSTO two-stage-to-orbit (aircraft)
V ratio of flight speed to circling speed at flight altitude
V flight speed

1. Introduction

A recurrent theme in aeronautics is the replacement of expendable ballistic space launchers with a fleet of reusable aerospaceplanes. Pioneered by Sanger in the 1930s, this approach has been periodically reassessed by design teams ever since. In Britain, the design studies of Wallis (1962), Jamison (1961) and Francis (1969) were conceptual forerunners of the later HOTOL single-stage-to-orbit studies. In Germany, Sanger is now the name of a two-stage aerospaceplane (figure 1*a*), which stands at the centre of a five year Hypersonic Research and Development Program, funded at over \$200M. In addition, in January 1990, the conceptual design of a turboramjet hypersonic research aircraft was funded by the Germans, and further design and fabrication is planned to permit a first flight in 1998.

A common feature of aerospaceplanes is the use of air-breathing propulsion to replace or enhance rockets for much of the acceleration period, the fundamental reason being shown in figure 1*b*. The prospect of much lower fuel consumption, however, is set about with practical reservations and operational constraints that together determine the extent to which, on a practical vehicle, the rocket can be replaced and an efficient air-breather fully exploited.

A second recurrent theme is the hypersonic airliner. The fluid dynamics of such aircraft, when analysed to the exclusion of variable sweep and artificial stability, were studied by Kuchemann & Weber (1965), and NASA produced a detailed assessment for a cruise Mach number of 6. Since then, the projected use of new airliners as fast or faster than *Concorde* has re-emerged and been considered technically feasible. In economic and environmental terms, however, both supersonic and hypersonic transport are subject to doubt, because operational restrictions on nighttime flying and on supersonic flight overland would severely restrict their productivity for routes they would otherwise benefit. The situation can be illustrated as in figure 2 (Mizuno 1986). Where a direct flight path cannot be drawn over the ocean, then major diversions are mandatory; and where a time curfew is in force, productivity falls still more. The result is that a truly hypersonic airliner may not be desirable except perhaps for trans-Pacific and Australasian routings, and that a replacement for *Concorde* may need to offer greater size and economy rather than a much greater speed.

A third and relatively new theme for the hypersonic aeroplane is that of the OTV. Here the airport is replaced by a Space Station and the vehicle may have a cruising Mach number exceeding 20. In essence, the vehicle is space-based and may never return to Earth, but for efficiency in its task it is required to enter the atmosphere and then to regain orbit after cruising at speeds far higher than a 'conventional' HST would ever reach: and when its purpose is to change the orbit plane, its 'design point' will be a highly banked turn.

This paper follows hypersonic aircraft on typical missions and isolates some of the

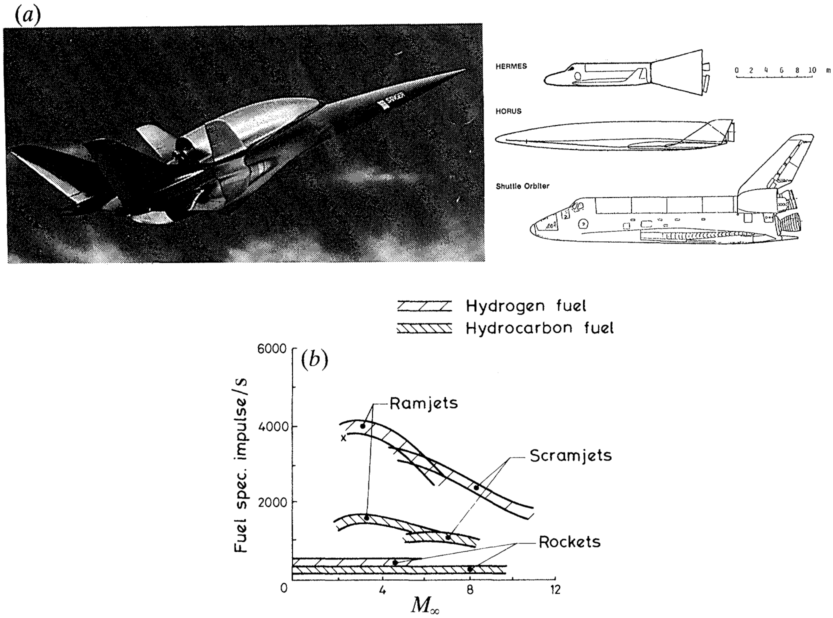

Figure 1. Air-breathing launchers. (*a*) Sanger, Hermes, and the Shuttle Orbiter. (*b*) The economy of propulsion units. ×, wake combustion experiment.

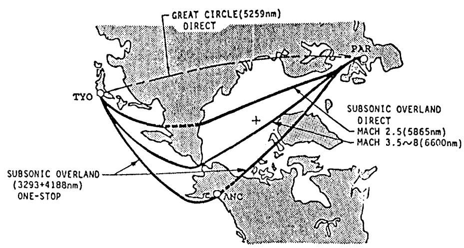

Figure 2. Supersonic transport routes from Tokyo to Paris.

problem areas which demand solution. Except for the OTV, they arise not only at hypersonic conditions, but in transonic and supersonic flight where, for example, air-breathing propulsion is heavily off-design. At higher speeds, the constraints of structural heating restrict both the flight path, and the extent to which the more efficient forms of propulsion can be fully utilized. In re-entry, the problems of heating and control are no longer so unfamiliar, thanks to the Space Shuttle and Buran which are providing the invaluable evidence of actual flight: however, for the AOTV these problems can arise in much more severe form (see Walberg, this Theme).

Finally, the hypersonics of planetary exploration is now an established discipline with emphasis on stability, control, heat transfer and gas physics: missions via the atmospheres of Mars and Venus are examples of current studies, and both these and other space science projects will call for detailed understanding of real gas aerothermodynamics (see Clarke, this Theme).

Current projects for aerospaceplanes are all many years from completion, and research and design are in hand, at various levels, in America, China, Western Europe, Japan and Russia. Given the complexities and costs, some at least may be

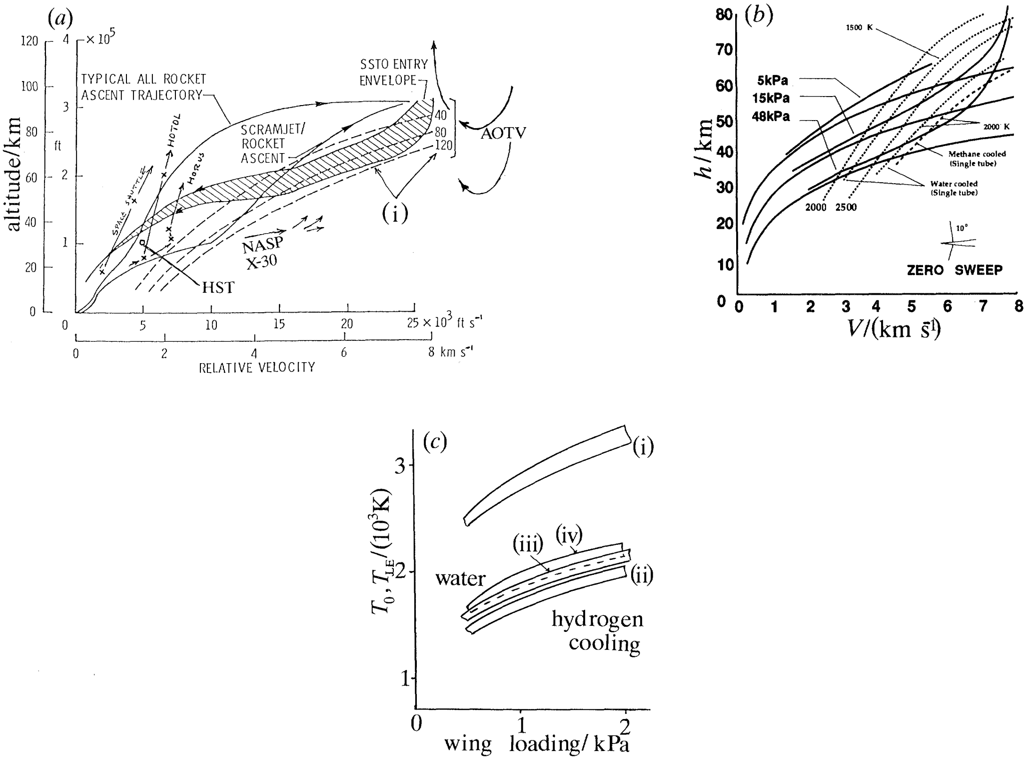

Figure 3. Trajectories and temperatures. (a) Trajectories: (i) reference heat rate contours (1 ft radius sphere; Btu/ft^2 s). (b) High-speed constraints (zero sweep active cooling). Solid lines and values are for $q/(1-V^2)$. (c) Passive cooling (i) and active cooling (ii) (zero sweep and streamwise upper surface) at very high speed ($V_\infty = 6.5$ km s^{-1}). The leading edges are copper/tungsten. (iii) Copper temperature < 1250 K; (iv) copper temperature < 1000 K.

undertaken by collaboration, but for the purposes of this paper data will be taken from separate efforts, and used to draw conclusions of general relevance.

Whatever view is taken of hypersonics, and both the philosopher and the philistine can be found, justifications for advanced transport have usually had their share of critics. It is nearly a century since the extension of the Ugandan railway prompted Henry Labouchere to write the following.

'What it will cost no words can express; what is its object no brains can suppose; where it will start from no one can guess; where it is going to nobody knows'.

If Labouchere had been composing today, he might have drawn comfort from observing that, for the hypersonic aeroplane at least, some of these questions can already be answered.

