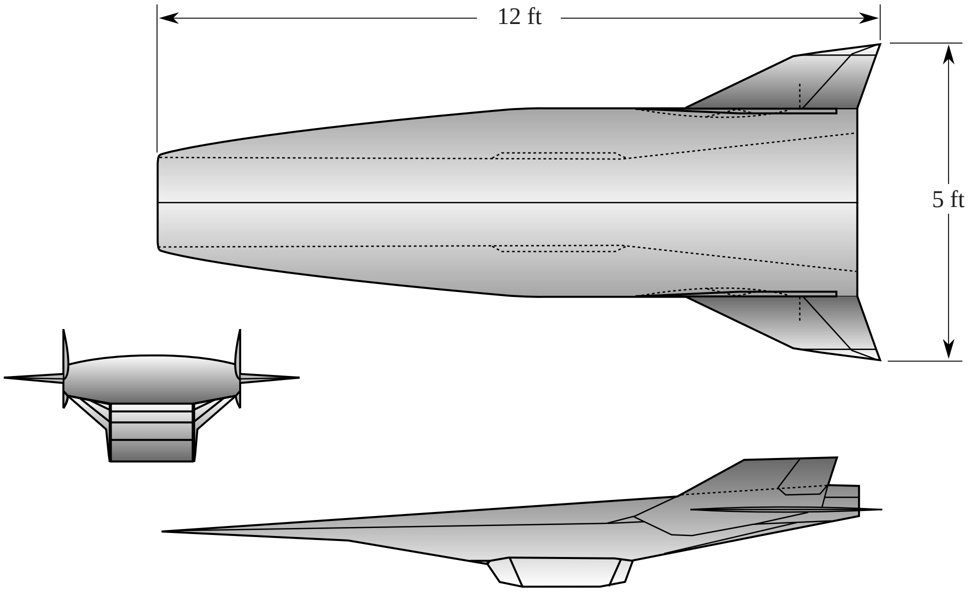
Topic II
Airbreathing propulsion



Hyper-X research vehicle configuration. (Reproduced with permission from NASA Langley.)

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In the first paper of Topic II, Czysz considers future reusable space launchers and the factors that will permit a choice to be made between the many possible airbreathing propulsion systems (see Murthy & Curran 1996). To explain the diversity of choice consider the following. The reason that turbojets have compressors is that, for the speeds at which most conventional aircraft fly, there is not enough ram compression ratio to provide an efficient engine of reasonable size. However, for higher flight speeds (in excess of Mach number 2 say), it is possible to use kinetic compression (i.e. the compression produced by slowing the air to subsonic speed within the engine) to replace the compressor—hence, the subsonic combustion ramjet. As flight speed increases, the stagnation pressure and temperature inside the engine become so great that, for practical structures of acceptable mass, the flow must no longer be slowed to subsonic speeds in the engine, but must pass through the engine at a speed that permits a lower static pressure. For that to happen, the flow must pass through the engine at supersonic speeds, hence the term scramjet.† At still higher speeds, the scramjet encounters its own limits to performance, and propulsion to even higher speeds must be by rocket. A large number of concepts can be configured to follow the above train of events. Instead of placing these different engine cycles separately, the concept of physically and thermodynamically integrating these many engines gives rise to the combined cycle engine. Building that integration around a rocket engine results in the proposed RBCC.

Czysz also considers the specification of a vehicle upon which to demonstrate the operation of those engine concepts that are eventually chosen to compete for full-scale application. Czysz concludes that the vehicle can be rocket-propelled, but should be designed to accept airbreathing propulsion modules of widely different kinds. Determining the speed up to which the demonstrator must operate as an airbreather prompts the question, 'How fast is fast enough?', which must be answered in terms of the eventual full-scale launcher. The handling of this question is basically propulsive, but the factors that Czysz considers in the design of a demonstrator illustrate the conflicting requirements that the designer must resolve in this intricate field of aerodynamic, structural and propulsive integration; from the propulsive point of view, Czysz illustrates the possibility of designing and flight testing engines that adjust their cycle to suit their airspeed, i.e. the RBCC.

