

11. DESIGN RECOMMENDATIONS

All the limestone neutralization processes demonstrated at Quakake are viable methods of AMD treatment within the limits described in this report. Selection of the most economical neutralization process or combination of processes is site specific, depending on physical site conditions, AMD chemical composition and AMD volumes. Reagent use and cost would be a relatively minor cost factor in any installation and would not be an accurate basis to evaluate treatment economics.

The following discussions present recommended design procedures and limitations of use for the processes used at the Quakake Demonstration Project.

Chemical Design Parameters: The first step in the design process is to evaluate the range of AMD flows and loads and level of treatment to be provided. Normally, treatment levels would be established from the results of a year's sampling program in order to determine water quality during high flow, low flow and any seasonal changes which may effect the discharge. Obviously, an extended sampling program would not be necessary for an AMD source with little variation in discharge or water quality.

The following design example will use the water quality parameters obtained at Quakake during the prototype operation period, 1979-1980. In most cases, the AMD discharge will show a marked change in pollutant load with flow. Therefore, the design example will consider a flow range of 10 to 60 cfs and variable water quality parameters as shown on Figure 2.2 and tabulated as follows:

<u>FLOW</u>	<u>pH</u>	<u>Al⁺⁺⁺</u>	<u>SO₄⁻⁻</u>	<u>TOTAL ACIDITY</u>	<u>MINERAL ACIDITY</u>
10	3.6	11.0	160	100	25
20	3.8	9.5	140	90	16
30	4.0	9.0	120	70	10
60	4.2	7.0	90	50	6

A curve of the load factor required to neutralize the rate of flow to a given pH will be developed from this data using a computer program which utilizes the procedures given in Appendix "D". In addition to the tabulated values, the computer program requires input for Ca⁺, Fe⁺⁺, Fe⁺⁺⁺ and C_t. The calcium and irons at Quakake are negligible and will be computed as the following constant values:

$$\text{Fe}^{+++} = 1.0 \text{ mg/l}; \quad \text{Fe}^{++} = 0.5 \text{ mg/l}; \quad \text{Ca}^{++} = 16 \text{ mg/l}.$$

C_t, as previously described, is estimated from the acidity and alkalinity test values.

$$\begin{aligned} \text{Acy} &= \text{H}_2\text{CO}_3 + \text{H}^+ + \Sigma\text{M}^+ \\ \text{Alk} &= \text{HCO}_3^- - \text{H}^+ - \Sigma\text{M}^+ \\ \text{C}_t &= \text{H}_2\text{CO}_3 + \text{HCO}_3^- = \text{Acy} + \text{Alk} \end{aligned}$$

Where ΣM^+ is the acidity contributed by protolized metal ions

However, the direct summation of the acidity and alkalinity test values would result in misleading C_t values. As shown in the test results from Run No. 4, the raw MID contains unoxidized metals which would affect the subsequent neutralization stages.

The following procedures are recommended in order to insure the chemical parameters used to develop neutralization curves actually represent the neutralization effort required.

1. Determine the acidity caused by CO₂ by subtracting the acid concentration attributable to the metals content of the AMD.

2. Use Figures 7.5 and 7.6 to estimate the correct Ct value and adjust the pH value to represent equilibrium conditions as determined by the Figures.

The acidity contributed by the metals content can be computed by the procedures in Appendix "D". Acidity values per mg/l of species is plotted on Figure 11.1 and can be used to estimate the metals acidity.

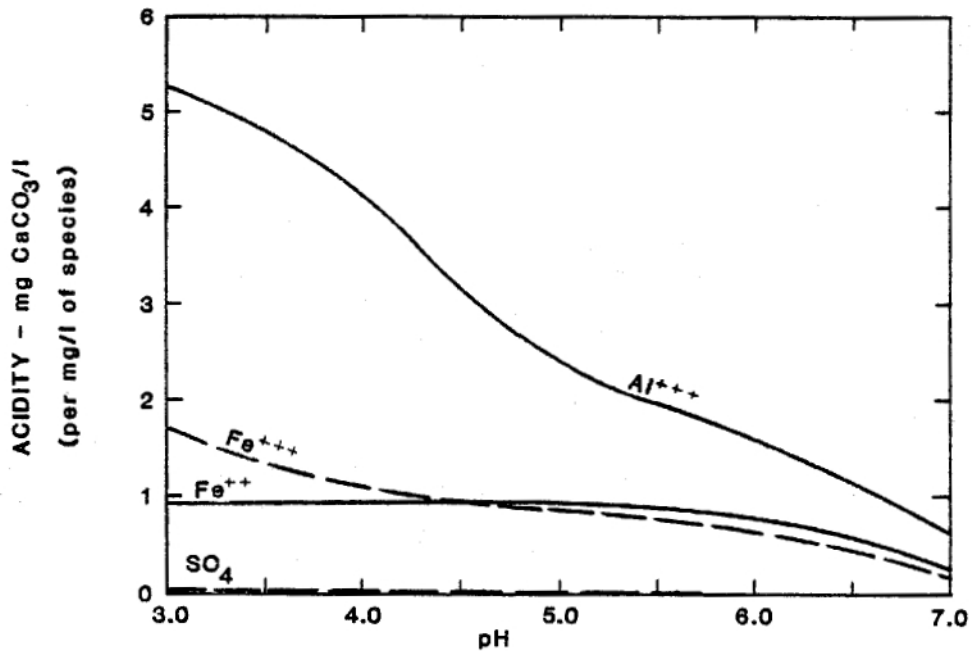


Figure 11.1 Theoretical Acidity from Various Species in the Quakake AMD

For example, the parameters for 10 cfs flow conditions are evaluated as follows:

