the reciprocal of the yield coefficients and can be readily estimated from growth experiments and compositional data on *P*.

The rate forms used here are by no means the only correct solution. A more extensive base of experimental observations would be needed to eliminate other possible formulations.

6.3.4. Cybernetic Models

Another modeling approach has been developed primarily to predict growth under conditions when several substrates are available. These substrates may be complementary (e.g., carbon or nitrogen) or substitutable. For example, glucose and lactose would be substitutable, as these compounds both supply carbon and energy. As the reader will recall, we discussed the diauxic phenomenon for sequential use of glucose and lactose in Chapter 4. That experimental observation led us to an understanding of regulation of the *lac* operon and catabolite repression. This metabolic regulation was necessary for the transition from one primary pathway to another. The reader might infer that the culture had as its objective function the maximization of its growth rate.

One approach to modeling growth on multiple substrates is a *cybernetic* approach. Cybernetic means that a process is goal seeking (e.g., maximization of growth rate). While this approach was initially motivated by a desire to predict the response of a microbial culture to growth on a set of substitutable carbon sources, it has been expanded to provide an alternative method of identifying the regulatory structure of a complex biochemical reaction network (such as cellular metabolism) in a simple manner. Typically a single objective, such as maximum growth rate, is chosen and an objective-oriented mathematical analysis is employed. This analysis is similiar to many economic analyses for resource distribution. For many practical situations this approach describes satisfactorily growth of a culture on a complex medium. However, the potential power of this approach is now being realized in efforts in metabolic engineering and in relating information on DNA sequences in an organism to physiologic function (see Chapter 8).

This approach has limitations, as the objective function for any organism is maximizing its long-term survival as a species. Maximization of growth rate or of growth yield are really subobjectives which can dominate under some environmental conditions; these conditions are often of great interest to the bioprocess engineer. Consequently, the cybernetic approach is often a valuable tool. It is too complex for us to describe in detail in this book; the interested reader may consult the references at the end of this chapter.

6.4. HOW CELLS GROW IN CONTINUOUS CULTURE

6.4.1. Introduction

The culture environment changes continually in a batch culture. Growth, product formation, and substrate utilization terminate after a certain time interval, whereas, in continuous culture, fresh nutrient medium is continually supplied to a well-stirred culture, and products and cells are simultaneously withdrawn. Growth and product formation can be maintained for prolonged periods in continuous culture. After a certain period of time, the