2. Trajectories

Trajectories to be followed by different types of vehicle are reasonably well defined (see figure 3a), at least over the lower speed range. On the other hand, SSTOS will face situations at very high Mach number where (i) air-breather thrust becomes insufficient (a so-called T–D 'pinch'), and (ii) heating becomes excessive. The first of these is not well understood and may occur at a Mach number between 10 or 15 (say) but the second can be analysed with some precision. Nonweiler (see Townend *et al.*

1990*a*) shows a variety of high speed flight paths that may be imposed on the SSTO, depending on how the leading edges are cooled and the extent to which they are swept. Figure 3*b* shows the particular case of zero sweep with active cooling.

It is worth noting that boundary layers form at high Reynolds number along air-breather acceleration trajectories, but that in spite of this, the fiercest heat loads are to some extent mitigated by the fact that leading edge flows should be locally laminar. It follows that, with correct design, leading edges can be not far from sharp, even at the highest speeds (figure 3*c*).

However that may be, the hypersonic transport or aerospaceplane must first accelerate through transonic and low supersonic Mach numbers and, in so doing, they will both experience an entirely separate (T–D) problem which must be effectively solved, in order to avoid the need for additional or more powerful engines. This problem, or at least its severity, results directly from one of the essential features of the aerospaceplane, that is, the use of air-breathing propulsion.

3. Transonics and take-off

3.1. *Low-speed acceleration and transonic drag*

In reaching transonic Mach numbers, the initial flight paths of the HST and the aerospaceplane may already have differed radically. Barnes Wallis (1962) demonstrated that acceleration at very low altitudes would be beneficial to the air-breathing aerospaceplane, and in many cases vehicles have been projected as using ramp or trolley launch facilities to avoid the need for a heavy duty undercarriage and a relatively slow takeoff. Since the HST must be more conventional in terms of take-off, acoustic constraints alone are likely to impose a more conventional flight path, and transonic Mach numbers may be achieved at somewhat different flight altitudes.

In addition to the usual transonic drag rise, both launchers and HSTs will incur potentially severe nozzle/afterbody base drags. High base drags result from a mismatch which becomes evident whenever an airbreather is operating well below its design Mach number. The fluid dynamics are illustrated in figure 4*a*, from which it is clear (see Novak & Cornelius 1988) that massive suctions may occur in and around a nozzle installation when it operates with the propulsive jet overexpanded and at flight speeds for which base drags are potentially significant (that is, transonic and supersonic flight speeds). The alternative is to use sophisticated variable geometry nozzles, but this will involve associated mass penalties and will sometimes convert the problem from 'internal propulsive' to 'external aerodynamic', while failing to solve the base drag itself; this gives rise to a particular need for base pressure control.

For a two-stage air-breathing launcher studied some twenty years ago (see Francis 1969) the rewards of base drag reduction were studied in some detail. Base pressure control was achieved by free combustion in the wake downstream of the vehicle. The use of wake combustion from Mach number 0.8 to Mach number 5 allowed a partial redesign of the vehicle and, in particular, the use of (40 %) fewer turboramjets (and intake ducting) in the first stage: this permitted various direct and indirect benefits to vehicle size, cost and operation, the most striking gain being a rise in predicted payload from about 2 % to some 3 % of gross take-off mass. For an aerospaceplane, the transonic problem may be mitigated by the use of airbreathers, which are variations on the ducted rocket, but the HST is likely to use turboramjets and, if Sanger is required to provide a cruise phase, then the turboramjet is a natural choice (see Hogenauer & Koelle 1989). The inclusion of base pressure control technologies

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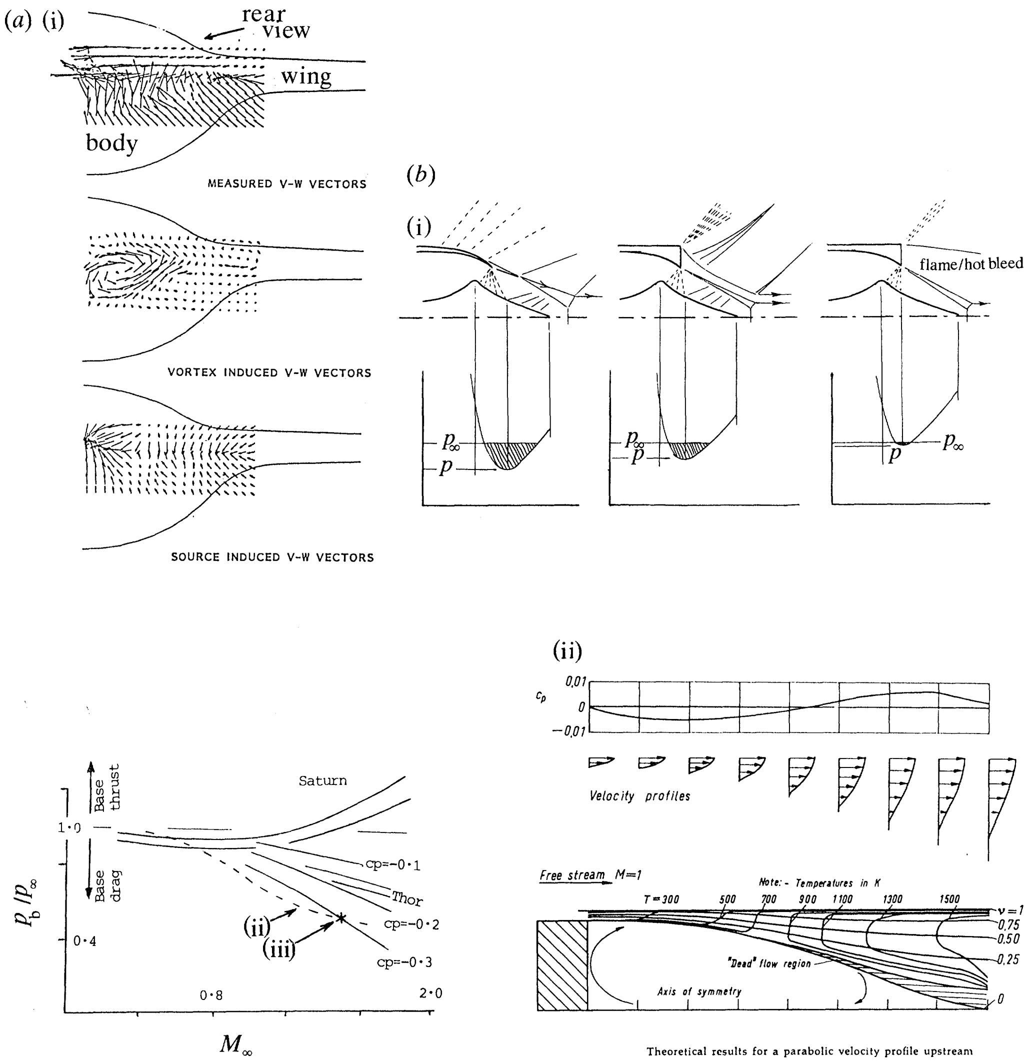

Figure 4. Transonic base flows. (*a*) Base flows around propulsive jets. (i) Shows decomposition of crossflow kinetic energy into the curl and divergence quantities, dynamic pressure ratio (2.25), 20° upswept afterbody. (ii) Mace *et al.* (iii) NASP-related tests. (*b*) Base pressure control by wake combustion. (ii) Bottom shows CFD method (Broadbent 1973), (i) top shows conceptual design. (Values of ν indicate streamlines.)

at the conceptual stage of turboramjet vehicles (see figure 4*b*) may radically improve both technical and economic viability, and the TSTO concept itself may be undermined by the difficulties of transonic base flows due to the second stage (see figure 1*a*).

The proposition that fuel should be burnt externally downstream of an aircraft is not to be made lightly, and it is only one form of base pressure control. For example, design decisions may depend on whether existing shock waves can be used to intersect the wake. At Mach number 2, shockfree wake combustion can give base pressure ratios of about unity (see figure 4*a*) but wake-shock interactions have given values approaching 2, and could probably give more (Townend 1990*a*). The basic decision, however, is no longer to recognize the importance of base pressure control, but whether base pressure control should extend to wake combustion or seek techniques of less apparent risk.

3.2. *Acoustics*

If the proposition of external flames were to be accepted, it becomes possible to consider the acoustics of unducted heat addition for jet noise shielding for take-off and initial acceleration. In the late 1960s, it was suggested that reductions in take-off noise might be sought by gas dynamic (rather than or in addition to conventional) means, for example by shedding gas sheets as impedance layers around the engines, and perhaps by enhancing the effects of density changes by combustion of the injectant or injectants. This suggestion was one of several pursued until the early 1970s, by which time experimental data became available from tests with helium sheets, and it was confirmed (Norum 1973) that gas sheets could reduce transmitted noise by some 10–15 dB.

Some of the high-speed aircraft currently under study already use hydrogen as a fuel, so the use of this gas injected as sheets for jet noise suppression need not introduce logistic problems nor additional hazard. The principal advantage of the technique for present purposes is that it offers a simple, lightweight system by which the use of heavy ducting and 'hush kits' is avoided in a vehicle, whose economics will be extremely responsive to weight growth.

4. Air-breathing technology

A hypersonic vehicle emerging from the transonic–low-supersonic drag peak will thereafter accelerate, on turbomachinery for the HST and probably a hybrid air-breather for the SSTO. The design of such units is not yet resolved. Some fundamentals and practicalities were reviewed by Lombard (1967), and at least the fundamentals of the problem have not changed. If combustion remains subsonic, the HST (and TSTO) will both reach maximum Mach numbers of between 5 and 7 (say), but with supersonic combustion, the SSTO (and the supersonic combustion TSTO) will accelerate further and will do so against a steadily falling drag coefficient: unfortunately, the air-breathing thrust coefficients will also be falling, and a gradual decrease in (T–D) may prevent acceleration beyond (say) a flight Mach number of 15 (see data due to Curran *et al.* (1987) and comments due to Whitehead & Yamanaka (1989)). Thus, whether or not it is arranged to switch from subsonic to supersonic combustion in the ducted air-breather, the ramjet must eventually be replaced by rocket propulsion into orbit; and if supersonic combustion is regarded as too advanced to entertain, the switch will occur at Mach numbers 5–6 (as with HOTOL in its original form, and Sanger). In these circumstances, there may exist a case for providing extra air-breathing thrust (or drag reduction) at very high Mach numbers, so that the vehicle may continue towards orbit without yet incurring the oxidant consumption that resort to a rocket will involve. Since the ducted ramjet is the cause of the problem, such extra thrust is best sought from the external flow, and here, external combustion (or simply mass additional by itself) is a recognized propulsive technique (see figure 5*a*).