For flight speeds ranging up to Mach 12 or so, the scramjet is a main contender, but the RBCC and the scramjet together prompt three major questions at the conceptual level. Given the RBCC, when is a scramjet required? What should a scramjet propel? And what should it burn? These questions are addressed in the second paper of Topic II, which is concerned as much with vehicle considerations as it is with engines.

For example, a horizontal take-off single stage to orbit (SSTO) using LH2 becomes huge for any commercially reasonable payload (and if take-off mass is reduced by LOX collection, Balepin (1996) shows the vehicle gets far bigger; for 350 t at take-off, LOX collection *increases* vehicle length from 85 to 96 m). Scramjets can be validly included in such vehicles (which have been widely examined during the 1980s), but the size of both vehicle and scramjets would impose phenomenal levels of cost and technical risk upon the builders. Thus any near-term scramjet application should be to a smaller vehicle, the mission must be chosen accordingly and the flight plan

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† The term scramjet is derived from supersonic combustion ramjet, and (as part of a rocket-based combined cycle (RBCC) or as an engine in its own right) is effectively unique among airbreathers in being operational up to flight Mach numbers 12 or possibly beyond.

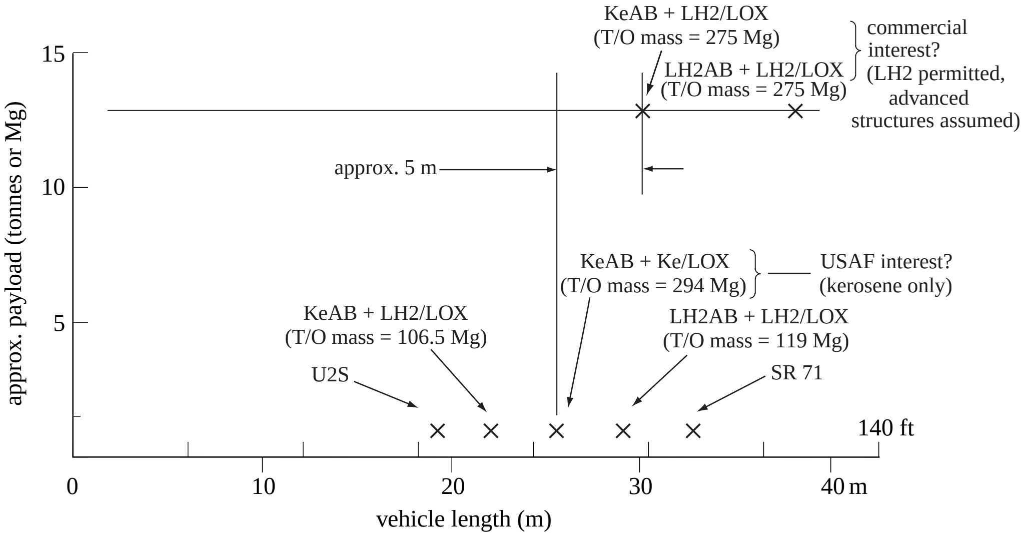

Figure 1. SSTOs large and small (APECS data due to East & Pike (1997)).

should exploit those features in which a scramjet excels. Since the scramjet is flexible in operation (provided flight Mach numbers are already high), and since it is outstandingly effective for hypersonic cruise, its best application may be to propel not an SSTO but the second stage of a vehicle having two stages to orbit (TSTO). Having provided acceleration from about Mach number 6 up to 12 (say) the scramjet can then allow a choice between airbreathing cruise or access-to-orbit using rocket propulsion. Such a vehicle would then fill a military role. Furthermore, with scramjet second stages, the use of kerosene fuel, instead of LH2, permits a reduction in vehicle size and in radar signature. In addition, trajectory optimization for access-to-orbit shows that transition to rocket should occur between Mach 10 and 12, which is consistent with the use of kerosene instead of hydrogen in the scramjet combustor.

