Here Q_{GR} is in units of kcal/h, while Q_{O_2} is in millimoles of O_2/h.

Metabolic heat released during fermentation can be removed by circulating cooling water through a cooling coil or cooling jacket in the fermenter. Often, temperature control (adequate heat removal) is an important limitation on reactor design (see Chapter 10). The ability to estimate heat-removal requirements is essential to proper reactor design.

6.3. QUANTIFYING GROWTH KINETICS

6.3.1. Introduction

In the previous section we described some key concepts in the growth of cultures. Clearly, we can think of the growth dynamics in terms of kinetic descriptions. It is essential to recall that cellular composition and biosynthetic capabilities change in response to new growth conditions (*unbalanced growth*), although a constant cellular composition and balanced growth can predominate in the exponential growth phase. If the decelerating growth phase is due to substrate depletion rather than inhibition by toxins, the growth rate decreases in relation to decreasing substrate concentrations. In the stationary and death phases, the distribution of properties among individuals is important (e.g., cryptic death). Although these kinetic ideas are evident in batch culture, they are equally evident and important in other modes of culture (e.g., continuous culture).

Clearly, the complete description of the growth kinetics of a culture would involve recognition of the *structured* nature of each cell and the *segregation* of the culture into individual units (cells) that may differ from each other. Models can have these same attributes. A chemically structured model divides the cell mass into components. If the ratio of these components can change in response to perturbations in the extracellular environment, then the model is behaving analogously to a cell changing its composition in response to environmental changes. Consider in Chapter 4 our discussion of cellular regulation, particularly the induction of whole pathways. Any of these metabolic responses results in changes in intracellular structure. Furthermore, if a model of a culture is constructed from discrete units, it begins to mimic the segregation observed in real cultures. Models may be structured and segregated, structured and nonsegregated, unstructured and segregated, and unstructured and nonsegregated. Models containing both structure and segregation are the most realistic, but they are also computationally complex.

The degree of realism and complexity required in a model depends on what is being described; the modeler should always choose the simplest model that can adequately describe the desired system. An unstructured model assumes fixed cell composition, which is equivalent to assuming *balanced growth*. The balanced-growth assumption is valid primarily in single-stage, steady-state continuous culture and the exponential phase of batch culture; it fails during any transient condition. How fast the cell responds to perturbations in its environment and how fast these perturbations occur determine whether pseudobalanced growth can be assumed. If cell response is fast compared to external changes and if the magnitude of these changes is not too large (e.g., a 10% or 20% variation from initial conditions), then the use of unstructured models can be justified, since the deviation from