It is sometimes argued that external burning cannot be advisable because a ducted ramjet will offer a higher specific thrust and specific impulse. In fact, this overlooks the structural and propulsive disadvantages of a conventional ramjet, which

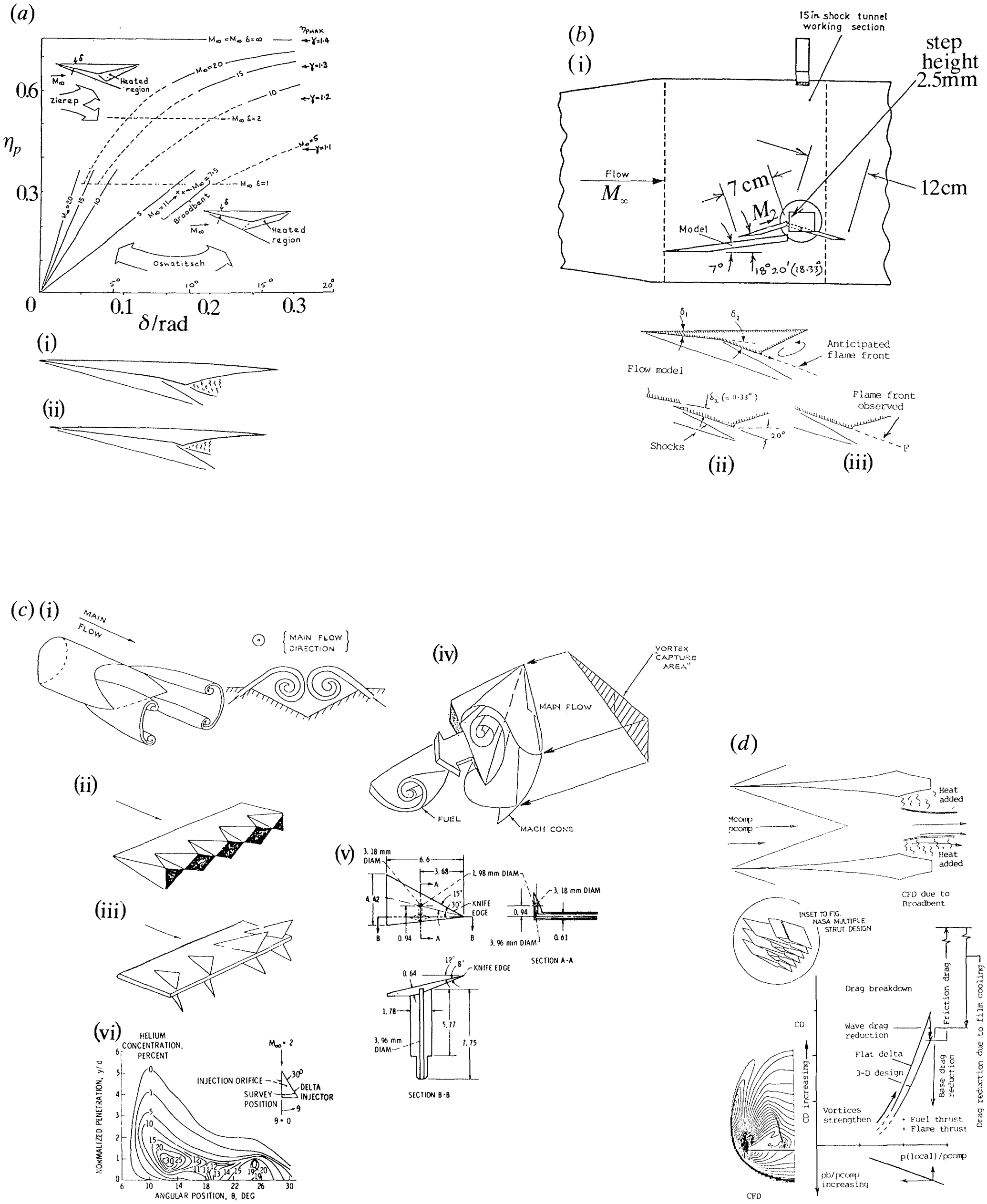

Figure 5. Supersonic combustion. (*a*) Propulsion by external combustion. (i) $C_L = 0.14$, $L/D = 28$, $T_{max} = 2900$ K; (ii) $C_L = 0.11$, $L/D = 15$, $T_{max} = 2700$ K. Mach number 6, friction drag > 0. (*b*) Experimental effects of hydrogen injection. (i) For $M_\infty = 7.4, M_2 = 4.02, p_2 = 37921$ N m^{-2}; for $M_\infty = 9.8, M_2 = 5.17, p_2 = 8687$ N m^{-2}. (ii) Nitrogen tunnel flow. (iii) Air tunnel flow. (*c*) Supersonic mixing concepts (i) Fuel–air vortex (Reid & Kuchemann 1959), (ii) modified wedge injector, (iii) modified plate injector, (iv) fuel–air vortex (Townend 1966), (v) and (vi) helium injection into M2 supersonic air flow (Povinelli *et al.* 1969). (*d*) Fuel injectors.

contains a ducted flame at very high temperatures, must run overrich to cool the wall, and incurs massive drag from internal skin friction (see Czysz & Murthy 1990).

Experimental data have shown that external combustion can be used to modify lift, drag and pitching moment on supersonic wings. For example, at a Mach number as low as 3, a wing at zero angle of attack has nonetheless produced a C_L of 0:06+ and a value of L/D_p exceeding 6. If the pressure distribution in this example of external burning is assumed not to change with injection position along the chord (and since the wing profile was only gently curved, this is not unreasonable), relocation of the injection points would be expected to give a reduction from 'zero injection pressure drag' of 25% and an L/D_p of about 8. Again, at Mach number 7, work by Aihara *et al.* (1986) has shown that pressure rises on wing-like surfaces can be produced by electric heat addition. In 1968, British research produced external combustion on a wind-tunnel model at freestream Mach numbers as high as 10 (see figure 5*b*; Townend *et al.* 1970; Holbeche *et al.* 1980).

Given the difficulty of modelling mixing and combustion, both these and other experiments are open to questions of scaling. Here there is a particular need for a reliable theory, in the application of which, scaling can be circumvented. The method used by Broadbent (see Townend *et al.* 1990*b*) is described in this series, and it is doubly important because (i) it permits the definition of a required pressure distribution to define a required heat and mass addition (that is, it permits the design of flames to achieve particular purposes), and (ii) it offers independence of the scaling factors which no model tests in wind tunnels will ever fully avoid. The nature and findings of the method are widely published over some twenty years (see, for example, Broadbent 1971, 1973).

Since the effectiveness of external burning (and in fact, of mass addition by itself) is likely to increase with flight Mach number and since its specific impulse may remain superior to that of a rocket, the use of external heat and mass addition may assist the launch of such craft as the airbreathing SSTO. It may also assist the reduction of propellant consumption during acceleration under rocket power, and contribute usefully to the propulsion and lift of a TSTO first or second stage.

4.1. *Some options in combustion research*

It is clear from the above that the propulsion of air-breathing hypersonic vehicles is open to many design options. At the fundamental level, and whether heat addition is internal or external, there will be flight régimes in which any supersonic diffusion flame must be mixing controlled and ignition may need to be piloted. Thus the combustion length (and mass penalties of associated combustors) will respond to research on both these topics.

The problem of introducing and spreading a fuel across a supersonic stream without producing prohibitive losses (entropy rises) is made worse by the likelihood of high shear. Techniques using vortices to enhance supersonic mixing rates are now well established, but retaining low losses in a supersonic flow is less than straightforward. Some ideas in this connection date from the 1960s (see figure 5*c*), and early experiments by Povinelli *et al.* (1969), by Swithenbank & Chigier (1968) and by Jacques *et al.* (1972) threw some light upon the fluid dynamic issues. A more conventional approach (see figure 5*d* and Kelly *et al.* 1979) shows how multiple struts may assist in achieving fuel spreading but it incurs a high cost in wetted area, heating and friction drag; these may be reduced by combining fuel injection with film cooling and the techniques of base pressure control.

With regard to the nature of supersonic flames, it is likely that as flight speed and temperatures increase the diffusion flame may be subjected to flame–shock interactions of a potentially detonative nature: Clarke's 'fast flames' may feature here (see Clarke 1989), and the efficiency and stability of combustion will reflect the fact. It is worth noting that detonation in a ramjet is quite acceptable provided that it occurs in steady oblique waves, and in predictable locations. Detonation in ramjets does not carry the stigma which attaches to detonation in diesels (see, for example, Oppenheim 1985) and, provided the waves are oblique, they permit flexible and efficient propulsion (see Townend 1966; Menees *et al.* 1990).

It is clear that combustion chamber design needs more detailed knowledge of supersonic aerodynamics than is normally required in combustion research, or is to be expected from standard aerodynamic approaches; but an intriguing possibility is that a knowledge of efficient supersonic wing design may be able to contribute to the design of vortex-controlling fuel injectors (see figure 5*c*, *d*). Supersonic fuel injectors may thus combine the shockwaves of the optimised, multi-shock waverider with the vortex flows of expansion surfaces, and in so doing, may help new types of air-breather to reach unprecedented speeds. Just how high those speeds could become is one of the most challenging questions in propulsion technology today.

