Appendix B
From Take-Off to Orbit—The X-30 Propulsion System[1]

For take-off, the X-30 will need an engine that can produce thrust from a standing-start. An example of such an engine is the *turbojet.* Air flowing into a turbojet is diffused and compressed before it is combined with fuel and ignited. The compressor is similar to a fan and is powered by a turbine driven by exhaust products. A limiting factor in the ability of turbojets to propel aircraft to high speeds is the ability of the turbine to withstand the high temperatures caused by combustion and compression processes. In practice, these problems prevent turbojets from propelling aircraft to speeds above approximately Mach 3. Even when aircraft speeds are supersonic, however, air speeds within the engine combustor remain subsonic as air is slowed during its passage through the turbomachinery.

An aircraft traveling faster than the speed of sound causes a shock wave as pressure builds up ahead of leading edges of the moving body. In effect, pressure disturbances that travel at the speed of sound build up faster than they can dissipate. In the ***ramjet, the*** compressor and turbine are eliminated, and instead, air entering the combustor is compressed by the compression wave (“ram action”) generated by air entering a suitably shaped engine inlet. Ramjets thus require auxiliary propulsion to boost the velocity to a point where they can sustain combustion and generate thrust. In practice, supersonic speeds are usually necessary before ramjet propulsion becomes practical.

In order to facilitate mixing and burning of the fuel in the combustion chamber (combustor) of a ramjet, air is slowed to subsonic speeds by passage through a diffuser. The heating inside the engine that results from the transition to subsonic air speed and from fuel combustion places a practical limit to ramjet propulsion by hydrocarbon-based fuels, such as kerosene. Even with special materials and cooling to solve the material creep problem at high temperatures,[2] if the temperature rises too high the efficiency of the combustion process decreases because fuel is no longer burned completely.[3] For conventional ramjets this translates into upper limits on speeds of about Mach 5 to 6. However, the engine I of ramjets falls off rapidly above about Mach 4 (figure 5.5).

For speeds up to approximately Mach 6 there are concepts for propulsion systems that combine turbo and ramjet operation. To propel vehicles faster than this with air-breathing engines requires a *scramjet* (supersonic combustion ramjet); an engine where compression, fuel mixing, and combustion all occur at supersonic speeds, This allows, in theory, an engine that could start to work at about Mach 5 and continue to produce positive thrust all the way to Mach 25. Hydrogen gas derived from liquid or slush hydrogen is planned as the fuel source for the scramjets. Its primary drawback to hydrogen is that its low mass density results in large containment structures.

There are several concepts for combining scramjets with lower-speed propulsion systems. However, as a result of several factors, the optimum engine design changes dramatically at the low- and high-speed extremes. A key challenge for X-30 designers is to maximize the performance of low- and high-speed propulsion cycles over their speed range. As the X-30 accelerates from takeoff to hypersonic speeds, designers plan to change the shape of engine air inlets by using variable panels and control internal engine geometry with movable structures. Still there are fundamental tradeoffs in design that are unavoidable.

Drag forces on an aircraft moving through the atmosphere increase as the square of the vehicle’s airspeed and the power expended in overcoming drag increases as the cube of the airspeed. However, drag is also proportional to air density, which decreases with altitude. To minimize drag and aerodynamic heating, the X-30 will accelerate to high speed in the uppermost parts of the atmosphere where the air density is very low. However, generating thrust at near-orbital speeds requires an engine with large and efficient air intakes to capture enormous quantities of air-both because of the thin air at high altitudes and because air entering the engine is expelled after combustion at a relatively small increase in speed (although the mass flow is much higher at the higher speeds). In contrast, at low speeds, engines take in a relatively small amount of air and accelerate it (in the combustion process) to high speeds.

While a subsonic jet might have an inlet covering 15 percent of frontal area, to capture sufficient air at Mach 6 an inlet covering 70 percent of frontal area would be desirable. However, at orbital speeds (Mach 25) an inlet covering some 95 percent of frontal area would be needed.[4] The geometric cross section of the engine inlet is too small to achieve these figures. In practice, to capture

[1]Some of the details of the NASP propulsion cycle are classified. However, the following discussion is illustrative of the propulsion concepts being explored by contractors waling in the NASP program. A final engine design has not been chosen yet by the NASP Joint Program Office.

[2]Creep describes the deformation of a material thermally cycled at high temperatures.

[3]At high temperatures the products of combustion dissociate into molecular fragments. The dissociation process absorbs energy (most fragments fail IO recombine in the nozzle) reducing the total kinetic energy of the fuel fragments, and thus lowering the thrust. See ‘‘The Pocket Ramjet Reader, ” Chemical Systems Division, United Technologies, Sunnyvale, CA, p. 12.

[4]Engine inlet data from Dr. Robert Jones Of NASA Langley.

the large amounts of air required for scramjets requires engine inlets where, in effect, the entire front of the aircraft functions as part of the engine inlet. This necessitates an integrated engine and airframe designs

On the other hand, a smaller engine inlet would be desirable to minimize drag for flight at low speeds and low altitudes. The size of the engine inlet is one design tradeoff. Another would arise if, as currently anticipated, auxiliary rocket-based power[6] were used to supplement the X-30'S air-breathing propulsion system. Igniting rockets at relatively low hypersonic speeds might allow smaller scramjet engines and inlets but only at the penalty of decreased payload. Alternatively, if designers opt to keep payload constant the increased weight associated with rocket propulsion could be compensated by, for example, designing the X- 30 to have greater lift. Larger wings would provide more lift, but vehicle size, weight, and cost would increase too.

[5]Pod mounted scramjet concepts were explored in the 1%0s but researchers found that air inlets could not capture enough air and, in addition, there was excessive drag from support struts.

[6]The auxiliary propulsion system would use liquid oxygen carried on-board the X-30 to supply either the scramjet engines or a small, separate rocket. The tam "rocket-based power" is used here to refer to either approach.