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Domain of the Scramjet

L. H. Townend*
APECS Ltd., Hants, England GU33 6NS, United Kingdom

As flight speed increases into the hypersonic regime, stagnation pressure and temperature inside an airbreathing engine become so great that, for practical structures of acceptable mass, the flow must pass through the engine at supersonic speeds so as to limit the static pressures, hence the term scramjet (supersonic combustion ramjet). The classic application for the scramjet is to a long-range airliner using hydrogen fuel and offering extended hypersonic flight. The scramjet is also widely accepted as propulsion for cruise missiles and as a possible complement to the rockets conventionally used for space launchers. The topic of how scramjets may best be used, especially in the near term, is explored. In particular, the advantages are demonstrated of using hydrocarbon fuel such as kerosene in a scramjet-powered second stage of a two-stage-to-orbit aerospace plane.

Nomenclature

A_i	=	intake capture area
C_L	=	lift coefficient (referred to planform area)
D	=	drag
f	=	acceleration
g	=	acceleration due to gravity
h	=	specific enthalpy
L	=	lift
L/D	=	lift-to-drag ratio
$(L/D)_p$	=	L/D calculated from pressure forces
$(L/D)_v$	=	L/D calculated from pressure lift and the sum of pressure and friction drags
M	=	mach number
n	=	number of shock waves in scramjet intake (Fig. 3)
p_∞	=	ambient pressure
T	=	thrust or temperature
t	=	time
Δf	=	gain in acceleration

I. Introduction

RECENT publications[1–3] address the propulsion of vehicles up to scramjet speeds, the design of oxidizer collection systems to enhance that propulsion, and the design of scramjets and aircraft themselves.[4,5] This paper considers the scramjet from several aspects in the near term and in the future: What is the scramjet likely to propel? What fuel should it burn? What does it offer in mission design?

The first question was only partially answered during the 1980s. Designs that concentrated on huge, single-stage-to-orbit (SSTO) aerospace planes burning hydrogen, taking off horizontally and offering massive payloads yielded to excessive cost and technical risk and have now led to exploratory vehicles such as Hyper-X. Insistence on hydrogen-fueled engines and hydrogen-cooled structures has moderated to allow that at least some hydrocarbons will offer smaller vehicles, logistic simplicity, and scramjet propulsion to flight Mach numbers of about 10. This combination would suit a small military aerospace plane and would allow access to orbit or hypersonic cruise on a vehicle that is not obliged to carry a large payload. Discussion of such a vehicle has been publicly acknowledged for many years and is associated with the establishment of global presence. It is shown in this paper that a small-payload aerospace plane can achieve orbit as an SSTO in three different forms: 1) as a vehicle that burns only hydrogen, 2) as a vehicle that burns hydrocarbons as an airbreather and hydrogen for subsequent rocket-powered acceleration to orbit, and 3) as a vehicle that burns only hydrocarbons throughout the entire launch. In no case does takeoff mass exceed that of large airliners such as the Boeing 777, and all three vehicles are shorter than the SR71, but the largest and logistically least convenient burns hydrogen.

If future aerospace planes and/or commercial space launchers are to be based on airbreathing propulsion and are propelled, for example, by rocket-based combined cycle (RBCC) engines, there are two obvious questions: 1) Given the RBCC, is the scramjet a requisite cycle? 2) Given the scramjet, is there a more appropriate use than as part of the RBCC? The first question is addressed elsewhere,[6] but the second invites the answer that, if the scramjet is to be given its maximum chance as a space launch acceleration engine, it would be on the second stage of a two-stage-to-orbit (TSTO) launcher in which it would accelerate a relatively small second stage (up to a flight speed at which rockets would take over) but would be uncomplicated by other engine cycles needed for self-acceleration from takeoff to Mach 5 or 6. It is shown in this paper that for a given commercial payload, that is, typically 6000 ± 1000 kg, and by comparison with hydrogen-burning vehicles, the second stage, having the same second stage launch mass and payload, becomes much smaller if it uses hydrocarbons for the scramjet while retaining hydrogen for the rocket. It also seems acceptable to use hydrocarbons because, with optimized trajectories, the scramjet is not required to operate beyond Mach number 10 or 11.

In application to the small military aerospace plane, the TSTO may offer one particular advantage: Because the TSTO second stage will be far smaller than the first stage or the equivalent SSTO, it should present the smallest radar image of the three, especially if components and configuration are shaped with stealth in mind.

Finally, the paper turns to a form of vehicle that uses airbreathing combustion in a uniquely different way. If appropriately applied, external heat addition is shown to offer significant drag reductions for hypersonic aerofoils, the possibility of lift enhancement, and the promise of high specific impulse.

II. SSTOs

A horizontal takeoff SSTO (using scramjets to high Mach numbers and hydrogen as fuel) becomes huge for many commercially reasonable payloads and although takeoff mass is reduced by liquid oxygen collection, that is, the in-flight filling of vehicle tankage with oxygen gleaned from the atmosphere, Balepin[7] shows the vehicle gets far bigger. For a total mass of 350 Mg at takeoff, liquid oxygen (LOX) collection increases vehicle length from 85 to 96 m. Scramjets can be validly included in such vehicles, but the size of both vehicle and scramjet would impose phenomenal levels of cost and technical risk on the builders not least because of the difficulty

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*Proprietor and Director, 3 Hawkley Hurst, Liss; apecscrado@aol.com.

Table 1 SSTOs using kerosene or hydrogen airbreathers up to $M_\infty \approx 5.5$[a]

Choice of fuel(s)	Mass at take-off, Mg, ton	Pullup Mach number	Mass to orbit, Mg, ton	Payload mass, Mg, ton	Vehicle length, m (ft.)
LH_2	275	5.5	63	≈12.5[b]	38.1 (125)
Ke + LH_2	275	5.5	50	≈12.5[b]	30.1 (98.7)

[a]No scramjets, LOX/LH_2 rockets to orbit, drag relief by base burning at transonic flight speed.
[b]Payload margin ≈1250 kg (1.25 Mg).

of adequate ground testing. Thus, any near-term scramjet should propel a smaller vehicle.

