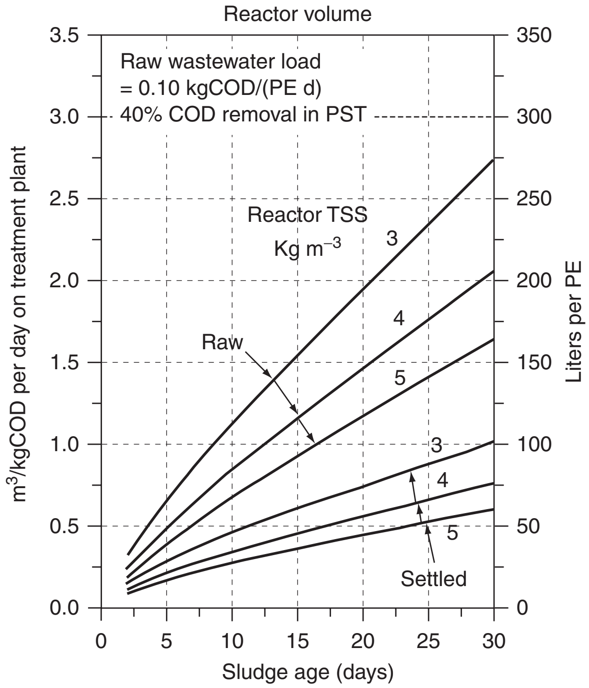

Figure 16 Reactor volume requirements in $m^3\,kg^{-1}$ COD raw WW load per day vs. sludge age at different average reactor TSS concentrations for raw and settled WW (assuming 40% COD removal by primary sedimentation). Reactor volume requirements in liter or person equivalent (PE) is also given on the right-hand vertical axis based on a raw WW COD contribution of 0.10 kg COD/person equivalent.

per PE is required or 1.45 $m^3\,kg^{-1}$ COD applied per day to the WWTP.

The comparative reactor volume requirements for settled WW per kgCOD load per day on the WWTP also is shown in Figure 16 taking due consideration of the COD fraction removed by primary sedimentation (40% for the example settled wastewater) and the reduction in settled wastewater UPO fraction ($f_{S'up}$) this causes (Table 6). From Figure 16, treating settled WW at a sludge age of 20 days and reactor TSS concentration of 4 kgTSS m^{-3} requires a reactor volume of 0.55 $m^3\,kg^{-1}$ raw WW COD load per day on the WWTP or 55 l per PE. Therefore, a significant reduction in reactor volume can be obtained by means of primary sedimentation – 62% for the example raw and settled WWs at 20 days sludge age.

4.14.11 Determination of Reactor TSS Concentration

The choice of the reactor concentration can be done empirically from past experience with similar WWs or selected from design guidelines such as those from Metcalf and Eddy (1991), for example, for conventional systems (with primary sedimentation) 1500–3000 mgTSS l^{-1} or extended aeration (without primary sedimentation) 3000–6000 mgTSS l^{-1}. Differences in the reactor TSS concentration for raw and settled WWs arise because (1) the WW flow per kgCOD load on the reactor for raw WW is significantly greater than that for settled WWs and (2) sludge settleability in conventional (settled WW) systems can be poorer than with extended aeration (raw WW) systems – in a survey of 45 full-scale AS plants in the Netherlands, Stofkoper and Trentelman (1982) found significantly higher DSVIs in settled WW systems than in raw WW systems (see Ekama and Marais, 1986).

The effect of WW strength and sludge settleability, as well as other factors such as the peak wet weather flow (PWWF) to average dry weather flow (ADWF) ratio (or peak flow factor $f_q = PWWF/ADWF$), WW and AS characteristics ($f_{S'up}$, $f_{S'us}$, f_i) and construction costs, can all be taken into account by determining the reactor concentration from a construction cost minimization analysis (Hörler, 1969; Dick, 1976; Riddell *et al.*, 1983; Pincince *et al.*, 1995). In such an analysis, the construction cost of the reactor(s) and the SSTs is determined as a function of the reactor TSS concentration. The reactor concentration at which the combined construction cost of the reactor(s) and the SST(s) is a minimum, is the design reactor concentration.