SPECIES	mg/l	ACIDITY mg/1 (at pH = 3.6)	TOTAL ACIDITY
Al ⁺⁺⁺	11	4.643	51.1
SO	160	0.021	3.4
FE ++	1.0	1.294	1.3
FE ⁺⁺	0.5	.0962	<u>0.5</u>
			56.3 mg/1
H ⁺ Acid = 50,000 x 10 ^{-3.6}			<u>12.8</u>
			69.1 mg/l

Therefore CO₂ Acy = 100 - 69 = 31 mg/l

Note for practical purposes in this pH range:

$$\begin{aligned}
 \text{CO}_2 \text{ Acy} &= \text{H}_2\text{CO}_3 = C_t \\
 [C_t] &= [\text{H}_2\text{CO}_3] + [\text{HCO}_3^-] = [\text{H}_2\text{CO}_3] \left(1 + \frac{k'}{[\text{H}^+]} \right) \\
 &= 1.001 [\text{H}_2\text{CO}_3] \\
 C_t &= 31 \text{ mg/l}
 \end{aligned}$$

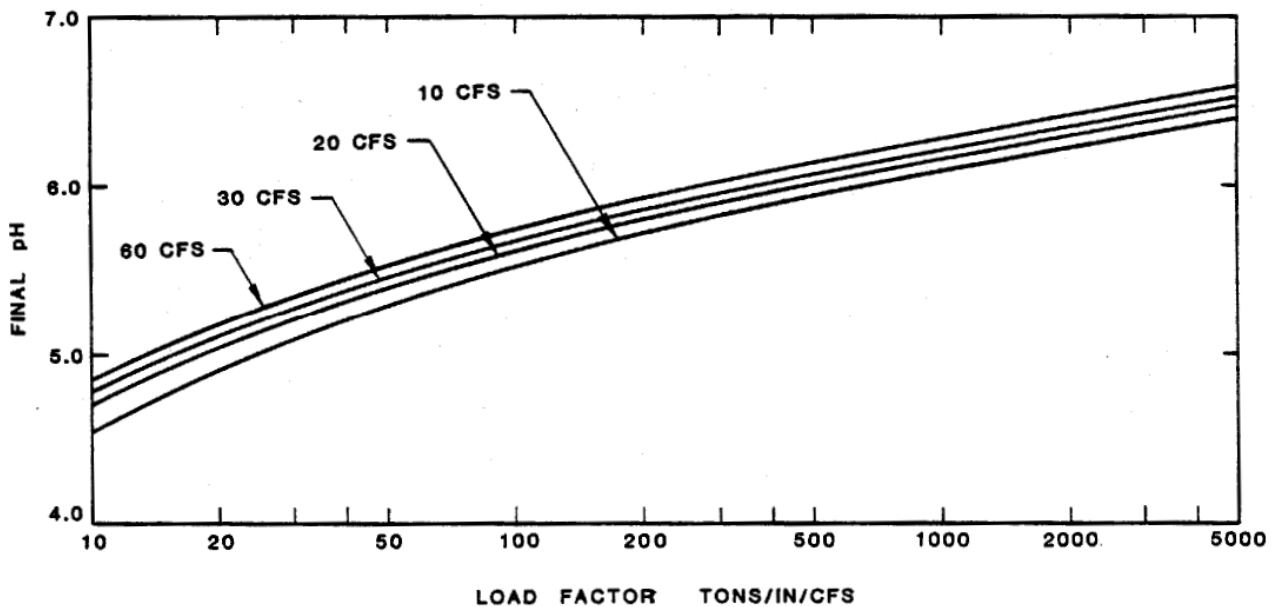
Then, using Figure 7.6, $C_t = 31 \text{ mg/l}$ and acidity = 100 mg/l, a $\text{pH}_1 = 3.2$ is obtained.

It should be noted that if the test values are plotted on Figure 7.5 and 7.6, they do indicate that equilibrium conditions are satisfied and the test results are valid for that particular state of oxidation and CO_2 content. However, if used unchanged, the amount of reagent required for neutralization would be underestimated as the acid forming potential of the metal species in AMD would not have been accounted for. If the AMD sample had been completely oxidized prior to the pH and alkalinity measurements, the results would be near the computed values. This can be confirmed by comparing Figures 7.5 and 7.6 and the "hot" and "cold" tests on raw AMD samples during Run No. 4.

The load factors required for neutralization are then computed for these values by the procedures in Appendix "D". The results of the computations are presented graphically in Figure 11.2.

Therefore, for design purposes, the initial water quality parameters are revised for load factor computations as follows:

<u>FLOW</u>	<u>pH</u>	<u>C_t</u>
10	3.2	31
20	3.3	38
30	3.4	27
60	3.5	20



Filter Type Units: Design of the filter type or static bed processes require only that the load factor versus flow curve be satisfied for the desired effluent pH. The load factor-flow criteria is represented on Figure 11.3 in terms of cubic feet of stone required per cfs for varying coefficients of reactivity.