5. Hypersonics: HSTs and aerospaceplanes

Acceleration of air-breathing aerospaceplanes such as the X-30 will rely on the preservation of adequate $(T-D)$ and thus upon low drag forces. The Hypersonic Transport will demand high values of L/D and significant C_Ls; but the L/D is still responsive to C_{D0} and thus to the forebody contribution. In both cases, therefore, low wave drag and skin friction on the forebody must be achieved, despite the fact that much of the undersurface supports static pressures that are sufficiently high to initiate a propulsively efficient compression process.

In addition, the probable use of hydrogen fuel will impose bulky tankage (especially for SSTOs, for which take-off mass is perhaps 80% propellants), and both the capacity and volumetric efficiency of the forebody must satisfy mission and structural constraints: for aerospaceplanes in particular, forebody upper surfaces will probably support substantial regions of negative lift and significant pressure drag.

Heat transfer and regenerative cooling also enter the problem. As already seen in figure 3, forebody leading edges introduce severe heating and the need for active cooling, and these parameters will form an important part of an aero-structural compromise (see Nonweiler 1990; Nonweiler *et al.* 1971; Czysz & Murthy 1990).

5.1 *Forebody drag*

The classic aerodynamic approach to the reduction of high-speed forebody drag is to reduce the 'cone angle' or 'wedge angle' of the forebody or nose, and to profile the forward facing surfaces in a conical or ogival manner. Geometric slenderness, however, gives rise to structural disadvantages, and to designs that are 'hot and heavy'. A length constraint is thus in practice imposed and it then turns out that trapezoidal planforms offer lower forebody drag (C_{D0}) than conventional shapes (see Pike 1977). They can also offer clean undersurface flows for the location of intakes (Czysz & Kendall 1966).

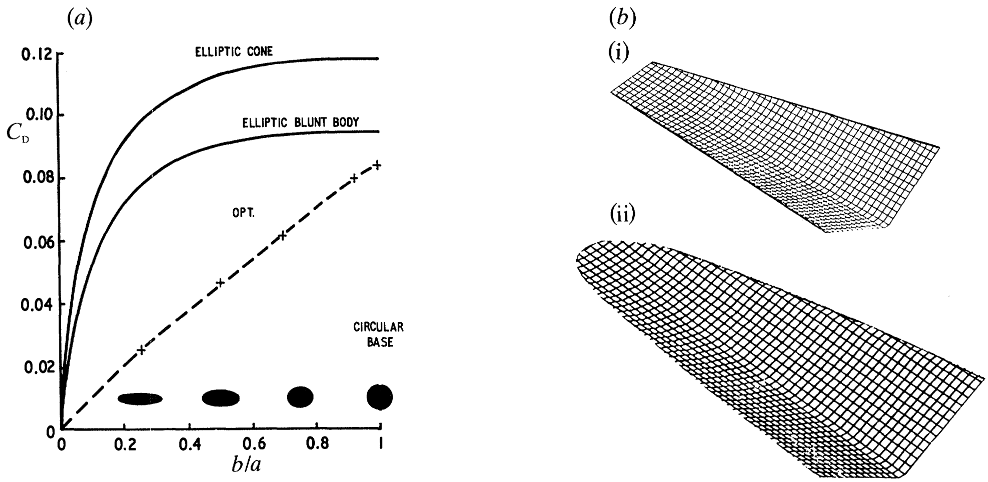

Figure 6. Forebody drag (Pike 1977). (*a*) Drag of conical and optimum nose shapes with elliptical bases of constant area. (*b*) Optimum (i) and near-optimum (ii) plan forms with diamond bases of equal area. For (i) $C_D = 0.02517$, for (ii) $C_D = 0.0252$. $C_f = 0.001$.

Drag-optimized forebodies can reduce forebody pressure drag by 50% or so (see figure 6*a*) when compared with cones or ogives having the same cross section and maximum length, that is, when matched to similar tankage. Their practical utility at high speeds will depend on that of sharp leading edges which, although in parts unswept, must survive protracted heating during each flight of a vehicle that nonetheless offers safety to the payload and low maintenance costs to the operator: this is the problem addressed by Nonweiler (see figure 3*b*, *c*).

The problem of cooling trapezoidal noses and planforms is made worse by the fact that unswept edges intensify local heating rates. There is thus a need to identify forebody shapes that impose less demanding cooling requirements, or to arrange such cooling as will permit the retention of sharp unswept leading edges. At some flightspeeds, heat pipes and advanced materials may permit leading edges to survive unharmed, but neither offers a simultaneously cheap and lightweight solution; none the less, the Dayton NASP Conference in July 1989 emphasised the need for a reasonably priced spaceplane, and component weights are major factors in the NASP performance equations. It is therefore encouraging to find that, if correctly approached, non-optimum forebodies allow zero sweep to be avoided at little cost in additional drag (see figure 6*b*).

5.2 *Wing design*

For almost any high-speed cruise vehicle, constraints will normally include the following.

1. Air-breathing propulsion will be necessary for efficient cruise, thrust deflection being provided so as to counter significant proportions of vehicle weight.

2. During acceleration, intakes and nozzles will need to be of variable geometry for sophisticated vehicles such as the HST.

3. Low-speed handling and safety considerations will combine with the need for efficiency in loiter to complicate configuration design by setting limits to sweepback, leading edge bluntness, aspect ratio, and anhedral–dihedral; all this being subject to CCV philosophy.

4. Altitude and heating loads will have to be tolerated at levels imposed by lift coefficients that permit satisfactory lift–drag ratios, and wing loadings that are structurally realistic.

Subject to these constraints, the emphasis for cruise vehicle wing design will be to improve cruise L/D, and to accept the (rather low) angles of attack thereby imposed.

For the aerospaceplane, the emphasis is on maximizing thrust per unit engine area, that is on minimizing engine mass and vehicle size. Thus the trend is towards higher kinetic pressures (and even lower angles of attack) than an HST will use for cruising conditions. Also, for acceleration vehicles, it can be shown that L/D is less important than for cruise vehicles, and the vehicle is required to be of minimum size and wetted area rather than of high efficiency at hypersonic flightspeeds. As a result, the SSTO can afford to operate with less regard to vehicle L/D than the HST, but since the wing is volumetrically of little value, there will remain some interest in the local L/D of the wing itself, because the drag incurred by the wing is essentially parasitic in any sense other than that of providing lift, and even when the lift requirement is low, the wing incurs skin friction.

For re-entry (and for vehicles which must offer supersonic manoeuvrability and/or maximum hypersonic lift) criteria may differ radically from either cruise or acceleration. The need may now be for high cross-range (i.e. lateral range achievable on either side of the plane of original orbit). For Earth, global cross-range calls for L/D no higher than 3.5 or so, and this is obtainable at higher angles of attack than for cruise. On the other hand, minimum re-entry heat transfer rates may be needed, in which case operation must be at still higher angles of attack, in principle up to that for C_{Lmax} (about 55°). In either case, the need will be for high values of C_{L} per unit L/D, since this will reduce heating rates at given velocity and wing loading, or will permit a reduction in planform area.

Wing design for high C_{L} and for high $(L/D)_{\max}$ are now considered separately.

5.2.1. *Wing design for high* C_{L}

A summary of wing performance at medium to high angle of attack is presented in figure 7, for flat and other undersurfaces. If undersurfaces are concave, or partly so, data due to Townend & East (1981), Penland (1962) and Galloway *et al.* (1976) show that:

(*a*) At about Mach 10, maximum lift coefficients can comfortably exceed unity (whereas newtonian considerations suggest that the maximum achievable should be about 0.75).

(*b*) Concave or partly concave undersurfaces consistently provide higher values of lift coefficient at given re-entry L/D for Mach numbers of 8 and upwards.

(*c*) Maximum lift coefficients at high supersonic speeds also rise if undersurfaces are concave or partly so.

(*d*) Heat transfer is reduced (although experimental data are so far available only at low Reynolds number).

Thus, for re-entry vehicles, the waverider may offer some real advantages in engineering terms: but as usual, the waverider must satisfy packaging and volumetric constraints, and in some forms, will imply unacceptable vehicle configurations. These and other problems were studied in October 1990 at the First International Waverider Symposium.