The purpose of in-flight LOX collection is to eliminate the massive load of oxidizer that is otherwise carried from takeoff. However, if LOX collection reduces vehicle takeoff mass at the cost of increasing vehicle size, then airframe dry mass increases and affects some of the gains. It is in fact equally logical to question the choice of liquid hydrogen (LH_2), which contributes very high calorific value (heat content per unit mass) and very good cooling capacity, but also imposes pressurized tankage of enormous bulk because the heat content per unit volume of hydrogen (even LH_2) is extremely poor. A denser fuel might allow a smaller and lighter airframe.

Many authors (e.g., Francis[8] and Martin[9]) have shown the value of using hydrocarbons for the initial stages of launcher acceleration and, if kerosene is chosen, the need for bulky tankage is much reduced. As an example, consider a vehicle such as SKYLON,[10] which starts with a gross takeoff weight of 275 Mg and is 82 m long (and does not use an airbreather beyond $M_\infty = 5.5$ or so). Vehicle length could be reduced (at some cost in structural complication but at the same takeoff mass) by using an integrated shape (and retaining LOX plus LH_2), but an additional reduction in length might be achieved if kerosene replaces LH_2 for $M_\infty = 0 - 5.5$, that is, if all airbreathing propulsion uses kerosene. This possibility is discussed next.

Because the commercially viable SSTO aerospaceplane is ambitious by any standards, it is realistic to say that a successful design may depend on advanced materials and lightweight structures. To determine the long-term potential of hydrocarbons, East[11] calculated various trajectories and gradually reduced the structure mass of an SSTO until a payload of about 12.5 Mg was obtained by an all-hydrogen-fueled vehicle weighing 275 Mg at takeoff. For the structural technology level thereby indicated, East then assessed the vehicle, which, for the same takeoff mass and the same payload, used kerosene instead of hydrogen for the airbreather; this vehicle proved to be some 8 m shorter than the all-hydrogen original, a reduction of 21% on external dimensions (see Table 1), except that wing area was independently adjusted to retain adequate lift at takeoff.

In the cases studied by East,[11] there was no performance gain in adding a scramjet to an SSTO of commercial size. For the commercial space launcher, the conclusions appear to be that the use of advanced structures may eventually offer a payload to takeoff mass ratio of 4.5%, that the use of kerosene will still significantly reduce vehicle size, but that the rocket must still burn hydrogen. For this commercial vehicle, in fact, continued use of hydrogen fuel throughout the launch may be justified, but that in turn may depend on advanced technology having provided not only advanced structures but also oxidizer collection systems of greatly reduced volume.

For a large military SSTO aerospaceplane, the position is clearer: Kerosene airbreathers hold out the prospect of vehicles with reduced radar signature, scramjets are not required for access to orbit (but may well be needed to allow efficient hypersonic cruise), and logistically the large aerospace plane would still be hampered by the need for LH_2 for the rocket. A small military SSTO, however, can usefully carry a light payload and, thus, offers the chance that all of the fuel can be kerosene. This offers both the logistic appeal of avoiding LH_2 and the operational appeal of reduced radar signature.

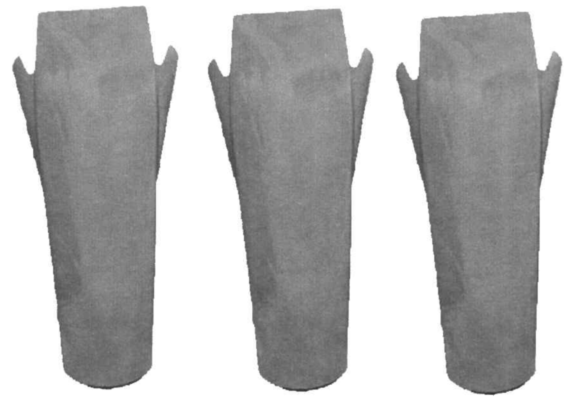


Fig. 1 ECHO 5.

A. Small-Payload SSTO

In late 1996, a study was undertaken by East,[11] Pike,[12] and the present author to determine how best to achieve orbit (with a payload of about 1 Mg) using an efficiently integrated aerodynamic shape, horizontal takeoff, and airbreathing propulsion up to a Mach number to be determined, with rocket propulsion thereafter. The cases examined were 1) hydrogen fuel throughout the launch, 2) kerosene for the airbreather and hydrogen for the rocket, and 3) kerosene fuel throughout the launch (these are described later as 1) LH_2AB + LH2/LOX, 2) KeAB + LH2/LOX and 3) KeAB + Ke/LOX). The vehicle shapes were all variants of ECHO 5 (see Fig. 1), itself a member of a family of shapes related to the X-30. The ECHO shape was designed with a variety of tankage arrangements to suit the propellant choice and with size and slenderness to suit the tankage and aerodynamic efficiency in each case.

Results of the study are shown in Table 2. The all-hydrogen SSTO is both longer and heavier than the vehicle that uses kerosene for the airbreather and LH_2/LOX for the rocket. The logistically convenient vehicle (defined as that which uses kerosene throughout) offers intermediate length but incurs a much higher takeoff mass (294 Mg); however, its takeoff mass is less than that of many current airliners. A summary of the data is shown in Fig. 2.

Because it weighs less at takeoff than recent versions of the Boeing 777, the Boeing 747, the Airbus A340, and the Lockheed C5, the small SSTO should be compatible with many existing runways (even if it uses kerosene throughout the mission and at takeoff may require a trolley to reduce runway loading and the mass of undercarriage carried on the vehicle itself).