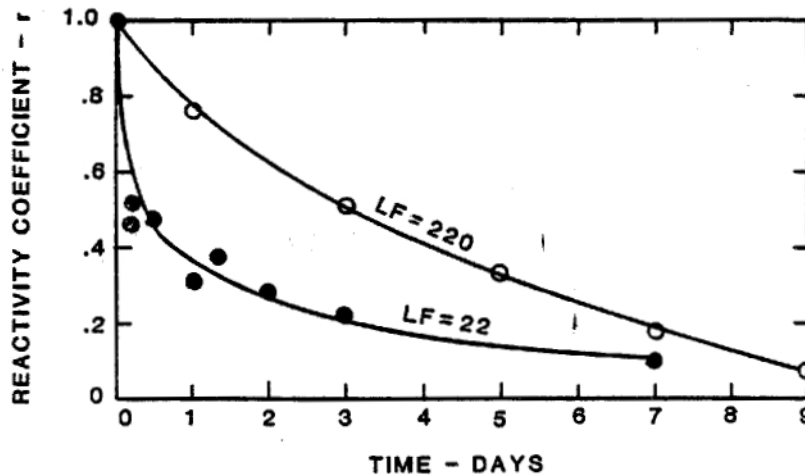


Figure 11.4 Observed Reactivity Coefficient Decay with Time based on the results of Barrier 5 - Run 2

However, all the static bed processes, whether they are downflow units, partially fluidized upflow units or beds of limestone with horizontal flow require periodic cleaning by hydraulic flushing and/or mechanical agitation.

The decline in the CaCO₃ dissolution rate, as described by the reactivity coefficient, with time is shown in Figure 11.4 for varying load factors. This data is numerically extrapolated in Figure 11.5 to create a design decision graph to determine backwash rates. [It should be noted that Figure 11.5 is applicable only to total iron and aluminum concentrations less than or similar to the Quakake AMD. The initial metals concentrations in the AMD should affect the rate of decline of the reactivity coefficient and additional investigation is required to determine the applicable rates for greater iron and/or aluminum concentrations.]

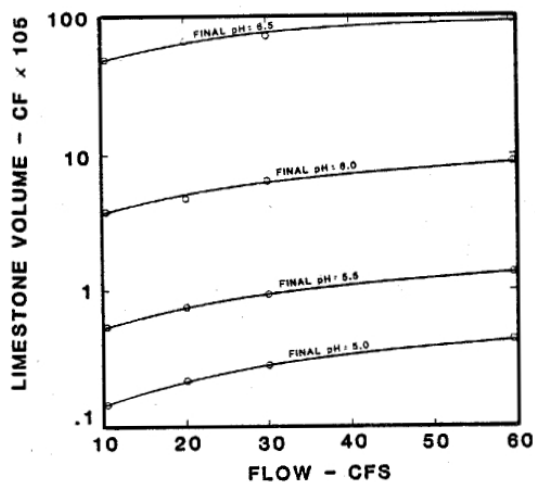


Figure 11.3 Computed pH - Limestone Volume Relationships

Figures 11.3 and 11.5 are sufficient to design the filter units. However, when Figure 11.5 is examined, we find that nearly 20 million cubic feet of limestone is required to treat 60 cfs of AMD to a pH of 6.5 with a design reactivity coefficient of only 0.5. This volume is equivalent to 900,000 tons of limestone and, if we assume the beds to be 5 feet deep, 92 acres of surface area is required to contain the beds. Obviously, there are some practical limitations on the use of the filter units. Only a portion of the maximum design flow can be treated, and treatment to a pH less than 6.5 must be considered. The remaining flow and acid load will have to be treated by tumbling drums.

Several important characteristics of the filter process should be considered when selecting the appropriate design parameters. Generally:

- a. The filter unit will be the most economical process and its use should be maximized.
- b. Filter units can effectively treat mineral acids even at high loading rates. Figure 11.2 shows that, for a 60 cfs flow, a load factor of 10 will raise the pH to 4.8.
- c. The filter process is relatively efficient at removing iron and aluminum from the AMD. Removal of these metals at various ratios of AMD to effective limestone surface areas Load Factors is illustrated in Figure 11.6. The plot indicates that where the effective load factor was maintained above 50, 90% of the iron was precipitated or absorbed onto the limestone surfaces. An effective load factor of 200 was required to achieve the same results for aluminum removal. A pH value between 5.4 and 5.8 would be obtained, according to Figure 11.2, if load factors of 50 to 200 were applied. Figure 11.7 indicates that the points of minimum solubility of Fe^{+++} and Al^{+++} species also fall within this pH range. Therefore, design of the beds for the 50 to 200 load factor range is probably optimal where iron and aluminum removal is considered.