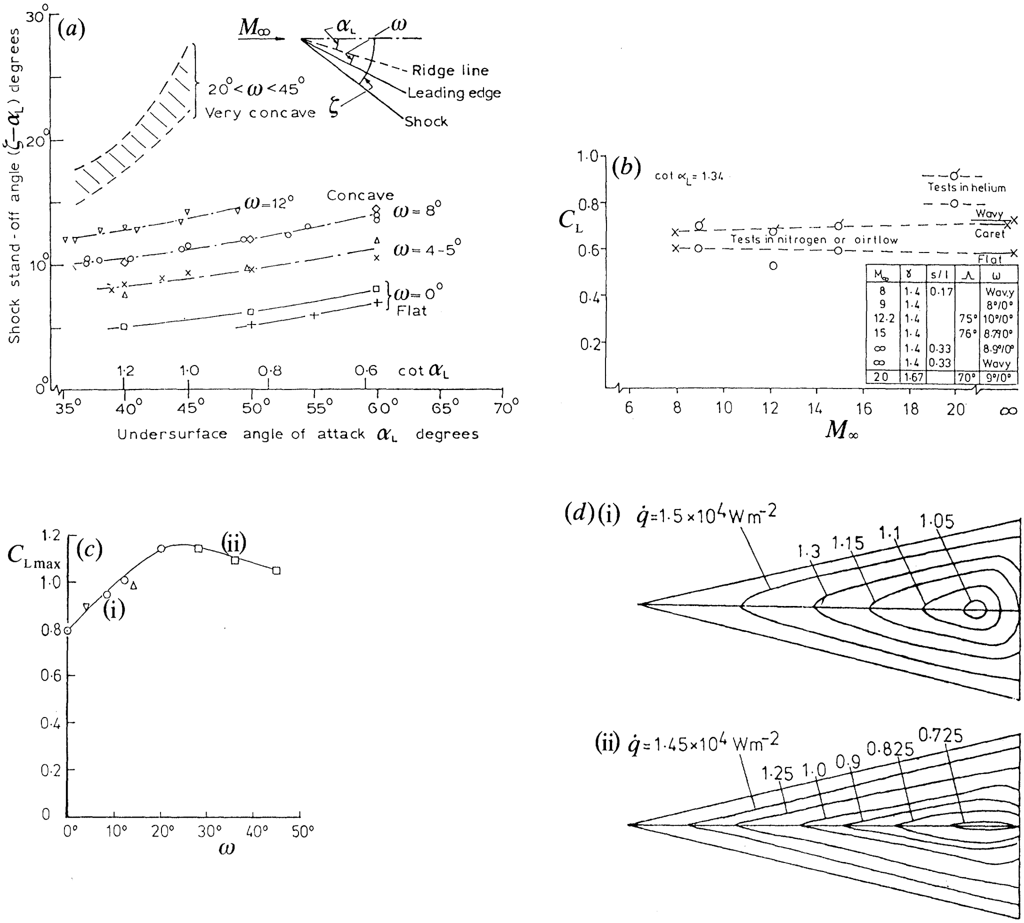

Figure 7. Waveriders and flat wings at re-entry conditions. (*a*) Various planforms at $M = 9.7$ and $Re \approx 3 \times 10^5$. (*b*) ×, theory; ○ experiment ($\omega = 0°$), flat delta; ○̸, experiment, concave delta. $\cot \alpha_{\rm L} = 1.34$. (*c*) Force measurements on wings of half-elliptic, trapezoidal and near-delta planform: □, half-elliptic planforms, $M_\infty = 9.7$, $Re = 4 \times 10^5$; ○, trapezoidal planforms, $M_\infty = 9.7$, $Re = 4 \times 10^5$; ▽, trapezoidal planform, $M_\infty = 8.4$, $Re = 3.8 \times 10^5$; △, near-delta planform, $M_\infty = 6.6$. At (i) $\partial C_{\rm Lmax}/\partial\omega \approx 0.018$ and at (ii) ≈ -0.006. Data due to East & Penland. (*d*) Heat transfer distributions on flat and caret delta wings. (Data due to Galloway *et al.*) (i) Flat delta, $\alpha_{\rm L} = 20°$, $M_\infty = 21.4$, $Re = 0.81 \times 10^5\ {\rm m^{-1}}$, $T_0/T_{\rm w} = 6.9$. (ii) Caret delta ($\omega = 8°$), $\alpha_{\rm L} = 20°$, $M_\infty = 21.2$, $Re = 0.88 \times 10^5\ {\rm m^{-1}}$, $T_0/T_{\rm w} = 6.71$.

5.2.2. *Wing design for high L/D*

Even though cruise is concerned with high L/D, lift coefficient must be high enough to avoid low implied wing loadings and/or low altitudes involving excessive heating rates. If variations from the flat delta wing are to be considered, it must be because their promise in this or some other respect is believed to exceed that of the flat delta at rather low angles of attack.

As far as undersurface shaping is concerned, the performance obtained from the basic wedge flow is difficult to improve upon if a single lifting-flow shockwave runs smoothly from leading edge to leading edge: even with optimization such as that by Bowcutt *et al.* (1987) and Anderson & Corda (1988), the performance of associated

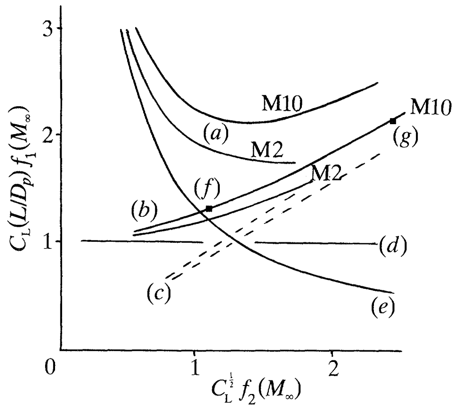

Figure 8. Lifting performance of wedges and optimized wings. (*a*) Optimized interference wings, (*b*) wedges, (*c*) hypersonic limit, (*d*), (*e*) small disturbance theory, (*f*) M6 curved shock, (*g*) M14 curved shock. ((*a*)–(*e*) due to Pike (Townend 1990*b*), (*f*), (*g*) due to Corda & Anderson 1988.)

wings does not exceed wedge flow values (see figure 8). In principle, Roe's interference wings (which add a central body to the wing undersurface, and give 'interference' by mutual compression) can offer some improvement by introducing undersurface flows with two distinct shockwaves (one per half-wing). Pike has considered the more general case of flows produced by swept wedges. In so doing, Pike has produced variants related generically to both the Nonweiler wing and the Roe interference wing; and, in practical terms of C_L and L/D, has shown that the interference wing can be aerodynamically optimized, and then has definite aerodynamic advantages (see figures 8 and 9).

Data allowing direct comparison of flat deltas with Pike's optimum wings are scarce, but an approximate comparison between waveriders and almost flat deltas can be made as in figure 10. Conically curved waveriders (derived from flows around cones and ellipses) are compared with interference wings and particular waveriders which include some whose undersurfaces are very nearly flat. For flight at Mach 4, two examples of interference wing outperform a flat delta in terms of inviscid L/D at given lift coefficient; in particular, they approach an approximate limit which, in inviscid flow, offers some 50% more lift–drag ratio than flatter wings at the same lift coefficient.

This apparent superiority would be worth investigating in greater detail. For the moment, the approach adopted by Pike already offers the following.

1. At flight Mach number 5 and lift coefficient of about one tenth, the interference wing offers inviscid lift–drag ratios some 33% better than the simple wedge.

2. At flight Mach number 8 and lift coefficient of about one tenth, the interference wing offers inviscid lift–drag ratios some 20% better than the simple wedge.

3. Interference wings at high supersonic speeds ($3 < M < 5$) give gains in L/D, in spite of viscous drag, over that of flat undersurfaces.

4. At flight Mach number 4 and for turbulent flow, the 'optimized' interference wing can produce L/Ds of about 10, together with a lift coefficient significantly higher than a flat-bottomed shape.

There are two further aspects.

5. Interference wings offer their best L/D at higher shock strengths than the simple wedge-flow, and can thus contribute more by way of intake precompression

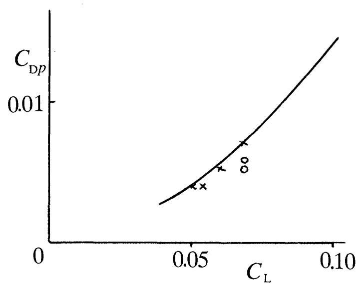

Figure 9. Lifting performance at $M_\infty = 4$. ——, 2-D wedge with plane oblique shock; ×, typical delta wings; ○, sub-optimum interference wings (these wings reduce C_{Dp} by 20–30 % at given C_L).

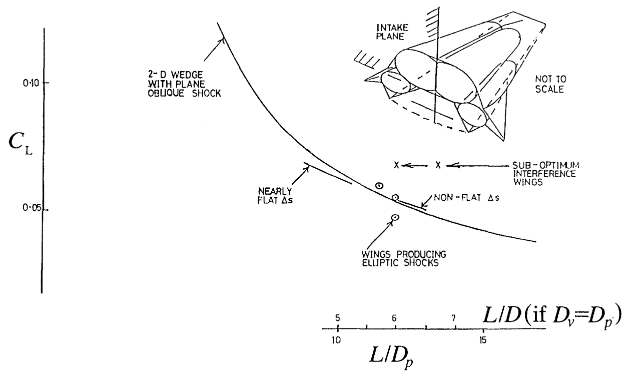

Figure 10. Wedges, nearly flat and non-flat delta wings and interference wings at $M_\infty = 4$.

than do their flat-bottomed counterparts. As a consequence, the integration of propulsive and lifting flows may be more efficiently performed especially as, in some cases, the shockwaves from two-dimensional wings are known to be weaker than would be optimum for correctly matched propulsive cycles, at least for those having moderate maximum cycle temperatures.

6. The planforms of 'optimized' interference wings may seem geometrically somewhat extreme from the viewpoint of configuration design, but they become much easier to use if integration with air-breathing propulsion units and volumetric considerations are introduced; as they must be.

In other words, the practicality of using interference wings and variants may depend upon correct integration and configuration design (see §5.4), but, at the fundamental level, they can offer a lifting performance far in excess of the classic flat delta, and provide both a stimulus to explore alternatives and an initial target at which to aim.

5.3. *Intake design: transition, compression and separation*

A crucial choice in configuration design is that of the intake. Its size and geometry influence both in the ease and efficiency with which the wing or forebody can accommodate it, and the achievement of an efficient air-breathing installation depends very strongly on intake pressure recovery (and spillage characteristics off-design). The intake will benefit from being immersed in the wing or forebody flow so that precompression is provided by lifting and/or volume-containing components, and so that excursions in vehicle attitude do not seriously distort the intake flow itself.

