solid–liquid system, intrinsic properties of the solute, conditions of the drying environment, and heat-transfer parameters.

The major types of driers used for drying fermentation product are the following:

1. *A vacuum-tray drier* consists of heated shelves in a single chamber and is usually used in pharmaceutical products. This is a good method for small batches of expensive materials, where product loss and heat damage must be minimized.
2. *Freeze drying (lyophilization)* is a method where water is removed by sublimation (from solid ice to vapor) from the frozen solution. The freezing can be accomplished either outside or inside the vacuum chamber prior to drying. This method is used for antibiotics, enzyme solutions, and bacterial suspensions.
3. *Rotary-drum driers* are not good for crystal solutions. Water is removed by heat conduction over a thin film of solution on the steam-heated surface of the rotating drum. The dried product is scraped from the drum with the aid of a knife at the discharge point.
4. *Spray dryers* employ atomization and spraying of product solution into a heated chamber through a nozzle. Hot gas inside the chamber provides the necessary heat for evaporation of the liquid. Dried particles are separated from hot gases using cyclones. Spray dryers are expensive to purchase but are the preferred method for heat-sensitive materials.
5. *Pneumatic conveyor driers* use a hot air stream to suspend and transport particles. The retention time of a particle in the gas stream is short, usually a few seconds. Such systems work well when surface drying is critical, but do not provide sufficient exposure times to dry large porous particles where water removal is diffusion controlled. Pneumatic conveyor systems are well suited for heat-sensitive and easily oxidized materials.

11.6. INTEGRATION OF REACTION AND SEPARATION

The separate optimization of fermentation and recovery does not necessarily yield the optimal process. Traditionally, the strain development, fermentation, and recovery experts worked essentially in isolation. A lack of formal training of engineers in basic biological concepts and of biologists in engineering and process concepts has made an integrated view of the bioprocesses difficult to obtain. Systems have been optimized sequentially, with only modest feedback from downstream to upstream. With improved training of both engineers and biologists, it has become possible to begin to build better processes.

One form of this integration is to try to couple some aspects of recovery and purification with the bioreactor. The motivation for such approaches has come initially from a desire to relieve product inhibition and thereby increase reaction rates and/or allow the use of a more concentrated feed. However, other advantages may accrue, such as improved selectivity for the product of interest, conversion of a primarily intracellular to an extracellular product, and protection of a product from degradation.

Isolated examples of attempts at bioprocess integration stretch back to the beginning of modern biochemical engineering. In the 1970s the energy crisis and interest in ethanol production spawned many suggested approaches to bioprocess integration. Some early approaches to such process integration include vacuum fermentation, membrane processes, addition of solid adsorbents, and liquid extractants.

One example is a reactor system that allows the use of tributylphosphate (TBP) as an extractant of ethanol from fermentation broths. Although TBP had been recognized as