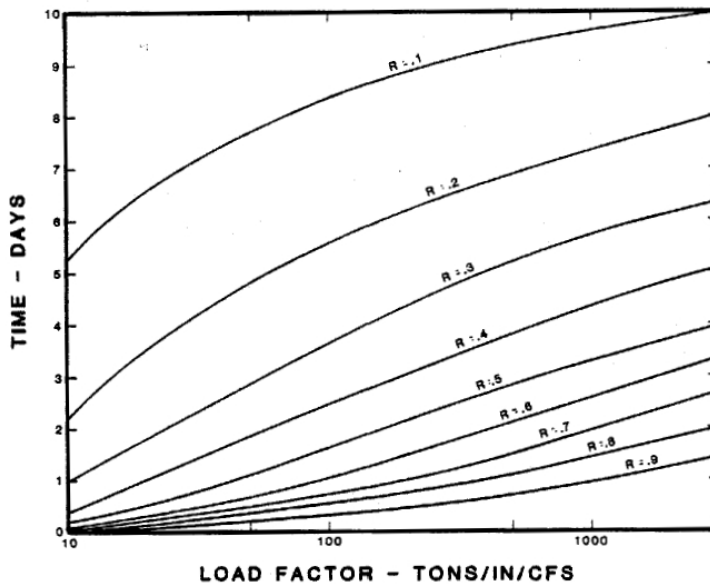


Figure 11.5 Filter Unit Decision Graph for Quakake AMD Neutralization

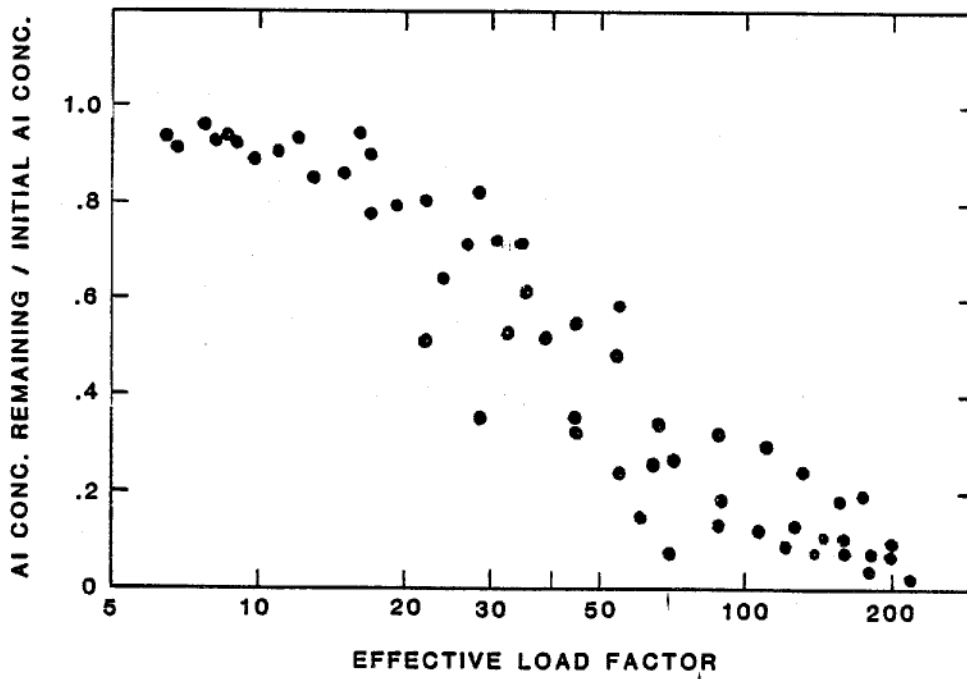
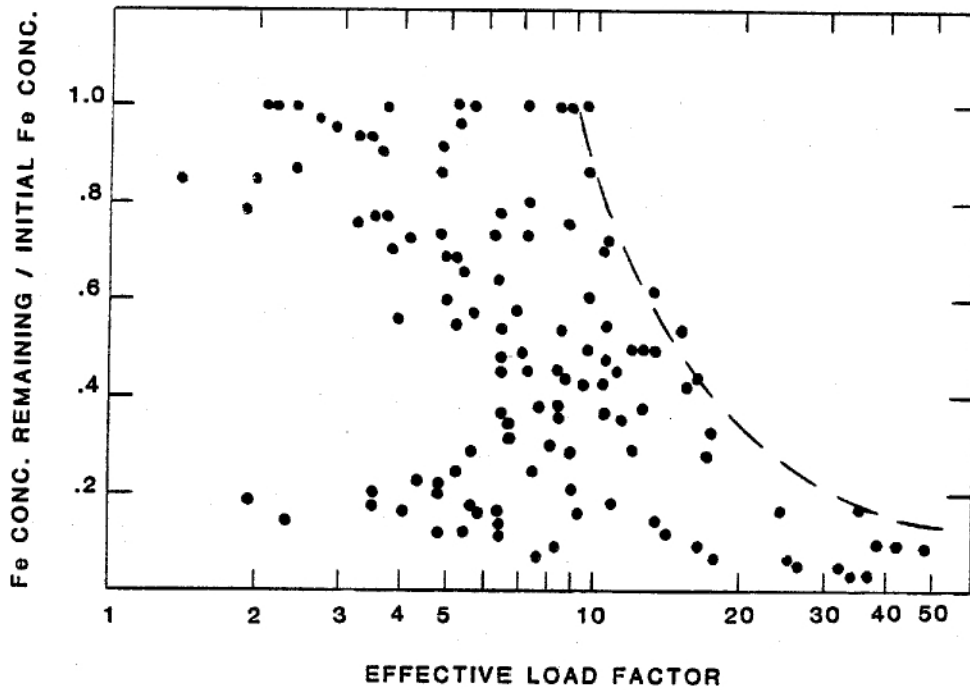


Figure 11.6 Load Factor Compared with Iron & Aluminum Removal based on Barriers 1 & 2 and selected downflow units

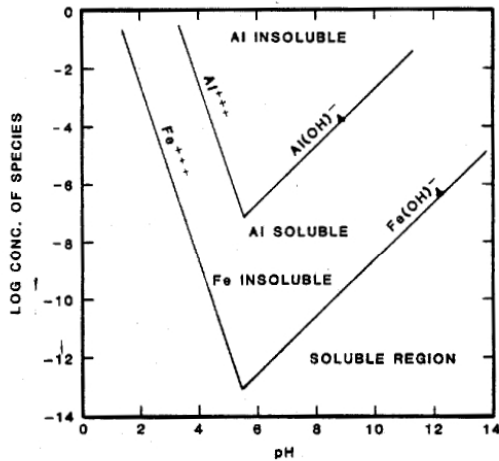


Figure 11.7 Iron and Aluminum Solubility (after Stumm and Morgan)

Hydrologic Design: Design of the filter units must also consider the hydrologic characteristics of the AMD discharge source. In the case of the Quakake discharge, the AMD source is gravity discharge from a sizable underground mining complex which behaves hydraulically similar to a watershed controlled by a large storage reservoir. Continuous stage records of the tunnel discharge were obtained in the early investigations (1973/74) and converted to hydrograph and mass curves form. The hydrologic data gathered during this period is presented in Appendix "A" and summarized as follows:

Average Flow During Study Period	22.1 cfs (14.3 mgd)
Average Summer/Fall Flow	16.9 cfs (10.9 mgd)
Average Spring Flow	30.7 cfs (19.8 mgd)
Lowest Recorded Flow	7.7 cfs (5.0 mgd)
Highest Recorded Flow	54.6 cfs (35.3 mgd)

The 45.8 inches of precipitation recorded during the 1973-1974 sampling period was slightly less than the normal average precipitation (47.2) at the nearest **NOAA** reporting station, Tamqua 4N.

