effective in killing organisms than moist heat. To kill spores, a temperature typically of 220°C for 30 s is required. Consequently, the adiabatic compression of process air certainly aids air sterilization. Since the exit air cools rapidly and the pipes connecting the compressor to the fermenter are difficult to maintain as absolutely sterile, an air-filtration step is almost always used. (Alternatives such as UV radiation, ozone injection, and scrubbing are not practical.)

The filtration of gases can be accomplished using either depth filters or surface filters. Historically, depth filters using glass wool were used, but *depth filters* have been almost totally replaced with membrane cartridge filters, which are *surface filters*.

Glass wool filters rely on a combination of mechanisms for the capture of particles. Possible mechanisms of removal for particles of about 1-μm diameter are direct interception, electrostatic effects, diffusion (or Brownian motion), and inertial effects. As the flowing gas approaches a fiber, the flow streamlines must curve around the fiber. If a particle had no density, it would follow the streamlines around the fiber. Only particles whose centers are on streamlines less than a particle radius away from the fiber could be intercepted. However, for real particles, inertial effects mean that particles with mass will have a tendency to maintain a straight-line trajectory as they approach the fiber. Thus, such particles deviate from the streamline and crash into the fiber. Both interception and inertial effects are important in removing bacteria.

Diffusional effects may be important for virus removal, but bacteria are sufficiently large that diffusion is relatively unimportant. The removal of a particle by these mechanisms is probabilistic. The deeper the filter is, the smaller the probability of a particle penetrating the depth of the filter.

Depth filters using glass wool can show shrinkage and hardening upon steam sterilization. In such cases, channeling can occur, and the filter becomes far less effective than would be predicted. More recent advances in the design of fiberglass filter cartridges have overcome much of this disadvantage. Another serious problem with such fibrous filters is wetting. If a filter wets, an easy path becomes available for a contaminant to penetrate through it. A wet filter also greatly increases pressure drop. Thus, any condensation within such a filter must be avoided.

Surface filters (membrane cartridges) work using another mechanism for particle removal, a sieving effect. Figure 10.16 depicts a membrane cartridge unit and its housing. Membranes with uniformly small pores prevent the passage of particles with a radius larger than the pore radius. Such filters can be steam-sterilized many times. Also, any condensate formed on the nonsterile side cannot pass into the sterile side.

With both depth filters and membrane cartridges, pressure drop is critical. The energy input for compressed air for a commercial-scale process is significant. Air treatment can account for 25% of total production costs. Thus, the design engineer has to balance the assurance of sterility against pressure drop.

Generally, the bioprocess engineer is not involved in the design of membrane cartridge units (a number of competent vendors offer suitable products), but the testing of such units for effectiveness is important. In the United States, an example is an aerosol test using corn oil nebulized to 1.0 to 1.5 mg oil/l of air. This test is recognized by the FDA. Such an aerosol would contain particles primarily in the range of 0.2- to 1.0-μm diameters. Aerosol in the exit gas from a filter cartridge can be monitored by a photometer. The number of sterilization cycles a cartridge can undergo before failure is an important criterion in the selection of membrane cartridge units.