4.14.11.1 Reactor Cost

For selected WW and AS characteristics ($f_{S'up}$, $f_{S'us}$, X_{IOi}, or f_i), sludge age (R_s), and organic COD load on the reactor ($FS_{ti\,Reactor}$), the mass of TSS in the reactor (MX_t) can be determined from the steady-state model (Section 4.14.9) and remains constant at a fixed sludge age. The reactor volume as a function of the reactor TSS concentration X_t is found from Equation (112), viz., $V_p = MX_t/X_t$ m^3, where X_t is the reactor concentration in kgTSS m^{-3}. To estimate the cost of the reactor from the volume, empirical functions relating the construction cost of the reactor to the volume are required. Such functions show (1) that as the reactor becomes smaller so its construction cost gets lower (Figure 17) and (2) a benefit of scale effect in that it is cheaper (per m^3) to build a large reactor than a small one.

4.14.11.2 SST Cost

On the basis of the flux theory, Ekama *et al.* (1997) show that provided the underflow recycle ratio R is above the critical minimum value, the maximum overflow rate at PWWF (q_{PWWF}, $m\,h^{-1}$) of the SST is a function of only the reactor (or feed) solids concentration (X_t) and the sludge settleability. Therefore, the maximum overflow rate in the SST must not exceed the settling velocity of the AS at the feed concentration (X_t). For a selected sludge settleability, if the reactor (X_t) concentration increases, the settling velocity of the sludge decreases, with the result that the maximum overflow rate in the SST must be lower for higher X_t. Hence, the required surface area for the SSTs (A_{ST}) gets larger as the reactor concentration increases. Therefore, as the biological reactor becomes smaller with increasing concentration, the SST area and its construction increase.

4.14.11.3 Total Cost

The total cost of the reactor–SST system is the sum of the reactor and SST costs. Qualitative results for the example raw and settled WWs are given in Figure 17, ignoring that the reactor volume and SST diameter may have upper and lower size restrictions. For real WWTPs, the reactor and/or SST may

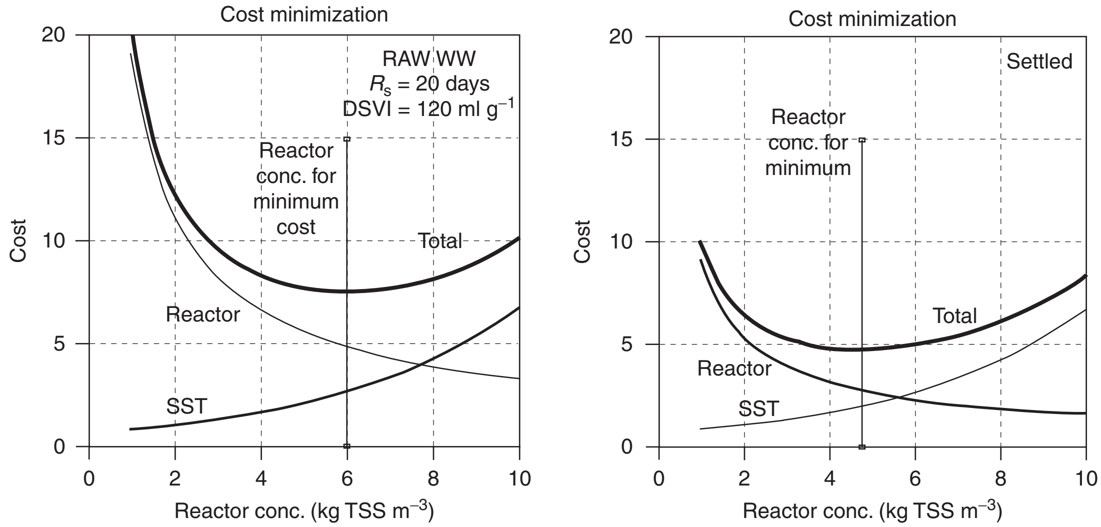

Figure 17 Reactor, secondary settling tank, and total construction costs to estimate the reactor TSS concentration for minimum total cost in single reactor and SST units for the example raw and settled wastewaters.

need to be split into two or more equal sized modules to bring the volume and diameter within the limit ranges.