In all of the SSTO calculations for Tables 1 and 2, the value of pullup Mach number was taken as 5.5, and a scramjet was not incorporated. Thus, the small military SSTO might then be unable to cruise at Mach numbers exceeding 5.5, which is too low a value to outperform SR71 derivatives. To fulfill the cruise/reconnaissance mission that may be required on some flights, the airbreather must be able to accelerate to maybe twice the given flight Mach number, and in consequence, the airbreather must be a scramjet, or an RBCC designed to operate at Mach numbers up to about 10. It is, therefore, important that the scramjet, if incorporated to provide efficient cruise, should at least not compromise performance on space access missions, and this will probably raise the pullup Mach number on

Table 2 Takeoff mass and vehicle length for transport aircraft and SSTOs

Aircraft type[a]	Mass at takeoff, Mg, tons	Vehicle length, m (ft)	Comments on payloads
SSTO (KeAB + LH_2/LOX)	106.5	22 (72.2)	≈1 Mg (1000 kg)
SSTO (LH_2 AB + LH_2/LOX)	119	29 (95.1)	≈1 Mg (1000 kg)
SSTO (KeAB + Ke/LOX)	294	26 (85.3)	≈1 Mg (1000 kg)
Antonov 225	589	84 (275.6)	——
Boeing 747-400	390	70.7 (231.8)	416–524 passengers
Lockheed C5B	373	75.5 (247.8)	——
Airbus A340-600	359	75 (245.9)	380 passengers
Boeing 777-300	294	73.9 (242.3)	357–550 passengers
Concorde	182	62.1 (203.8)	100 passengers
Boeing 757-300	120	54.4 (178.6)	243 passengers
Boeing 727-200Adv.	86	46.7 (153.2)	145 passengers

[a]Current Boeing plans include the Boeing 747-400X or 747-500. Its entry would be 475 Mg, 85.4 m (280 ft), and ≈600 passengers.

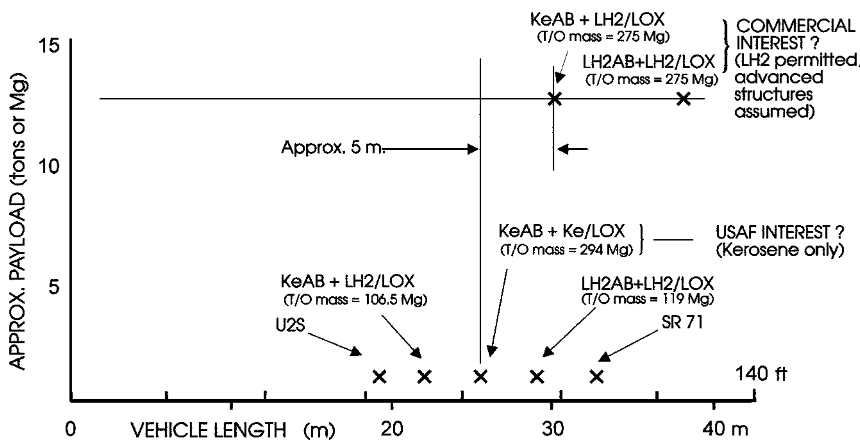


Fig. 2 SSTOs large and small (data due to East[11] and Pike[12]).

space access missions toward 11 ± 1. Alternatively, range might be curtailed if an RBCC is providing cruise propulsion[6] because an RBCC would probably offer a lower specific impulse than a scramjet, unless the RBCC itself operates in scramjet mode.

III. TSTOs

By the end of the 1980s, it became clear that, for commercial payloads, the SSTO using scramjets for airbreathing acceleration (up to Mach numbers as high as 15) was too risky an undertaking and offered payloads that could easily become zero due to mass growth in the airframe and elsewhere. If the scramjet was to have a chance to contribute to the orbiting of large payloads, it seemed more likely to succeed on the second stage of a TSTO for the following reasons.

1) This would allow the first stage to achieve a maximum Mach number of only 7 (or less).

2) The scramjet would be accommodated on a smaller and simpler vehicle than an SSTO, with only a rocket as additional propulsion.

3) The use of hydrocarbons for the scramjet might make the vehicle smaller still.

The scramjet second stage was analyzed in general terms by Heiser and Pratt.[2] Specific studies of scramjet second stages were published by Hardy et al.[13] and Koelle,[14] but both assumed hydrogen to be the fuel. Drawing on the work of Jamison and Hawkins,[15] the author, East,[11] and Pike[12] performed in 1994–1996 an in-house study of scramjet second stages burning a much denser fuel than hydrogen so as to secure a smaller volume of tankage and a smaller, lighter vehicle.

For commercial payloads and for a given second stage launch mass, comparison with scramjet second stages using hydrogen (or hydrogen plus neon as studied by Rudakov and Krjtchenko[16]) confirmed that, at the same launch mass and launch Mach number, the kerosene-burning scramjet second stage offered much smaller vehicles. Unlike the hydrogen-burning scramjet second stage, the size required by a kerosene-burning vehicle grew smaller as pullup Mach number was increased, and in contrast to the hydrogen-burning vehicle, the problem of rapidly rising vehicle bulk was thereby avoided.

Nonetheless, even the kerosene-burning scramjet did not easily provide a payload significantly different to that of a Sanger-launched rocket-powered HORUS.[17] This was partly because the fuel tanks were now so much smaller that the vehicle needed to be further repackaged, so that additional reductions in size could be achieved. On the other hand, the data suggested that the scramjet second stage could well offer both space access and hypersonic cruise on an even smaller aerospaceplane than the SSTO discussed earlier (Table 2).