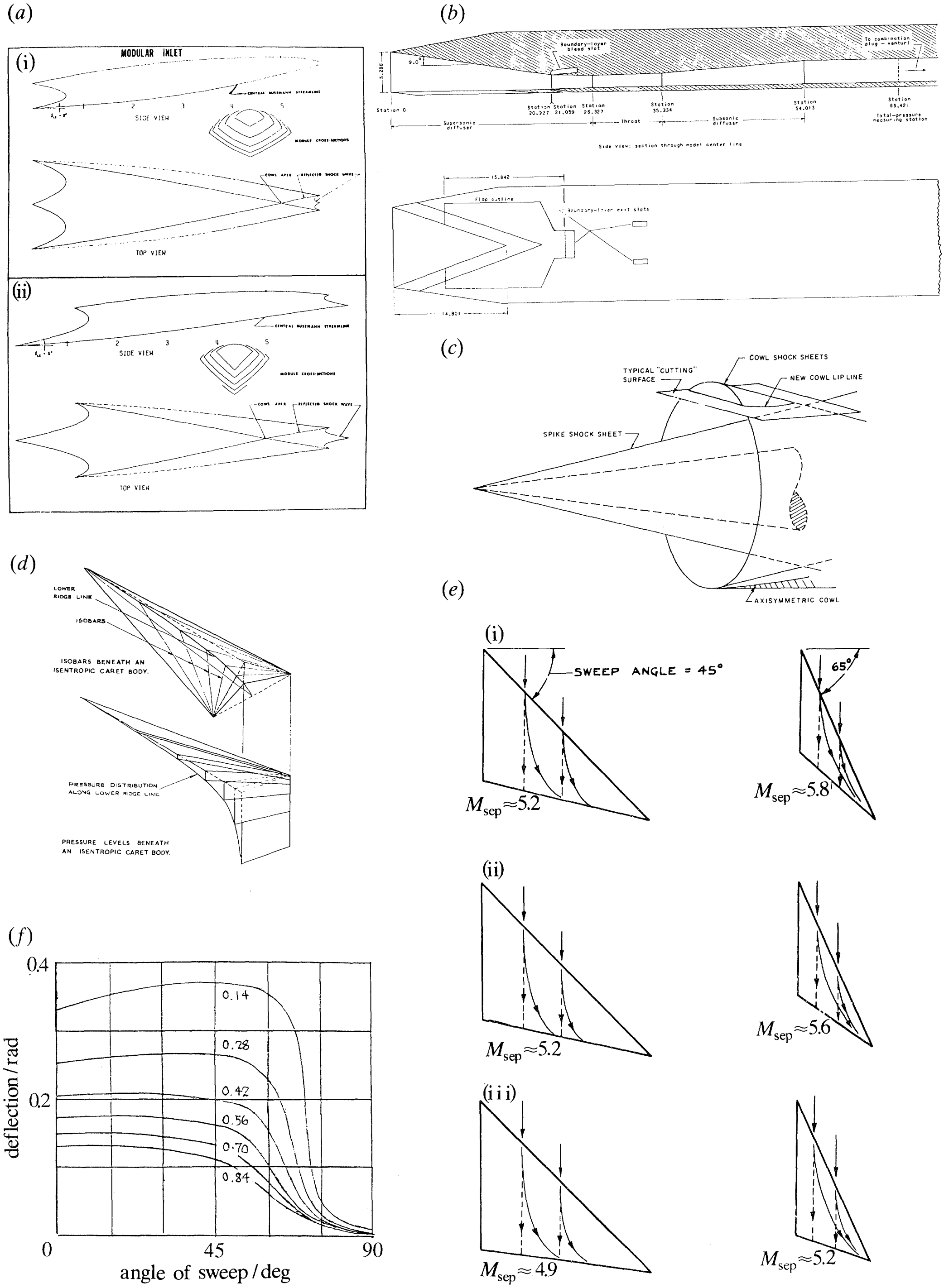

Figure 11. Hypersonic intakes. (*a*) Computer drawing of modular inlet used by Mölder *et al.* (1968), together with its three-module counterpart. (i) $M_\infty = 8.33$, $M1 = 7.74$, $M2 = 4$, $M3 = 3.27$, PT32 = 0.92, area ratio = 36.17. (ii) $M_\infty = 8.33$, $M1 = 7.67$, $M2 = 5$, $M_3 = 4.42$, PT32 = 0.97, area ratio = 13.08. (*b*) General arrangement and principal dimensions of model (all dimensions in

Combining these components so that C_{D0} is minimized (or the L/D increased) is considered in §5.4, as a problem in integration. In fluid dynamic terms, the major problems of immersing an intake in an existing flow are:

(*a*) accommodating the boundary layer conditions provided;

(*b*) producing sufficient compression while preventing boundary layer separations beneath flows which impose adverse pressure gradients;

(*c*) restricting boundary layer control to subtle shaping rather than ducted bleeding, while exploiting those aspects of laminar, transitional and turbulent flow that are the least unfavourable.

In particular, turbulent boundary layers are more resilient to adverse pressure gradients (see, for example, Needham & Stollery 1966; Stollery 1990), and it is necessary to determine the likelihood that transition will have occurred ahead of the intake. East & Baxter (1990) have examined just this problem.

Where it is necessary to compress a laminar flow, the situation may be relieved by introducing flows that are 'known' not only in the main compression wave but also in the associated laminar boundary layer. Recent work by Nonweiler has cast new light on this possibility and extended the prospect of achieving 'viscous known flows' (see Cooke & Jones 1965; Nonweiler 1990).

5.3.1. *Viscous known flows*

The 'classical extremes' of axisymmetric and wedge-like intakes are joined by several infinities of three-dimensional, doubly curved shapes based for example on a Busemann flow model (as by Molder *et al.* 1968), related shapes intended to assist cooling and intake starting, for example those tested by Dennard & Boney (1966) for NASA, and those for use up to orbital velocity by Kutschenreuter (1963) for the USAF (see figure 11 *a*–*c*). Thus, in the field of intake design, there is an embarrassment of complex and three-dimensional riches.

To simplify the research and design process, but also to ease the structural problem, it may be prudent to accept:

(*a*) that boundary layer control should be available in simple form, but that the deliberate generation of surface crossflows may permit intakes to dump boundary layers in required directions and into selected regions of the external flow without the need for internal ducting;

(*b*) that double curvatures not only introduce enormous scope for the study of variables, but may also imply surfaces that are inflexible in operation: thus it may be realistic to include singly curved surfaces in intake design, and to look for viscous known flows.

A possible approach, which may form a singly curved compromise between the classic but heavy wedge-like intake and the fully three-dimensional intake such as Molder's, could be that of figure 11*d*.

For the framing of intake research, the pragmatic approach may be to include simple geometries that permit crossflows to develop in a manner which can be understood and which offer scope for the design of boundary-layer crossflows rather than their toleration as unavoidable secondary flows.

centimetres) (Dennard & Boney 1966). (*c*) USAF design (Kutschenreuter 1963). (*d*) Pressure distributions. (*e*) Laminar boundary layers on isentropic caret surfaces: effects of sweep angle and specific heat ratio, γ; (i) $\gamma = 1.4, M_\infty = 6.8$; (ii) $\gamma = 1.35, M_\infty = 6.8$, (iii) $\gamma = 1.3, M_\infty = 6.8$ (data due to Cooke & Jones (1965)). (*f*) Effect of sweep on achievable deflection in the tip region of isentropic caret surface: $M_\infty = 6$, data due to Nonweiler (1990), numbers on graph refer to H_w/H_{tot}.

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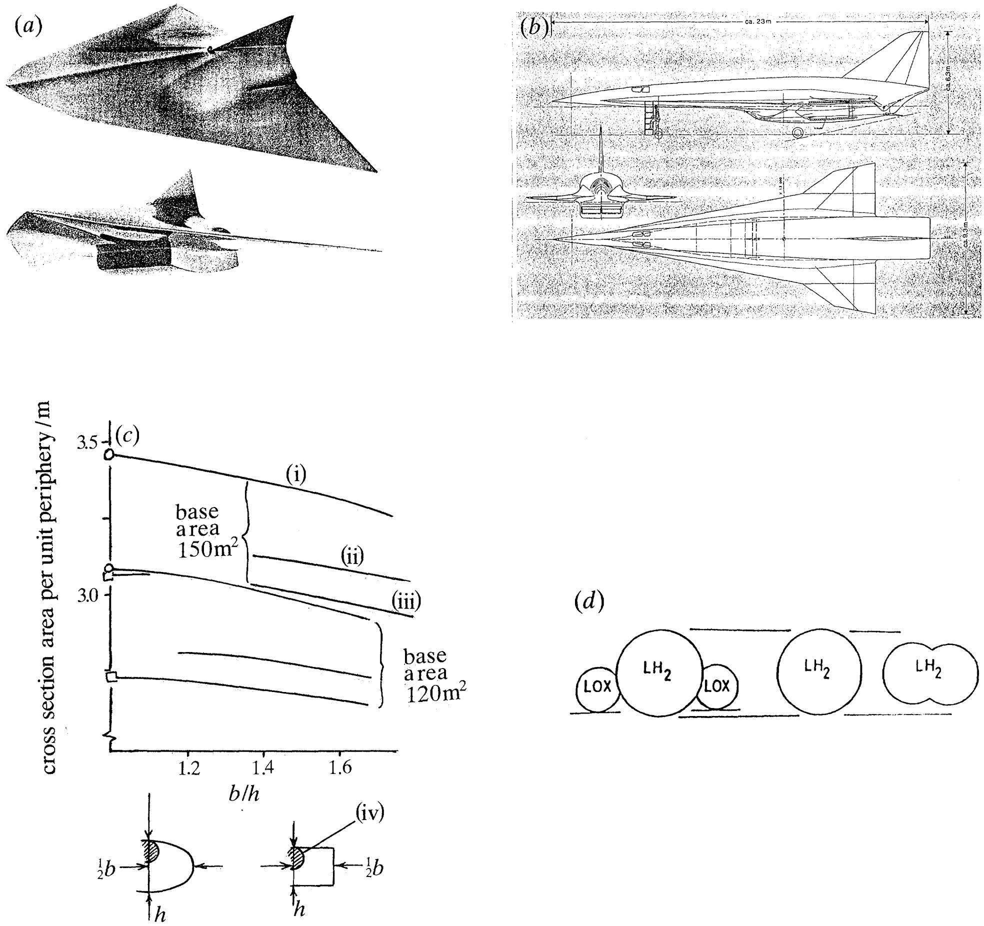

Figure 12. Configuration. (*a*) Supersonic cruise vehicle (1968). (*b*) Hypersonic demonstrator (1990). (*c*) Cross-section design. (i) Ellipses (circular at $b/h = 1$), (ii) chamfered rectangles, (iii) pure rectangles, (iv) payload diameter 4.6 m. (*d*) Cross-section and tankage.