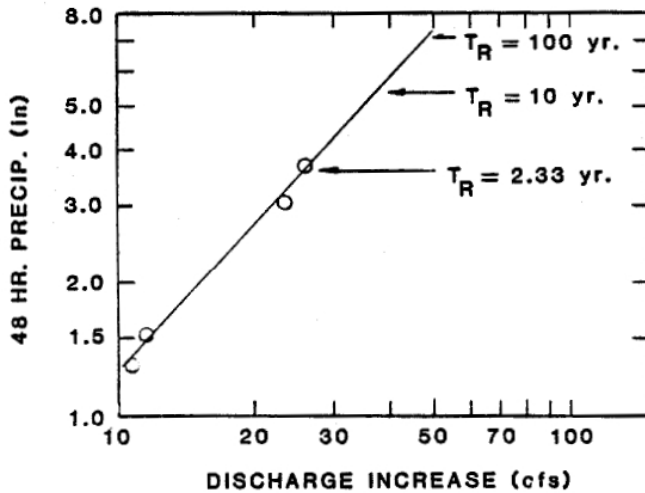


Figure 11.8 Quakake Tunnel Discharge Hydrology

Figure 11.8 indicates a definite relationship between precipitation and increases in tunnel discharge. However, the peak discharge for the year of record was not associated with the maximum precipitation amount. Peak discharges apparently are a product of rainfall, snowmelt and base flow in the early spring for this region of Pennsylvania. Base flow is seasonally oriented with the higher flows corresponding to the dormant vegetation season. Therefore, prediction of extreme tunnel discharge events is difficult and must take into account precipitation probability with seasonal variations, snow cover probability and snow melt probability during the corresponding precipitation event. Statistical analysis of the closest USGS gaging station (Trexler Run at Ringtown) for peak winter - early spring runoff events, indicates that the peak flow for the sampling period was approximately a 3-year event. Extreme frequency events based on this analysis yields:

<u>RETURN PERIOD</u> <u>(Years)</u>	<u>PEAK FLOW</u> <u>(cfs)</u>
10 65 25 75 100	87

Peak flow projections based on precipitation frequencies would be somewhat less than the tabulated amounts.

The 60 cfs maximum treatment level in the design example corresponds to an approximate 10 year return frequency discharge. It would seem reasonable to design the filter units for the average spring flow of 30 cfs. Therefore, the example design criteria will be as follows:

Design Flow	30 cfs
Load Factor at Design Flow	200 tons/in/cfs
Back Wash Frequency	3.5 Days
Reactivity Coefficient R	0.3
Limestone Volume	20,000 cf
Weight of Limestone	900 tons
Depth of Beds.....	4 Feet
Surface Area of Beds	5000 Ft. ²

The projected effluent water quality parameters from the beds are estimated as follows:

<u>FLOW</u> <u>(cfs)</u>	<u>pH</u>	<u>ACIDITY*</u> <u>(mg/l)</u>	<u>ALKALINITY</u> <u>(mg/l)</u>	<u>SO₄</u> <u>(mg/l)</u>	<u>C_t</u> <u>(mg/l)</u>	<u>Al⁺⁺⁺</u> <u>(mg/l)</u>
10	6.1	33	15	170	48	0.9
20	5.9	35	13	160	48	1.0
30	5.8	37	11	130	48	1.1
60	5.5	44	6	100	50	4.0

* Assumes CO_{2(aq)} = 32± mg/l

Aeration: Theoretically, the final treatment step could almost be achieved by the use of aeration alone. The table below indicates the change in pH that would occur should all the CO₂ be driven off:

<u>FLOW</u>	<u>pH_o</u>	<u>pH_f</u>
10	6.1	7.4
20	5.9	7.0
30	5.8	6.8
60	5.5	6.2

Where:

pH_o is the effluent from the bed and;
pH_f is the effluent after CO₂ exsolution.

The effect of detention and aeration can be estimated by the use of Figures 10.14 and 10.16 or computed more precisely using Pearson's procedures (24). The importance of CO₂ exsolution is illustrated by Figure 11.9 where the alkalinity required to maintain a pH of 6.5 is plotted against acid created by dissolved CO₂. For example, if the AMD contains 40 mg/l of acidity due to CO₂, then 24 mg/l of CaCO₃ must be added to obtain a pH of 6.5. However, if the CO₂ acidity is reduced to 20 mg/l by aeration, then only 12 mg/l of additional alkalinity is required.