A. Small-Payload Second Stage Scramjet Orbiter

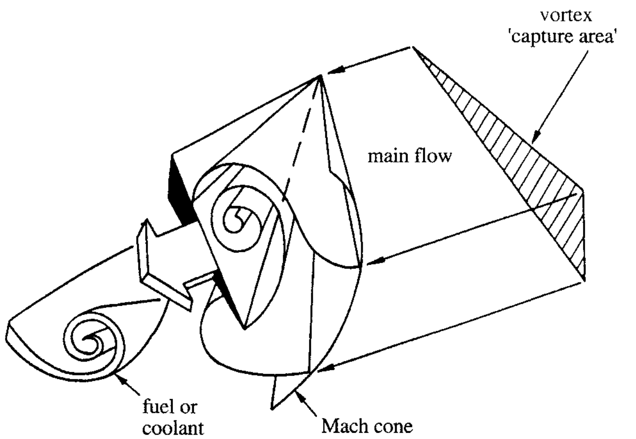
Results for three possible second stage scramjet orbiters are shown in Table 3, for which it is assumed that packaging gives a ratio of void to available volume ~30%, and that vehicle design depends on good engineering of available materials and structural techniques rather than on the application of potential material properties as yet unachieved.

Clearly, the results of Table 3 depend on using a scramjet that can operate (as a ramjet or as a scramjet) from flight Mach numbers of 3–10 (see Curran et al.[18]). Conventionally, the transition from subsonic to supersonic combustion is achieved at flight Mach numbers as high as 6 or 7. Alternatively, the use of an injected precoolant to chill the intake flow[19] allows a scramjet to retain supersonic combustion at flight Mach numbers as low as 3 or 4 and at specific thrust levels that are enhanced by precooling and may still allow acceleration on scramjet power. These data are due to Nonweiler[19] in whose work the precoolant was taken to be ammonia (see Fig. 3), but as

Table 3 TSTO second stages using kerosene-burning ramjet/scramjets[a]

Mach number at launch	Mass at launch, Mg, ton	Pullup Mach number[b]	Mass to orbit, Mg, ton	Payload mass, Mg, ton	Vehicle length, m (ft)
3	80	10	12.5	0.03[c]	18.3 (60)
3	90	10	13.8	0.80[c]	19.1 (62.6)
3	95	10	14.4	1.20[c]	19.4 (63.6)

[a]Ramjets/scramjets are used from launch to pullup, and scaled RD 120 kerosene/LOX rocket(s) from pullup to orbit (or kerosene-burning scramjets for cruise).
[b]Second stage launch occurs at Mach number 3, and pull-up Mach number implies the ability to cruise at Mach 10+.
[c]Payload margin taken to be zero.



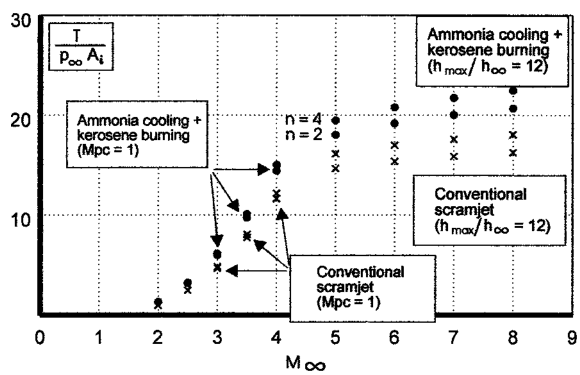


Fig. 3 Scramjet specific thrust at design conditions.

Nonweiler pointed out, water injection could also be effective. The use of chilled compression would also enhance the thrust of the engine while in ramjet mode, so that in practice the scramjet may operate in dual mode with chilled compression in both modes.

The mixing of ammonia into a supersonic airstream could possibly be achieved by the use of liquid jets and streamwise vorticity as was proposed[20] for supersonic combustors in 1966 and subsequently developed by NASA (for example, see Povinelli et al.,[21] Northam et al.,[22] and Riggins and McClinton[23]).

The possibility of the ammonia coolant burning in the combustion chamber may offer some temporary economies in kerosene consumption, but its use as an airflow coolant may also ease the partial achievement of stealth as will be discussed.

If neither the transition from subsonic to supersonic combustion nor airflow chilling is acceptable, the first stage launcher would need to achieve a higher Mach number such as 6 or 7. At the cost of this more advanced first stage,[17] the scramjet would be simpler and the second stage smaller still.

B. Hypersonic Stealth

Hypersonic cruise vehicles are liable to surface temperatures that render the airframe easily detectable. Whereas, for an aircraft at Mach number 2, even the stagnation temperature will be below 500 K, a large vehicle cruising at $M_\infty = 10$ will incur (with turbulent flow) temperatures of 900 K or more at the underside trailing edge, and the remaining undersurface will be hotter. If M_∞ is 10, if the flow is turbulent, and if radiation is taken as proportional to T^4, then at positions along a chord length of 30.5 m (100 ft), temperatures are as in Table 4.

Table 4 Temperatures at M_∞ = 10

x/c	T, K	T^4, $\times 10^{11}$
0	T_{LE}	T_{LE}^4
0.05	1220	22
0.10	1180	19
0.25	1140	17
0.50	1110	15
1	1090	14

All of these values of T^4 are much greater than the worst possible value for $M_\infty = 2$ (i.e., $T^4 = 500^4 \approx 0.6 \times 10^{11}$), but the worst case for $M_\infty = 10$ will depend on the leading-edge temperature T_{LE}, and that will depend on edge radius, cooling, and sweep. For leading edges swept at 75 deg and having a nose radius of 2 mm, it is known[24] that conductive cooling offers T_{LE} values between 1314 and 1527 K, that is, T_{LE}^4 values of 30×10^{11} and 54×10^{11}.

Uncooled leading edges invariably provide local hotspots on hypersonic vehicles, especially if they are unswept. Either their temperature (and T^4) must be very high, or bluntness must be increased. In either case, the total radiation increases, and the vehicle becomes more vulnerable to early detection and attack. There is, therefore, a case to examine hypersonic intakes that combine leading-edge sweep with leading-edge sharpness and, thus, to study means by which to select the intake shape, to retain the requisite compression flow, and to cool the sharpened edge.