At a more philosophic level, the design of supersonic intakes was one of the first fields in which 'known flows' were deliberately produced, and it is this philosophy which Nonweiler extended to the design of hypersonic wings. Where hypersonic intakes are dominated by complex viscous considerations, and where conventional measures such as bleed ducts are structurally undesirable, it seems logical to seek intake flows in which the viscous behaviour can also be described as 'known'; although a truly simple flow is much harder to achieve than it was for wings, any reduction in viscous obscurity may save time and money.

5.4. *Integration and configuration design*

The general philosophy of integration has not changed greatly since it was reviewed by various authors in the 1960s (Kuchemann 1978; Townend 1966; Gregory *et al.* 1967). Some constraints have been added since then, and the details of power plant installation will vary with intake design, propulsive concept and the details of base pressure control (figure 4*b*). The figures presented here, however, are not concerned with the demands for integration, but with the problems of supply;

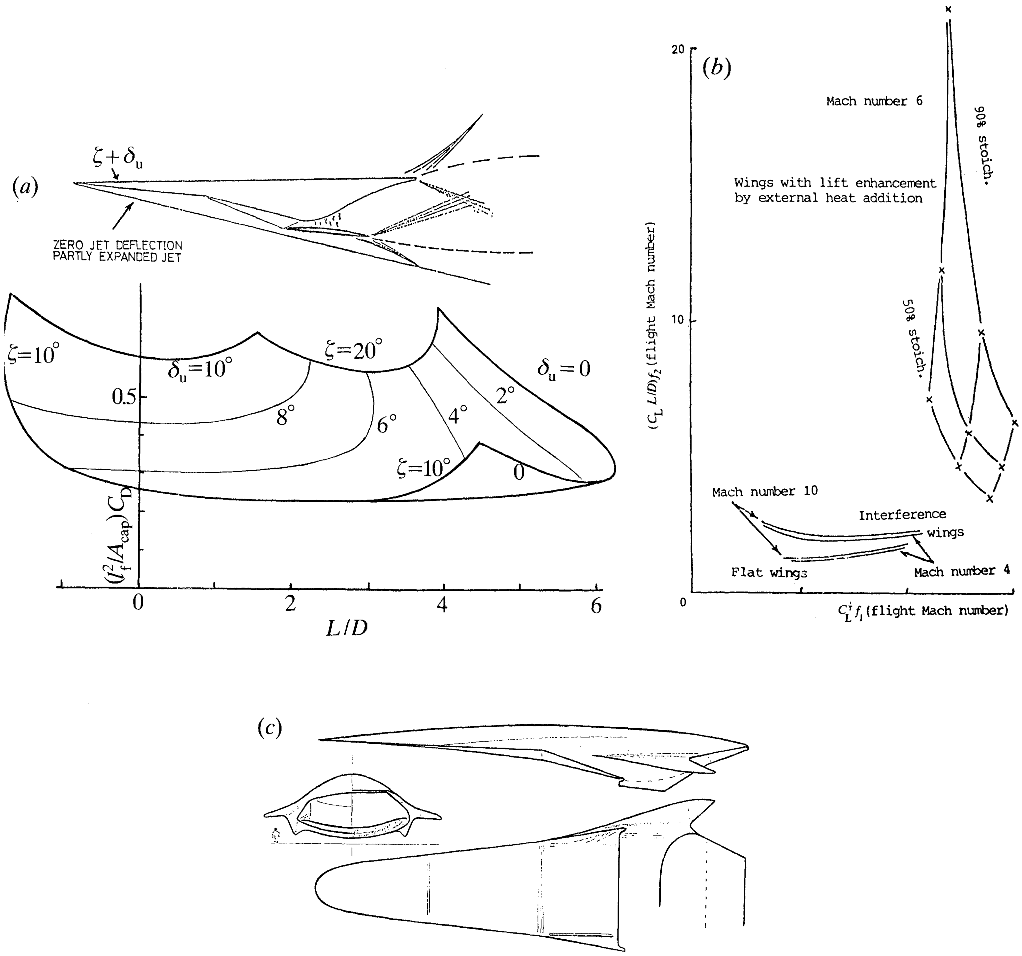

Figure 13. Integration and vehicle design. (*a*) Intake–forebody integration. $M_\infty = 6.8$, $\gamma = 1.4$, $C_f = 0.001$, trapezoidal planform. Unswept leading-edge length $= \frac{1}{2}l_f$. (*b*) Lifting and lifting–propulsive wings. (*c*) Conceptual waverider aerospaceplane.

that is, the provision of configurations which combine desirable components into structurally and aerodynamically realistic shapes.

Figure 12*a*, *b* shows a supersonic cruise vehicle (based by Pike on cone–cylinder waverider shapes (see Jones *et al.* 1968)), and the projected HYTEX vehicle currently proposed by Deutsche Aerospace for research up to Mach number 6. An essential difference is in the provision not merely of adequate volume, but of adequate usable volume within a structurally tractable shape.

Many hypersonic vehicles will be dominated by the sheer volume of tankage, the ‘balloon cross-sections’ of individual tank segments, and the need to instal a payload compartment of operationally useful (and therefore rather small) size. The influence of these features and of vehicle size itself are shown in simple terms in figure 12*c*. Clearly, large vehicles offer some economy in panel area per unit volume, some cross-sections are more sympathetic than others, and some vehicle designs have been dominated by these facts (see figure 12*d*).

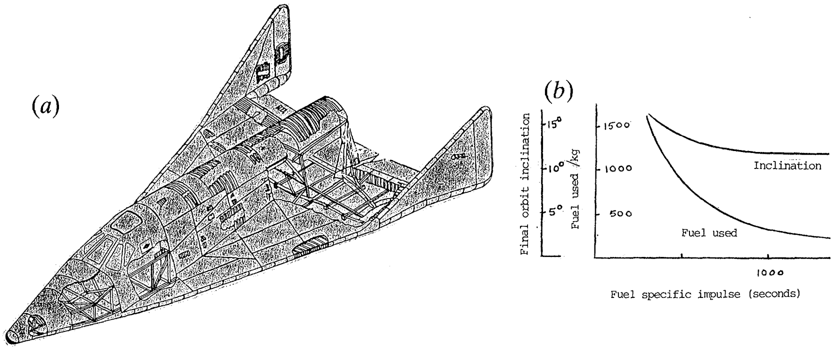

Figure 14. Dynasoar and the AOTV. (*a*) Boeing X-20. (*b*) AOTV propulsion (East and Hewitson in Townend *et al.* 1990*b*). Time of flight is 5ks.

Given that not all vehicles will have single circular tanks, but will respond to mission demands for low drag (even though a mass penalty will normally result), it is of value to study the application of earlier items, for example, the integration of intake and forebody to permit spatulate planforms and complex cross-sections such as those of figure 12*d*. For these, it is possible to plot the drag of the intake-forebody against L/D for 'matched' components, and so to design the front half of an SSTO or HST from figures such as 13*a*. It is already seen that the design will vary with the level of L/D required: the remaining question is to what extent such shapes will permit the addition of efficient wings and cowls. Figure 13*b*, *c* shows the enormous choice that is on offer, together with one possible solution.

6. Theme 3: orbital plane change and the AOTV

The principal role of the AOTV is to permit an efficient change from one plane of orbit to another, by re-entering the atmosphere, performing an efficiently lifting powered turn and leaving the atmosphere in the new plane of orbit. Thus, although the extreme speed of the vehicle permits centrifugal force to counter most of its weight, the wings may need to provide high lift to hasten the turn. As propellant is expended to prevent a loss in flight speed, it follows that economy requires a reasonable L/D to be available at flight Mach numbers of about 20 to 30 (say), despite the desirability of high C_L and such complexities as real-gas effects (see figure 3*a*, and Walberg's (this Theme) figure 2).

Details of OTV studies have been summarized by Walberg (1985) and are not repeated here. Instead, some comments are made on possible developments in AOTV design and are used to illustrate likely environments and operation.

6.1. *Trajectories and gas dynamics for the* AOTV

For an AOTV operating at constant angle of attack and velocity, it is reasonable to assume a constant L/D, provided the value is not too high. For many transfers, calculation shows that angles of attack should be between 20° and 30°, so that L/D is less than 2. Rocket propulsion is usually assumed, but an exception was a paper by Cuadra & Arthur (1966) in which the possibilities of external burning were assessed. This study was therefore contemporary with the Boeing Dynasoar project (see figure 14*a*), and from figures 1*b* and 14*b*, it seems that the performance of an AOTV could change radically if rockets were replaced by air-breathing propulsion.

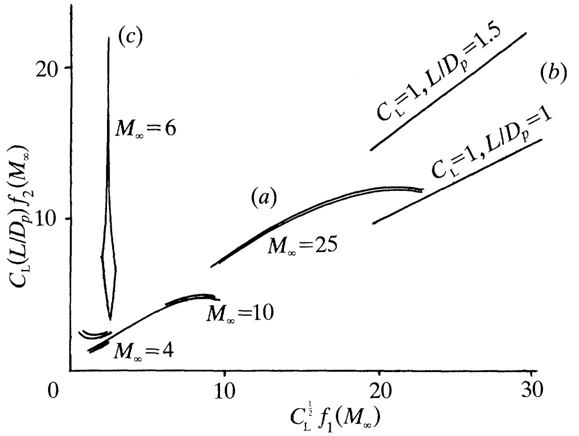

Figure 15. Hypersonic wing performance with (*a*) cruise and lifting re-entry, (*b*) high-lift re-entry, (*c*) lift enhancement and drag reduction (see figure 13*b*).