Tumbling Drum Design: For our example, we will assume that no aeration is available and the CO₂ remains at the 32 mg/l concentration previously assumed. Therefore the required alkalinity input from tumbling drums is as follows:

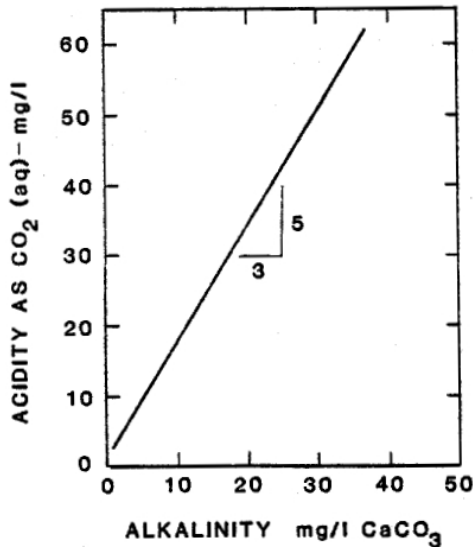


Figure 11.9 CO₂ Acidity Compared to Alkalinity Required for Neutralization. This figure illustrates the trade-off decision which must be made when designing a process series. The pH can be increased by adding CaCO₃ or by removing acidity by aeration. The ratio of these processes is 3 to 5 which can be used for economic comparison of treatment alternatives.

FLOW (cfs)	REQUIRED* ALKALINITY (mg/l)	AVAILABLE ALKALINITY (mg/l)	REQUIRED INCREASE (mg/l)
10	36	15	21
20	36	13	23
30	36	11	25
60	38	6	32

* From Figure 7.5

The required increase in alkalinity in terms of pounds per hour versus flow is plotted on Figure 11.10. The remainder of the design process is a trial and error procedure matching the required fines production with estimated fines production of a set or sets of drums. Estimates of production will be based on the data presented in Section 10. Ideally, the design process at this point would be an extension of the chemical/load factor theory previously used. However, a precise knowledge of the particle size produced by the drums is required to extend this method.

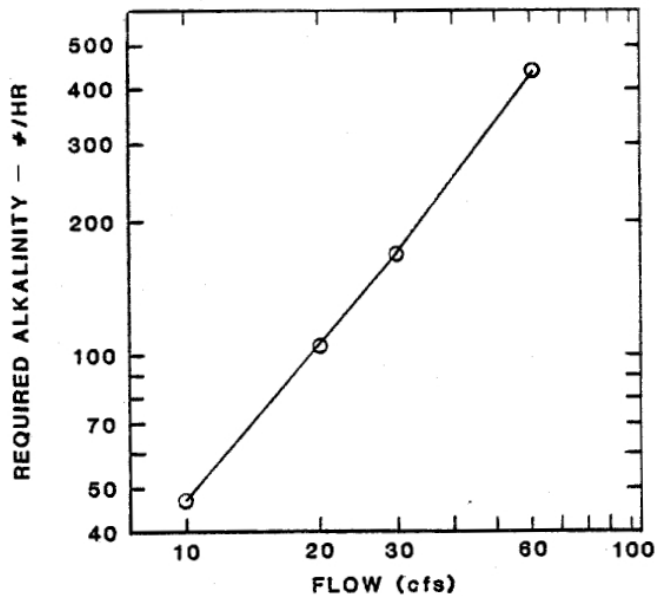


Figure 11.10 Required Alkalinity Compared with Flow For a process which does not include aeration or detention.

The first step in sizing the drums will be to determine the work required to produce necessary fines. Fines productions will be estimated at the rate observed for normal operation at Quakake; i.e. 26.5 lbs/Hp-Hr. As shown in Figure 10.13, the efficiency of the dissolution process is pH and time dependent. For this example, it will be assumed that the detention between and after the drum processes is minimal and the efficiency of conversion of fines to soluble CaCo3 is 0.25 as determined from Figure 10.12. Therefore, the Effective Production Rate = .25 x 26.5 = 6.63 lb./Hr. and the Required Power = Req.d Alk./Prod. Rate. Design valves are as follows:

<u>FLOW</u> <u>(cfs)</u>	<u>REQUIRED</u> <u>PRODUCTION</u> <u>(#/HR)</u>	<u>REQUIRED</u> <u>POWER</u> <u>(HP)</u>
10	47	7.1
20	103	15.5
30	168	25.4
60	431	65.1

It should be noted that this example represents a "worse case" situation. The initial alkalinity requirements could have been halved if aeration of the bed effluent had been provided. In addition, the fines conversion efficiency would be greater than 0.5 if detention of the drum effluent is provided between units. Therefore, the required fines production rate in this example could be reduced by 50 to 75 percent through the use of aeration and detention.

Input power described by Eq. 10.2 and converted to horse power:

$$P_I = \frac{\epsilon Q H \gamma_w}{550} \quad \text{or} \quad H = 14.7 P_I / Q$$

Assuming a total drum efficiency of 0.60, the required head or wheel diameter can be estimated:

<u>FLOW</u> <u>(cfs)</u>	<u>H</u> <u>(ft.)</u>
10	10.4
20	11.4
30	12.4
60	15.9

The next drums design step consists of selecting trial wheel and inner drum diameters, computing their geometric characteristics and estimating their fines production rates under the assumed design conditions. For our example we will assume our drum geometry is the same as those used at Quakake as the necessary geometric computations are already presented in Section 10. Dividing the H = 15.9 by 4.67, we find that at least 3 and possibly 4 tiers of drums will be required. Larger wheel drum diameters would reduce the required number of tiers. It must be remembered that the resisting moment drum geometry relationships available are for the 3' I.D. Quakake Drums. The reliability of extrapolating these results to smaller or larger drums, will be unknown until field verification tests are performed. However, it is felt that inner drums up to 4 feet in diameter can be designed by the present methods as the production rates will probably be underestimated and the design will be conservative.

Therefore: Wheel Diameter = 4.67'
 Drum Diameter = 4.00'
 Number Vanes = 16

After selecting a trial drum and wheel vane configuration, the hydraulic-geometric relationships of the drums should be computed by the following procedure:

(a) Compute the maximum bucket area for the applicable FLOW/RPM ratios using Equation 10.4
 $AI = 60Q/(LN_r)$

(b) Compute the hydraulic efficiency for the flow/RPM range using Equation 10.5

(c) Solve Equation 10.6 for the turning moment for each of the trial flow/rpm values

(d) Plot the hydraulic and geometric data on a graph similar to Figure 10.2.