As far as basic geometry is concerned, all-swept intakes were designed in the 1960s (for example, by Mölder and Romeskie[25] and Townend[20]), and the application of conductive cooling was examined by Capey[24] and Nonweiler[26] giving leading-edge temperatures of about 750 K at $M_\infty = 5$ (for 2-mm leading-edge radius and 75-deg sweep) and 1300–1400 K at $M_\infty = 10$ (again for 2-mm. leading-edge radius and 75 deg of sweep). Typical intakes are as shown in Fig. 4, and the swept edges should not only run cooler but will reduce the radar signature offered in frontal aspect. Variants of such intakes can be installed on modifications of the ECHO shape or on configurations of stealthier design.

For a given release of heat, intake size will vary as between kerosene and hydrogen. From data given by Küchemann and Weber,[27] observe that 1 kg of kerosene will release 10,200 kcal and 1 kg of H_2 will release 27,600 kcal; thus, to release 27,600 kcal requires 1) 1 kg of H_2 plus at least 34.2 kg of air or 2) 27,600/10,200 kg of kerosene plus at least 14.8 (27,600/10,200) kg of air, that is, the air intake must capture at least 34.2 kg of air for H_2 or 40 kg of air for kerosene. Thus, the use of kerosene must reduce vehicle areas to, at most, 34/40th of those for the hydrogen-burning vehicle. Vehicle length must, therefore, fall to 92% (or less) of the original length. If it does not, the kerosene scramjet may be more easily detectable in terms of intake radiation, and the flame itself will be more exposed in terms at least of flame area discernible from the front.

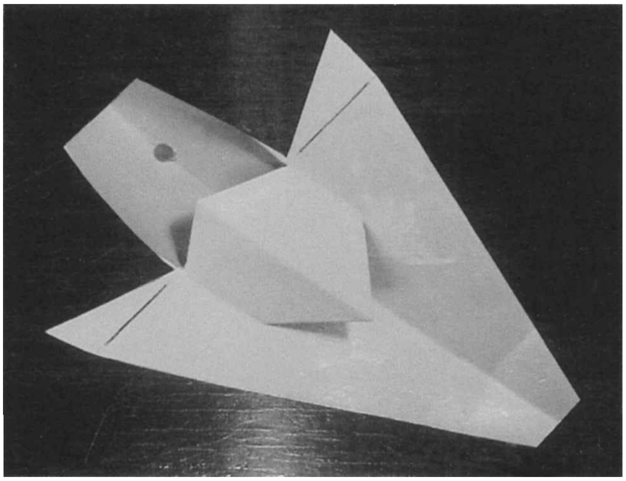


Fig. 4 All-swept intakes (1966).

Because kerosene is much denser than liquid hydrogen, its use will frequently reduce the length of the vehicle by considerably more than 8% (see Table 2 in which SSTO length is reduced from 29 m to 26 m or 22 m, respective reductions of 10% and 24%). Also, where coolant injection is used to chill the intake flow at low flight Mach numbers, its intermittent use in cruise could impair the chance of interception by heat-seeking missiles because it would mask the forward radiation from the scramjet flame.

As far as detection of the jet is concerned, and again, for a given release of heat, the kerosene flame temperature will be roughly 85% of that for hydrogen and its radiation some 0.85^4, about half that for hydrogen. Cycle design for stealth may reintroduce the topic of propellant selection.

IV. Flameriders: Uses of External Burning

There are at least three well-established situations in which a hypersonic aircraft may suffer from a so-called thrust-minus-drag pinch, that is, not enough thrust or too much drag. The first occurs transonically, where base drag on the nozzles (which are sized for high speeds) becomes a significant proportion of the total. The second occurs hypersonically, where the thrust of a scramjet is decreasing with flight Mach number, and its capacity to accelerate a launch vehicle eventually falls short of requirements. The third occurs in lifting reentry, where a gliding vehicle may need more cross range (and, hence, a higher lift-to-drag ratio) than can be provided at a vehicle attitude that permits a high enough lift coefficient (and thus sufficient altitude to avoid excessive heating of the structure). In all three cases, the problem can be met by the release of heat externally to the airframe, as opposed to conventional release inside an engine combustion chamber.

The first of the three problems noted in the preceding paragraph (transonic and supersonic base drag) has been addressed, for example, by Townend and Reid[28] and by Billig[29] and is not further considered here. The second and third problems are considered as follows. First, however, basic illustrations are presented for external heat addition and in particular lift enhancement, with external heat addition treated as a variation in the design of high-speed aerofoils.

A. Lift Enhancement

As originally studied by Oswatitsch,[30] external heat addition was applied above and below a symmetric aerofoil and was shown to offer the prospect of external thrust at supersonic speeds. Subsequent theoretical work and various experiments demonstrated that external heat addition applied to one side of an aerofoil (for example, see Billig[31] and Dorsch et al.[32]) would offer both a drag reduction (or a potential thrust) and lift enhancement. These experiments used pyrophoric fuels such as aluminium borohydride or triethyl aluminium but Kallergis (see Ref. 33) demonstrated the external combustion of hydrogen and generated an external pressure thrust at $M_\infty = 4$. Theoretical flow models were elaborated by Zierep[34] and Baldwin,[35]

Table 5 Lift and drag at flight Mach number 6 (see also Fig. 5

Number	Reference	C_L	$(L/D)_p$
1	Corda and Anderson[37]	0.030	13.61
2	Wedge flow	0.062	8.13
3	Pike[12]	0.030	20.9
4	Pike[12]	0.062	10.84
5	Broadbent[38]	0.062	28.2
6	Broadbent[38]	0.124	16.36
7	Broadbent[38]	0.248	8.18

for example, but one of the more detailed analytic methods was that of Broadbent,[36] who enabled the details of streamline shape, streamline pressure distributions, and other properties throughout the flow to be predicted. In all cases, the flame was preceded by at least one oblique shock and was followed by a supersonic expansion, so that the three essential elements of the scramjet cycle were included. As a result, external combustion came to be classified as propulsion and was criticized on the grounds of low specific thrust and low specific impulse. As a further result, it was often reserved for applications such as control rather than propulsion; however, if correctly applied (as a variation in aerofoil design) a low thrust (or simply a reduction in drag) can be valuable, and if obtained by external heat addition, it can offer specific impulses that compete with conventional scramjet values. A range of data is presented in Table 5, in which the performance levels of a wedge and of two conventional wings (both waveriders but of different kinds) are compared with wings having external heat addition.