For military missions, it may be operationally inconvenient to use a TSTO. For the small SSTO aerospaceplane (offering cruise or space-access options but with only a small payload), it remains realistic to use kerosene, not only for the airbreathing flight but also for the rocket-powered acceleration into orbit. By comparison with vehicles using liquid hydrogen for the rocket and/or for the airbreathing flight, the vehicle using only kerosene is much heavier at take-off but intermediate in size (see figure 1); since its take-off mass is no greater than the largest Boeing 777 (and 96 t lighter than the Boeing 747-400), it should be compatible with existing runways, even if take-off may require a trolley to reduce the mass of undercarriage on the vehicle itself.

With kerosene as the fuel, both the airbreathing SSTO and the scramjet second stage would be relevant studies for future spaceplanes of the kind that the US Air Force Space Command and Material Command have been reviewing for the past several years; and in the third and fourth papers of Topic II, Nonweiler and Pike provide a wider insight into the influence of propellant choice.

Nonweiler studies the effects on scramjet specific thrust (and on the lowest feasible flight Mach number) that result from the extraction of heat from the air flowing through the scramjet inlet. Where Czysz analysed the scramjet as a Brayton cycle (which precludes the extraction of heat from the air flowing through the inlet and for which supersonic combustion is not introduced until around flight Mach number 6), Nonweiler shows that the cooled compression allows a scramjet to offer usable specific thrusts at 'low' flight Mach numbers (such as 4 or so). More detailed work, based on the injection of ammonia, has been performed by Nonweiler through APECS on behalf of industrial clients, but the basics of that approach were as now set out by Nonweiler in this Theme.

Pike shows that for a scramjet second stage fuelled with hydrogen, propellant additives such as neon or helium will give a smaller vehicle (or an enhanced payload) by comparison with an equivalent scramjet vehicle using hydrogen alone and flying the same airbreathing trajectory. He extends the analysis to confirm that hydrocarbons can be competitive over the same airbreathing trajectory, which gives theoretical support to the proposition that a denser fuel than liquid hydrogen will allow savings in vehicle dry mass, even though the denser fuels offer a much reduced calorific value per unit mass. If Pike's analysis is then complemented (as by R. A. East, personal communication 1994) to allow trajectory optimization (and thus airbreathing acceleration up to whatever airbreathing Mach number maximizes the payload-to-orbit), it is found that a scramjet burning kerosene need not accelerate beyond Mach number 10 or 12, and can be much smaller than a trajectory-optimized scramjet vehicle using hydrogen (or hydrogen plus neon). This combination of similarity analysis and trajectory optimization guides the designer towards a much wider interest in propellants than in hydrogen alone, and offers in operational terms the logistic simplicity of a safe and standard fuel. It also invites a study of denser fuels than liquid hydrogen for engines other than scramjets.

Finally, and fundamentally, Broadbent's method for designing ducts for supersonic flows with heat and mass addition is here extended by the originator to permit three-dimensional flows. As already shown, Broadbent has used his original two-dimensional method to illustrate various aspects of hypersonic design (e.g. the lifting scramjet and the use of external combustion). Elaboration to include three-dimensional duct design allows the drafting of ducts for supersonic combustion and of various types of nozzle for use in scramjets, rockets or wind-tunnel design. It is a method that has enabled several informative analyses in which the designer asked the question, 'How can a flow be set up to give a defined pressure distribution?', and could expect a quantified answer for flows with or without heat addition, mass addition and magnetohydrodynamic effects. Its extension to three-dimensional flows can only be helpful.

References

Balepin, V. V. 1996 Air collection systems. In *Developments in high-speed-vehicle propulsion systems* (ed. S. N. B. Murthy & E. T. Curran). AIAA Progress in Aeronautics, vol. 165. Washington, DC: AIAA.

Murthy, S. N. B. & Curran, E. T. (eds) 1996 *Developments in high-speed-vehicle propulsion systems*. AIAA Progress in Aeronautics, vol. 165. Washington, DC: AIAA.