Now the drum operating range will be defined by the resisting moment and available turning moment. The resisting moment is computed by Equation 10.13:

$$M' = \gamma_s C^3 \sin \phi L/12 \quad (10.13)$$

Where:

- γ_s = Unit wt. of stone = 90 lbs/ft.³
- ϕ = Angle of internal friction of the stone-degrees. The enveloping value of 55° as shown on figure 10.6 is recommended.
- C = Chord length of stone bed - ft.
- L = Drum width - ft.

The maximum resisting moment is developed when the drum is half full of limestone. The condition of maximum moment per foot of drum will be used to define the drum operating range. For the Quakake drums half full:

$$M' = 90 \times 3^3 \sin 55^\circ / 12 = 166 \text{ ft.-lb./unit length}$$

The hydraulic efficiency of the water wheel will adjust itself in accordance with the flow/RPM ratio so that the turning moment will equal the resisting moment. The bulk of limestone fines production data available is for the RPM range of 4 to 7 and operation of the drums in the 6 to 7 RPM range appears to represent optimum conditions for this type of drum and filling procedure. Therefore, the recommended operating range at 1/2 full is not less than 5 RPM and no more than 10 RPM.

If Figure 10.2 is examined, it is apparent that the relationship between Flow/RPM and turning moment (M_t) is nearly linear. Therefore the following approximation will be used.

$$\begin{aligned} & 0.24 M_t = 300 Q/\text{RPM} \\ \text{or} & \text{RPM} = 1250 Q/M' \\ \text{with} & M' = 166 \\ & \text{RPM} = 7.5Q \end{aligned}$$

So that the maximum and minimum flow per foot of drum ranges between 1.3 and 0.67 cfs/ft. This gives the criteria required to establish the length and number of drums.

The first treatment condition to be considered is low flow. The lowest recorded flow was 7.7 cfs. However, 0.67 cfs/ft. would require an 11.5' long drum, which is probably impractical when fabrication, handling and operations are considered. A drum length of five feet is a reasonable length to consider. One 5 feet long drum will operate in the 5.4 to 6.5 cfs flow range. Nine such drums would be required per tier to treat the full 60 cfs.

Total fines productions and required fines productions are plotted in Figure 11.11. Production from three tiers of nine drums each slightly exceeds the requirements in the 10 to 30 cfs range and are just under the required amount at 60 cfs. Additional drum and hydraulic control could be used to provide a better fit, but probably are not justified. Other drum sizes and arrangements will also meet the requirements and a complete design should examine other configurations to find the most economical. An important point to consider during design is the excess limestone production. In this drum operation example, the excess fines produced approach 300% of the amount required. This limestone is never completely lost from the treatment system and provides a neutralization source for periods of equipment non-operation or unusually high flows. In addition, fines accumulated in the process units will cause the overall treatment level to increase with the length of operation time. There is, unfortunately, insufficient data to quantify this.