A conventional wing designed for $M_\infty = 6$ (in fact, a case calculated by Corda and Anderson[37] for a conical flow waverider) gives the top line of data in Table 5 (see also Fig. 5). In viscous flow the L/D might be 10 or so, but a wing could be reshaped to give a stronger oblique shock wave [at some cost in $(L/D)_p$ and $(L/D)_v$] to give higher static pressure beneath the wing and in consequence, a higher C_L, for example, see line 2 (which is for a 7-deg wedge). Some complexity in lower surface shaping (geometrical optimization as by Pike[12]) potentially offers the same C_L values as lines 1 and 2 but at an extra 30% in $(L/D)_p$ (see lines 3 and 4) and the introduction of additional changes to the shape and of external heat addition[38] below modified wings allows significant improvements to C_L (see lines 5–7).

Comparison of lines 2, 4, and 5 shows that, for a $C_L = 0.062$ at flight Mach number 6, the $(L/D)_p$ of a simple lifting shape with a single shock wave can be increased from 8.13 to 10.84 by reshaping the undersurface but that further reshaping, a second oblique shock wave, and appropriate external heat addition can together raise the $(L/D)_p$ to 28.2, while a C_L of 0.062 is retained. Alternatively, comparison of lines 2 and 7 shows that, by combining well-judged geometry changes with appropriate external addition of heat, the C_L can be quadrupled from 0.062 to 0.248 while, in both cases, $(L/D)_p$ is approximately the same (8.13 and 8.18, respectively).

The conclusions are that 1) for $(L/D)_p$ around 15 ± 1, external heat addition offers a quadrupling in C_L and 2) for $(L/D)_p$ around 8.1 ± 0.1, external heat addition again offers a quadrupling in C_L. In more general terms, external heat addition may allow 1) significant increases in wing loading (and possible reductions in structure mass); 2) the use of direct lift control and substantial C_L enhancement at constant angle of attack, thus a scramjet vehicle can gain altitude or pull a high-g turn without driving the scramjet intakes off-design by altering vehicle attitude, which could be useful for rapid adjustments to reconnaissance altitude, for other types of evasive manoeuvre or for first stage return; and 3) useful performance without giving an external net thrust: In Table 5, $(L/D)_p$ is high, but it is not a negative number as it would become if pressure drag had become a pressure thrust.

B. Drag Reduction and Thrust

Where lift and component planform areas are already selected (the wings, perhaps, by takeoff or landing considerations, and the

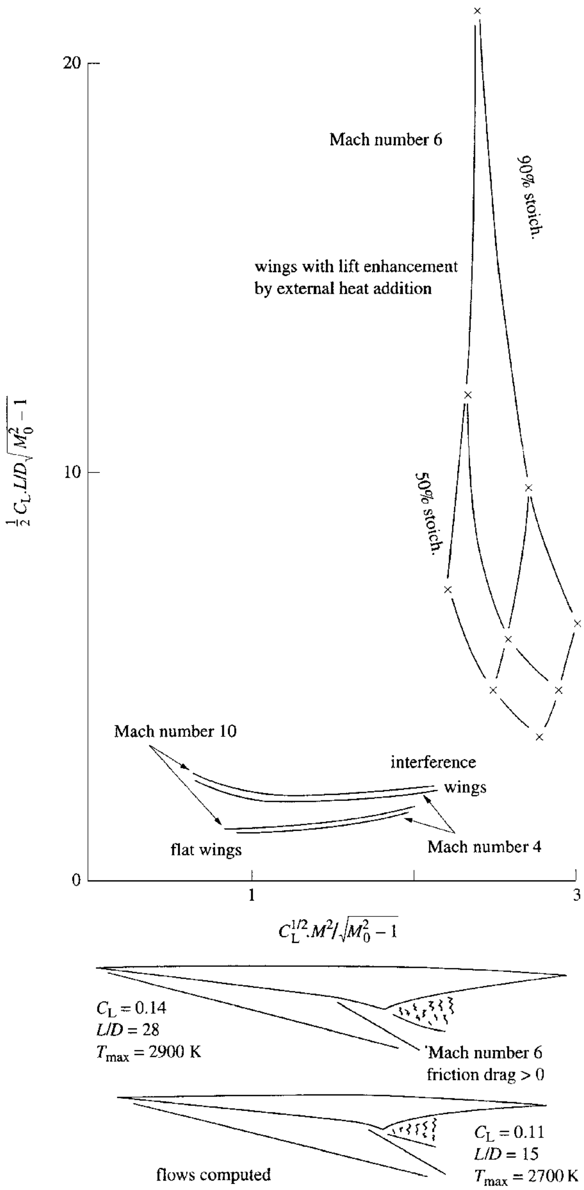


Fig. 5 Wings with external heat addition.

cowl by intake width and scramjet combustor length), there is a need to retain (rather than to enhance) the C_L and to use external combustion to cut the drag. A conventional wing (or unmodified cowl) giving $C_L^{1/2} M_\infty^2 / \sqrt{(M_\infty^2 - 1)} = 3$ would give a value of $\frac{1}{2} C_L (L/D_p) \sqrt{(M_\infty^2 - 1)}$ no higher than 3 and, thus, a C_{D_p} of about 0.058. The C_L would be 0.243 (and the L/D_p would, thus, be about 4.2). A modified wing with external heat addition could still give a C_L of 0.243 but C_{D_p} would fall to 0.028, effectively by one-half.

