In Example 8.6 we indicated the reasons why an air-breathing power plant for high Mach number, hypersonic vehicles would have to be a supersonic combustion ramjet engine—a SCRAMjet. The design of such an engine depends heavily on the properties of oblique shock waves and expansion waves—the subjects of this chapter. In this design box, we examine some of the basic design features of SCRAMjet engines. Looking ahead to the future of aerodynamics in the twenty-first century, hypersonic flight is essentially the last frontier of our quest to fly faster and higher. Many of the hypersonic vehicles of the future will be powered by SCRAMjet engines. So the material in this design box is much like peering through a window into the future.

Several types of conceptual SCRAMjet-powered vehicles are shown in Figure 9.26. Reference 71. Figure 9.26(a) illustrates a hypersonic air-to-surface missile. Figure 9.26(b) shows a conceptual strike/reconnaissance airplane, and Figure 9.26(c) shows the first stage of a two-stage-to-orbit vehicle for access to space. All of these futuristic vehicles would fly in the Mach 8–12 range, and all would be powered by SCRAMjet engines.

The side view of a generic hypersonic vehicle powered by a SCRAMjet is shown in Figure 9.27. Essentially, the entire surface of the vehicle is an integrated portion of the air-breathing SCRAMjet engine. The forebody shock wave (1) from the nose of the vehicle is the initial part of the compression process for the engine. Air flowing through this shock wave is compressed, and then enters the SCRAMjet engine module (2) where it is further compressed by reflected shock waves inside the engine duct, mixed with fuel, and then expanded out the back end of the module. The back end of the vehicle is scooped out (3) in order to further enhance the expansion of the exhaust gas. At the design flight condition, the forebody shock wave impinges right at the leading edge of the cowl (4), so that all the flow passing through the shock will enter the engine, rather than some of the air spilling around the external surface.

It is also possible to further compress the air before it enters the engine module by creating an isentropic compression wave downstream of the shock. This is shown in Figure 9.28, patterned after Reference 72. Here, the bottom surface of the vehicle is contoured just right to form an isentropic compression wave that will focus at the leading edge of the cowl, right where the forebody shock wave is impinging as well. An isentropic compression wave is the opposite of the isentropic expansion wave discussed in Section 9.6, but the calculation of its properties is governed by the same Prandtl-Meyer function given in Equation (9.42), except in this case the local Mach number decreases through the wave, and the pressure increases. To create such an isentropic compression wave in reality is quite difficult; the contour of the body surface must be a specific shape for a specific upstream Mach number, and most efforts over the years to produce isentropic compression waves in various supersonic and hypersonic flow devices have usually resulted in the wave prematurely coalescing into several weak shock waves with associated entropy increases and total pressure loss. SCRAMjet-powered vehicles might incorporate such an isentropic compression surface. Other physical phenomena that influence SCRAMjet engine performance and vehicle aerodynamics are also noted in Figure 9.28. The leading edge must be blunted in order to reduce the aerodynamic heating at the nose (to be discussed in Chapter 18). The viscous boundary layer over the surface of the body creates drag and aerodynamic heating, and when a shock wave impinges on the boundary layer, flow separation and local reattachment may occur, creating local regions of high heat transfer (the shock wave/boundary layer interaction problem). There is always the important question as to where transition from laminar to turbulent boundary layer flow occurs along the body, because turbulent boundary layers result in increased aerodynamic heating and skin friction. Finally, when the forebody shock impinges on the leading edge of the cowl, it will interact with the local shock wave created at the blunt leading edge of the cowl, resulting in a shock-shock interaction problem that may create a local region of intense heating at the cowl leading edge. All of these phenomena influence the quality of the flow entering the SCRAMjet module, and they pose challenging problems for the designers of future SCRAMjet engines.
Figure 9.26

(c) Suction powered space access vehicle concept

(d) Suction powered underwater vehicle concept

(e) Suction powered under-surface missile concept
A generic sketch indicating the flow path through the SCRAMjet is shown in Figure 9.29. Here again we see the forebody shock impinging at the leading edge of the cowl, and a contoured compression surface to encourage an isentropic compression behind the shock. The cross-sectional area of the streamtube flowing through the shock wave, as noted in Figure 9.29, is greatly reduced behind the shock and through the compression wave owing to the large increase of air density through these compression processes. Because of this, the flow path through the combustor has a much smaller cross-sectional area. In Figure 9.29, points 4 and 5 denote the entrance and exit, respectively, of the combustor. Billig (Reference 73) has calculated typical flow conditions entering the combustor (at point 4) as a function of free stream Mach number $M_\infty$ and flight altitude. Some of his results are tabulated below, where $A_4$ is the cross-sectional area of the streamtube in the freestream (see Figure 9.29), $A_4$ is its

<table>
<thead>
<tr>
<th>$M_\infty$</th>
<th>Altitude (ft)</th>
<th>$M_4$</th>
<th>$A_3/A_4$</th>
<th>$p_4/p_{\infty}$</th>
<th>$\rho_4$ (lb/in$^2$)</th>
<th>$T_4$ (°R)</th>
<th>$V_4$ (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>80,077</td>
<td>3.143</td>
<td>10.85</td>
<td>47</td>
<td>19.03</td>
<td>1451</td>
<td>5,757</td>
</tr>
<tr>
<td>10</td>
<td>95,500</td>
<td>4.143</td>
<td>16.49</td>
<td>89.6</td>
<td>17.78</td>
<td>1958</td>
<td>8,744</td>
</tr>
<tr>
<td>15</td>
<td>114,250</td>
<td>5.502</td>
<td>20.33</td>
<td>185.9</td>
<td>15.44</td>
<td>2880</td>
<td>13,908</td>
</tr>
<tr>
<td>20</td>
<td>137,760</td>
<td>6.680</td>
<td>33.11</td>
<td>313.6</td>
<td>10.02</td>
<td>4074</td>
<td>19,648</td>
</tr>
</tbody>
</table>

(continued)
vehicle is an integral part of the SCRAMjet engine cycle. For air-breathing hypersonic vehicles, the problem of airframe/propulsion integration is paramount; it is a major driving design feature of such aircraft.

At the time of writing, America is preparing to fly its first SCRAMjet-powered flight vehicle, the X-43, also labeled the Hyper-X. A three-view of the X-43 is given in Figure 9.31. This is a small unpowered test vehicle that will be launched from a modified Orbital Sciences Pegasus first stage rocket booster, which in turn is launched from a B-52 bomber in flight. The primary purpose of the X-43 is to demonstrate the viability of a SCRAMjet engine under actual flight conditions, as opposed to research results in ground test facilities. In particular, it is intended to demonstrate acceleration performance at $M_\infty = 7$ and cruise performance at $M_\infty = 10$. The X-43 is a NASA project, and when it flies it will be the first free-flight of an airframe integrated supersonic combustion ramjet engine.

**Example 9.8**

In the preceding discussion on SCRAMjet engines, an isentropic compression wave was mentioned as one of the possible compression mechanisms. Consider the isentropic compression surface sketched in Figure 9.32a. The Mach number and pressure upstream of the wave are $M_1 = 10$ and $\rho_1 = 1$ atm, respectively. The flow is turned through a total angle of $15^\circ$. Calculate the Mach number and pressure in region 2 behind the compression wave.

**Solution**

From Appendix C, for $M_1 = 10$, $\alpha_1 = 102.3^\circ$. In Region 2,

$$\alpha_2 = \alpha_1 - \theta = 102.3 - 15 = 87.3^\circ$$

From Appendix C for $\alpha_2 = 87.3^\circ$, we have (closest entry)

$$M_2 = 6.4$$