A conventional ducted ramjet is likely to be unusable due to thermal loading and internal skin friction drags (see Czysz 1990). Thus, the most probable form of air-breathing combustion will be external to the airframe and associated flow fields could derive from Oswatitsch (1959), Broadbent (1971) and Zierep (1966) as already shown in figure 5*a*. The more elaborate calculations of Broadbent give lower propulsive efficiencies, but external combustion is apparently as good as is required, and is probably the best that can be offered. The gas dynamics of AOTVs may thus include not only the real-gas effects of high-speed airflow, but the chemistry of high-temperature mass and heat addition within an already relaxing flow (see Clarke 1969 and this Theme).

A further feature of external combustion is that it contributes directly to lift. A rocket is most effective on an AOTV if thrust is deflected downwards: with external combustion, the pressure field almost inevitably provides a lift component, and integration of propulsion, lift and volume becomes complete.

6.2. *Vehicle design*

For the AOTV using rocket propulsion only, both trajectories and vehicles have received some attention (Walberg 1985 ; Wilhite *et al.* 1984; Tauber & Menees, 1986) and possible design features are shown in figure 12*d*. Since required tankage could be reduced by air-breathing propulsion, it may be that cross sections would become less bulky, but other changes to geometry could result from the operational results of air-breathing propulsion. In particular, the requirements of air-breathing propulsion are responsive to the undersurface pressure ratio, and the potential exists not only to accommodate this propulsive requirement, but to reduce the severity of heat transfer.

It may in fact be realistic to look for combinations of high C_L and fairly high L/D_p (up to 2 say) at very high flight Mach number. This would involve operating at higher angles of attack than are usual for orbit plane changing. Heating rates would be reduced since altitude would be greater at given wing loading and given speed, while high plane changing capability would be retained due to reasonably high L/D_p and specific impulse, together with reduced skin friction drag. The above approach would extend (to very high flight speeds), the philosophy already developed for lift enhancement at lower speeds.

The situation is summarized in figure 15, but it is emphasized that, at these extreme conditions of atmospheric flight, figure 15 presents possible aims for the future, rather than guarantees of achievement. If future designs are to achieve these aims, the need is for at least some chapters in research to be planned on a recognition of the designer's need.

7. Conclusions: enabling technology and research required

Some areas in which research will probably assist the design of hypersonic aircraft are:

(*a*) transonic and supersonic base pressure control around nozzles and afterbodies;
(*b*) acoustic shielding by fluid dynamic and combustion techniques;
(*c*) low-drag forebody-intake integration with wings producing interference flows;
(*d*) transition and turbulence control;
(*e*) cross-flow control in boundary layers by use of 'known viscous flows';
(*f*) supersonic fuel–air mixing enhancement using low-loss devices, and including flame–shock interactions;
(*g*) hypersonic propulsive-lift-enhancement by external mass and heat addition;
(*h*) active cooling of sharp edges and hot-spots.

Much of the above will need to be studied in viscous flows of both perfect and real gases, but full inclusion of all real-gas characteristics is not always essential, and the flight analyses of Walberg have shown that, in certain cases, representative research and design can be performed without including the full complexity of flow chemistry.

However that may be, it is clear that significant progress is likely to depend on an improved understanding of the complete flow fields around realistic shapes, and the efficient integration of geometrically compatible parts; this paper has attempted to show some of the problems which, if hypersonic aircraft are to be built, research and design must jointly solve.

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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
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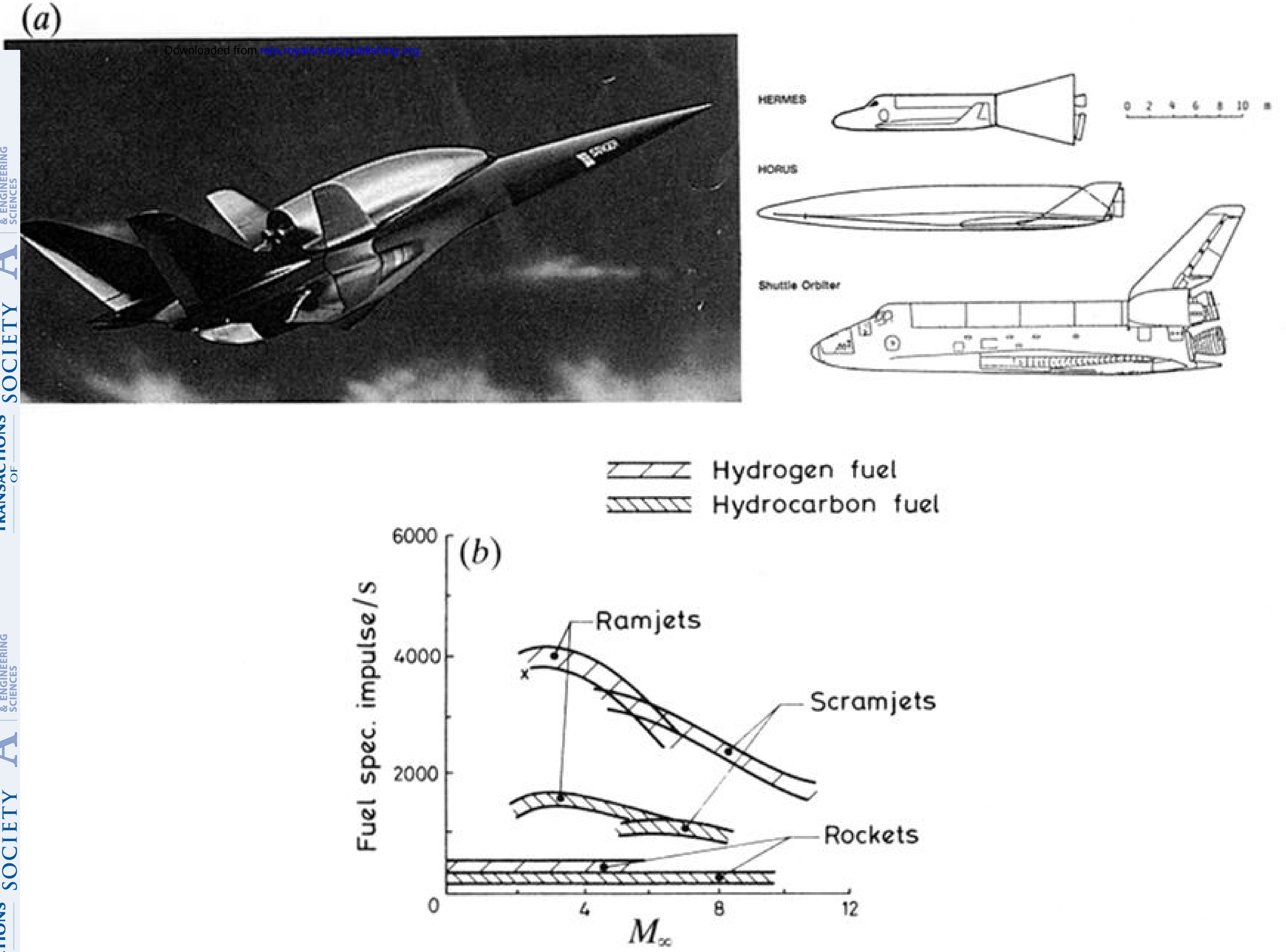
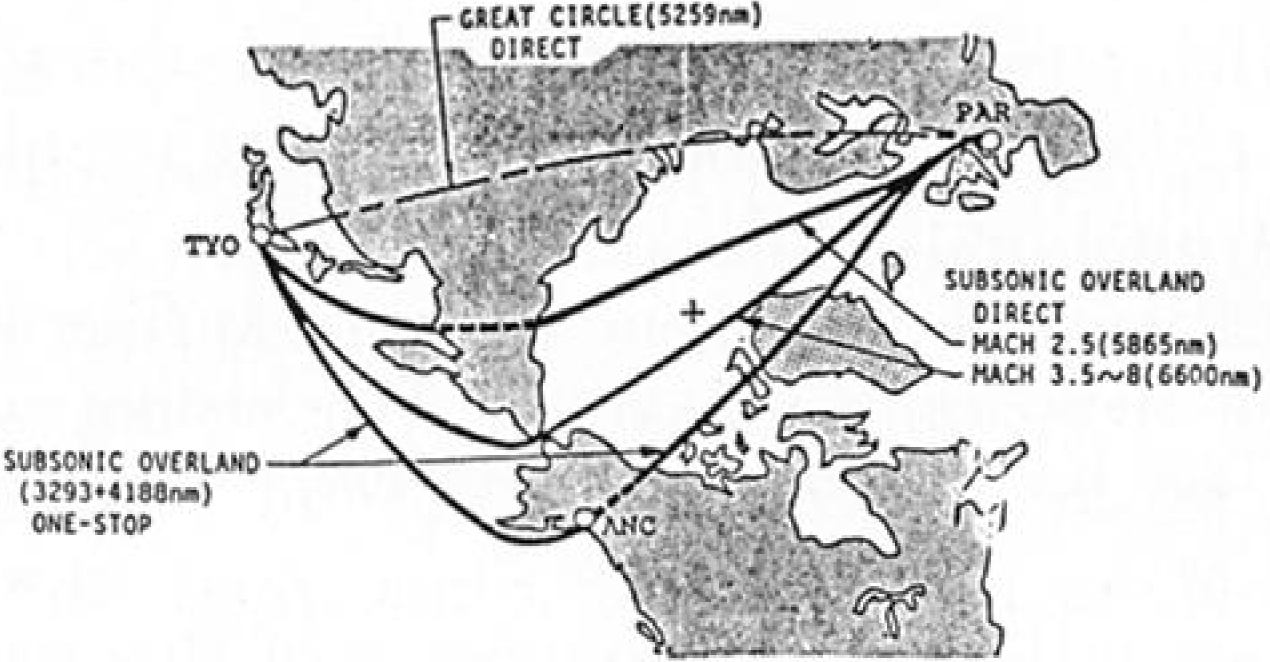


igure 1. Air-breathing launchers. (*a*) Sanger, Hermes, and the Shuttle Orbiter. (*b*) The economy of propulsion units. ×, wake combustion experiment.



gure 2. Supersonic transport routes from Tokyo to Paris.