Basically, the reactor volume depends on organic load (FS_{ti}) and the SST surface area on hydraulic load (PWWF). This is the reason why in Figure 17 the cost of the SST for the raw and settled wastewaters is the same but the cost of the reactor for the raw wastewater is higher than for the settled wastewater. From cost minimization analyses such as that above, generally it will be found that the range of reactor concentration for minimum construction cost (1) is higher for higher influent WW strengths (BOD_5, COD), (2) is higher for longer sludge ages, and (3) is higher for raw WW than settled WW at the same strength, because these three changes all increase the size of the biological reactor relative to that of the settling tank, (4) is lower for higher peak flow factors (f_q), and (5) is lower for poorer settling sludges because these two changes all increase the size of the settling tank relative to that of the biological reactor. A universal optimum therefore cannot be specified. In countries with low WW strengths and short sludge age plants (e.g., North America), the reactor concentration tends to be low (2000–3000 mgTSS l^{-1}) and in countries with high WW strengths and long sludge age plants (e.g., South Africa), the reactor concentration tends to be high (4000–6000 mgTSS l^{-1}) as the example WWs demonstrate.

4.14.12 Carbonaceous Oxygen Demand

4.14.12.1 Steady-State (Daily Average) Conditions

The mean daily carbonaceous oxygen demand per kgCOD load on the reactor ($FO_c/FS_{ti\ Reactor}$) is calculated from Equation (111). For sludge ages longer than 15 days the increase in $FO_c/FS_{ti\ Reactor}$ is small with further increase in sludge age for both raw and settled wastewater (Figures 15(b) and 15(d)). The $FO_c/FS_{ti\ Reactor}$ for raw and settled wastewater is usually within 10% of each other, with the demand for settled wastewater being the higher value. This is because compared to raw wastewater, a higher percentage of the total organics (COD) load in settled wastewater is biodegradable. For example, the wastewaters at 20 days sludge age, the $FO_c/FS_{ti\ Reactor}$ is 0.604 kgO/kgCOD for raw wastewater and 0.653 kgO/kgCOD for settled wastewater.

Although there is only a small difference in $FO_c/FS_{ti\ Reactor}$ between raw and settled wastewaters, there is a large difference in the oxygen demand (FO_c) because primary settling removes a significant proportion of the WWTP organic load as primary sludge (PS). For settled wastewater, this is given by 0.653 × (1–0.40) for 40% COD removal in PSTs, which gives 0.38 kgO/kgCOD load on the WWTP. For the raw wastewater, it would remain 0.604 kgO/kgCOD load on the treatment plant, making the settled wastewater oxygen demand 37% lower than that for the raw wastewater. Clearly, primary sedimentation leads to significant aeration energy savings – because primary settling tanks remove about 30–50% of the raw influent COD, the carbonaceous oxygen demand for settled wastewater generally will be about 30–50% lower than that for raw wastewater.

The carbonaceous oxygen demand is the oxygen demand for the oxidation of the influent organics (COD) and the associated OHO endogenous process only. In N removal systems, oxygen is also required for nitrification, which is the biological oxidation of ammonia to nitrate by autotrophic nitrifiers. However, with denitrification, which is the biological reduction of nitrate to nitrogen gas by facultative heterotrophic organisms, some of the biodegradable organics are utilized with nitrate as electron acceptor, for which oxygen is then not required. Thus, denitrification leads to a reduction in the oxygen demand. The total oxygen demand for a N removal system therefore is the sum of the carbonaceous and nitrification oxygen demands less that saved by denitrification. The procedures for calculating the oxygen demand for nitrification and the oxygen saved by denitrification are discussed in Sections 4.14.22.3 and 4.14.27.2. The equations given here for calculating the carbonaceous oxygen demand are based on the assumption that all the biodegradable organics are utilized with oxygen as electron acceptor, that is, for fully aerobic systems.