Analysis shows that specific impulse is a strong function of the value of $(C_L \cdot L/D)$ before and after the introduction of external heat addition. This parameter $(C_L \cdot L/D)$ also arises in wing optimization theory (see Pike[12]) and allows consideration of various cases whether external heat addition provides a drag reduction or a thrust: It eases the process of linking the disciplines of lift production and thrust production (or drag reduction), which are implicit in external heat addition and are essential to its evaluation. It is also a dominant term in $\Delta f/g$, where $\Delta f/g$ is a measure of the *additional* acceleration potentially achievable with external heat addition.

For stoichiometric external combustion of hydrogen, injected at a fuel Mach number of 2 and fuel temperature of ~950 K, pressure drag can become pressure thrust as shown in further data due to Broadbent[38] (see Table 6), and specific impulse values are comparable with those of conventional scramjets (see Fig. 6).

Table 6 External heat addition giving pressure thrust

M_0	C_L	$C_L^{\frac{1}{2}} M_\infty^2 / \sqrt{(M_\infty^2 - 1)}$	$\frac{1}{2} C_L (L/D_p) \sqrt{(M_\infty^2 - 1)}$	I_{sp}, s[a]	$\Delta f/g$
6	0.125	2.151	−4.71	2608	0.25
9	0.064	2.298	−4.12	1832	0.18
12	0.04	2.412	−4.05	1403	0.13

[a]Much higher I_{sp} values result if a pressure drag is permissible (see Broadbent[38] data, Fig. 6).

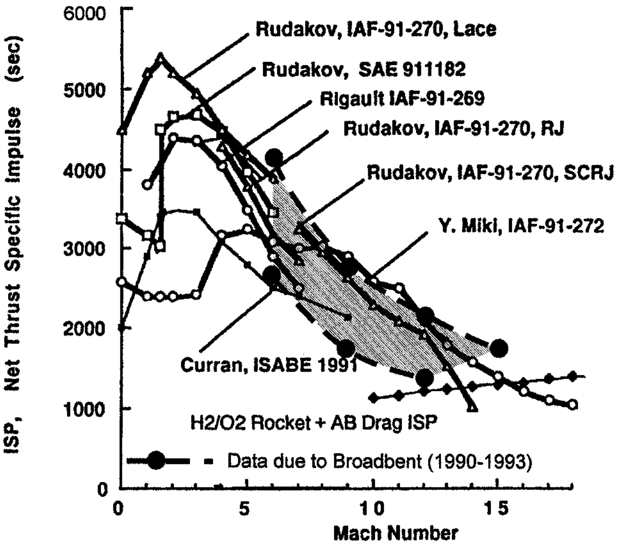


Fig. 6 Data correlation (Czysz[6]) plus data points for external heat addition (Broadbent[38]).

The values of $\Delta f/g$, which measure the gains in acceleration due to external combustion, equate roughly to $\Delta f = 2.45$, 1.8, and 1.3 m/s^2, and they are based on a vehicle design in which external combustion is spread across the whole span of the underside.

C. Drag-Relieved Reentry Craft

For really high cross range, a lifting reentry glider needs to provide an L/D of perhaps 3.5 throughout reentry (see Love[39]), but the associated C_L is low and the heating rates are greatly increased by the high kinetic pressures which result. Thus in practice, high C_L is needed during the heat pulse (which occurs at flight Mach numbers 20 ± 3), and L/D at these conditions will be less than 1.5. With this constraint, a trajectory can resemble that of Fig. 7, but the gliding cross range is reduced to some 3000 km. In principle, external combustion could be introduced at flight Mach numbers 12 down to 6 or lower, so that L/D would increase, maximum deceleration would be delayed, cross range would be greatly extended, and heating of the structure by the flame would occur well after the conventional heat pulse was past.

A typical reentry trajectory at $L/D = 1.5$ would allow a glider to cover some 10,000 km (downrange) while decelerating to $M_\infty \approx 12$. In so doing, the vehicle could also turn through some 90 deg in heading and, from $M_\infty = 10$, direct contributions to cross range would accrue at about 800 km per unit L/D. Thus, if external combustion were used at flight Mach numbers 10 down to 3, so as to secure a value of L/D of 10, the total cross range covered would be some 8000 km, plus the cross range already provided during the hypersonic turn (about 1000–2000 km). It appears that with external combustion, global cross range may be achievable even though airbreathing combustion would be needed only below $M_\infty = 10$. This reasoning effectively combines some cruise and reentry studies[20,40–42] in the 1960s with recent design and assessment of a reentry glide vehicle. This was envisaged as a space station ambulance[4] and was, therefore, designed to give very low-g forces in reentry and, thus, a high cross range (see Fig. 8).

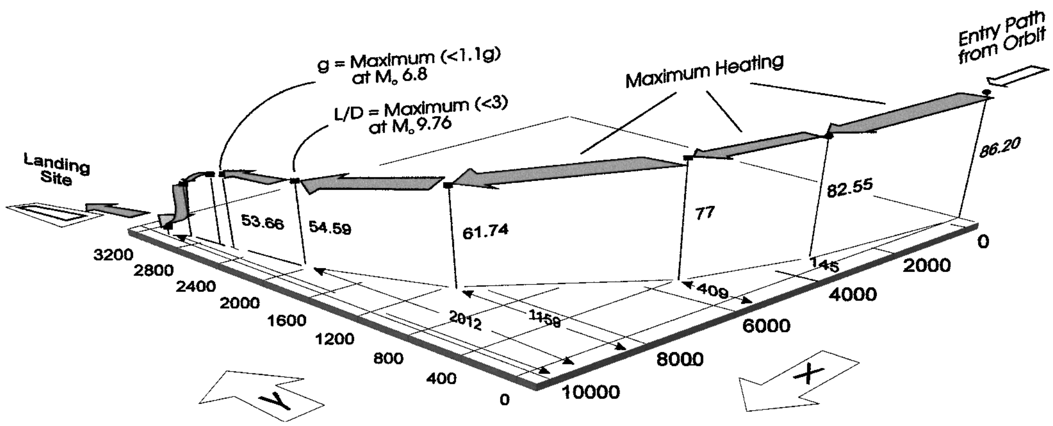


Fig. 7 Reentry at low deceleration (<1.1 g) (data due to Nonweiler[43]).