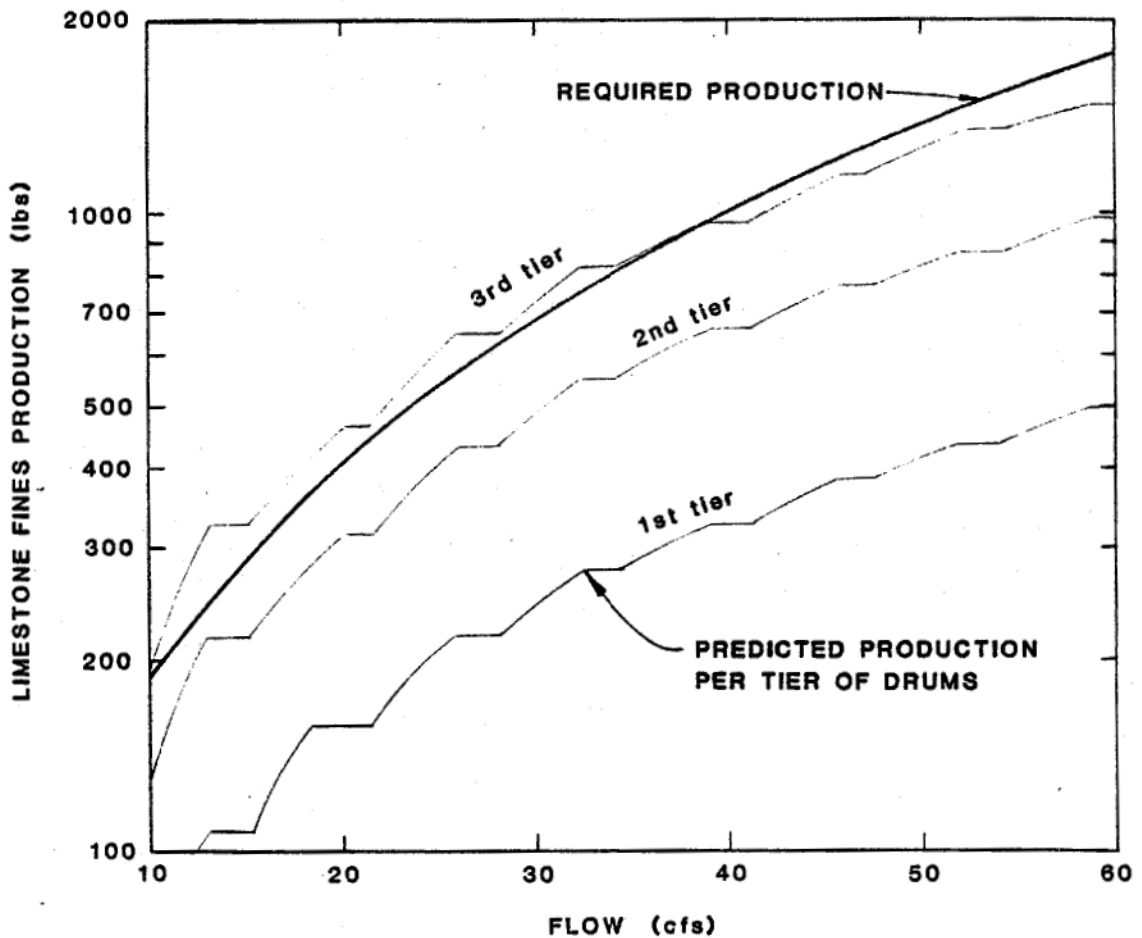
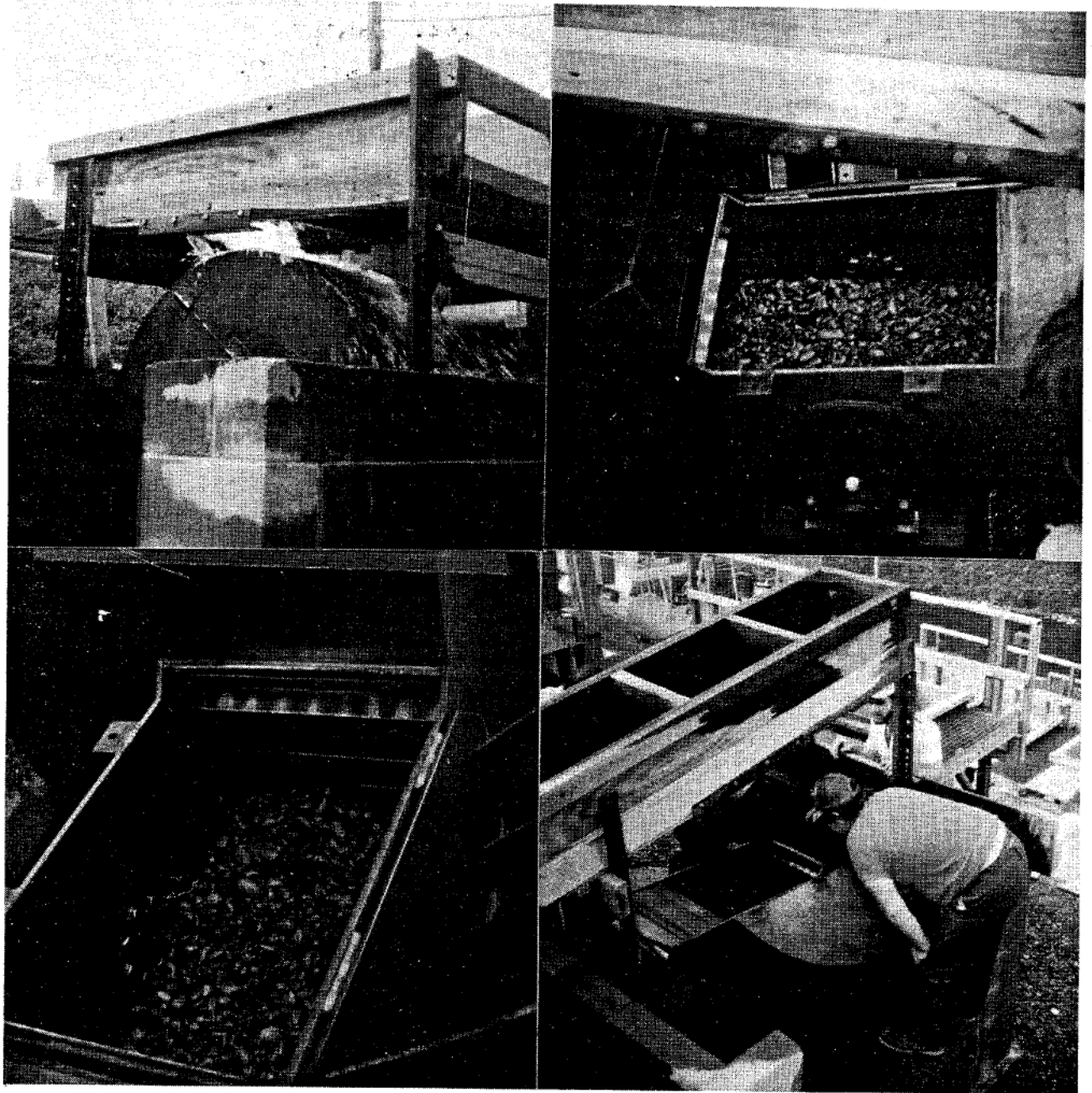


Figure 11.11 Design Example - Limestone Fines Compared with Flow

As previously stated, the overall efficiency of the drum process can be greatly increased by aeration and detention. In addition controlling the particle sizes produced by the drums would also enhance the process efficiency. The Quakake drums allowed particle sizes as large as 1/4 inch to be discharged from the drums. Particles this size are relatively inefficient for neutralization unless large detention times are provided. Ideally the particles discharged should be less than a 325 mesh (.044 mm) screen for quick reaction with the AMD. Control of the particle sizes produced by screening or hydraulic separation is recommended for future designs. The use of Ball Mill type equipment could also produce the smaller particle sizes.



VIEWS OF TUMBLING DRUM OPERATION & LIMESTONE ROUNDING