Table 7 Reentry at low deceleration[43] (<1.1 g)

t, s	Altitude, km	M_0	X, km	Y, km	L/D	g
0	86.20	28	0	0	1.19	0.205
450	82.55	25.13	3,264	143	1.29	0.299
800	77	21.6	5,543	409	1.35	0.531
1,350	61.74	14.06	8,335	1,159	2.47	1.046
1,700	54.59	9.76	9,329	2,012	2.96[a]	1.046
1,900	53.66	6.83	9,597	2,490	1.72	1.085[a]
1,950	50.90	6	9,640	2,587	1.86	1.077
2,150	40.81	3.64	9,721	2,885	2.41	1.054
——	0	0	10,000	3,000	——	——

[a]Maxima in L/D and g.

East[11] and Nonweiler[43] have reported on two designs of space station ambulance,[4] of which the more innovative was SLEEC 22, a well-streamlined glider having a low wing loading and a length of 9 m. The basic SLEEC 22 trajectory, shown in Fig. 7 and Table 7 would be ideal for a space station ambulance reentry craft (because the deceleration nowhere exceeds 1.1 g, whereas injured astronauts with broken limbs and internal bleeding would risk embolism at higher g). With external combustion added, both the cross range and the reentry window would increase and, with them, the versatility of SLEEC. It is in fact possible that an enlarged SLEEC with external combustion might qualify as a military aerospace plane that would operate from orbit.

Fig. 8 Space station ambulance.

V. Antiballistic Missile Missile

A current concern is to intercept ballistic missiles having a range of 150–300 km but operating from mobile launchers and offering the ability to reach launch readiness quite rapidly. Interception by missiles such as Patriot or Patriot PAC implies a last-ditch defense. It would certainly be safer to complement Patriots with missiles capable of boost phase interception (BPI), so that the ballistic missile could be destroyed within a minute or two of launch (for example, within 30 miles of the ballistic missile launcher). This implies the need for an antiballistic missile (ABM) missile of at least 275-km range, but very short flight time and final speeds of $\sim M_\infty = 20$. If the ABM is to be of restricted launch mass, an all-rocket system will not provide sufficient range or final Mach number. A scramjet could be used for the Mach number range from 6 to some much higher value ($\sim M_\infty = 13$) at which a rocket would again be used: This implies a minimum of three or four stages, of which the penultimate is scramjet powered. Thus, most of the trajectory is constrained by the need for moderate lateral accelerations and for very high longitudinal accelerations.

Analysis shows that some overlap between the launch rocket boost and the first few seconds of scramjet power would be helpful. With rocket launch, the ABM would reach Mach number 3 in perhaps 3 s, the scramjet would overlap for another 3 s (by which time longitudinal acceleration would be approaching 50 g) and the scramjet alone would then continue to accelerate the ABM (at 10–20 g) for $\sim$15 s. At this point, some 50 km (30 mile) from ABM launch, the final rocket stage(s) would accelerate the warhead or projectile to Mach numbers exceeding 20 to intercept some 240 km downrange from ABM launch. The Patriots would provide defence against any incoming missile that survived the BPI.

The production of a scramjet ABM for BPI would depend on compactness and, thus, on the use of a hydrocarbon (such as kerosene) or of a solid fuel, but with either, air-breathing combustion would need to remain secure under 50-g acceleration and the vehicle must survive the panel loadings due to kinetic pressures of many megagram (tons) per square meter. The scramjet would lead an active life of less than 20 s.

VI. Conclusions

Because the propulsive role of the scramjet in high-speed cruise is well established, this paper has considered the wider domain. In particular, applications to space launchers and the military aerospace plane are considered in various forms and with fuels that are logistically more convenient than liquid hydrogen. For small payloads, the SSTO, or the scramjet second stage of a TSTO, can both operate with kerosene as the only fuel throughout the mission. The work described has been exploratory rather than definitive and conclusions are tentative.

1) A large SSTO for commercial use will need not only advanced structures but careful optimization of propellants; at given takeoff mass and payload mass, hydrocarbons for the air-breather offer smaller airframe size.

2) A small SSTO for military uses (cruise and space access) will benefit from exclusive use of hydrocarbons in both the airbreather and rocket modes because takeoff mass remains acceptable and size can be lower than for a hydrogen-fueled vehicle.

3) An even smaller vehicle may be achievable by using hydrocarbon-fueled scramjets on the second stage of a TSTO, subject to chemical constraints on hydrocarbon combustion.

4) Scramjet performance (especially specific thrust at supersonic and low hypersonic Mach numbers) could be improved by the injection of evaporative coolants into the intake or the airflow upstream.

5) External combustion should be used as a means to achieve low-drag lift rather than to attempt significant net thrust. In other words, external combustion serves best, not as an engine, but as a modification to aerofoil design and can then return specific impulses that rival conventional scramjet values.

6) The most urgently needed hypersonic vehicle is a reentry glider, serving as a low-*g* space station ambulance (SLEEC), but the addition of external combustion to an enlarged SLEEC offers a small, simple, space-based military aerospace plane.

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