5. PROTOTYPE DESIGN AND CONSTRUCTION

The Quakake Tunnel prototype installations were designed and constructed during 1978 and 1979. A total of 30 individual process units representing variations of 4 basic design processes were installed. All the units employed crushed limestone for neutralization of AMD. The installed processes included both static and abrasive processes and are characterized in Table 5.1. The combined treatment capacity of the prototypes was 3 cfs. Flow was delivered to the units by a turbine pump capable of delivering 1800 GPM at a 50 foot head. A schematic layout of the project is presented in Figure 5.1 and aerial views are shown in the frontispiece.

Pumping of a portion of the AMD to the treatment units was employed for the prototype demonstration rather than gravity flow which is envisaged for a permanent project. Pumping was used to minimize site work and disturbance of adjacent woodlands as the use of the land for the project was obtained through gratis easements. It is intended that a permanent treatment facility would not require outside power sources to operate the treatment units.

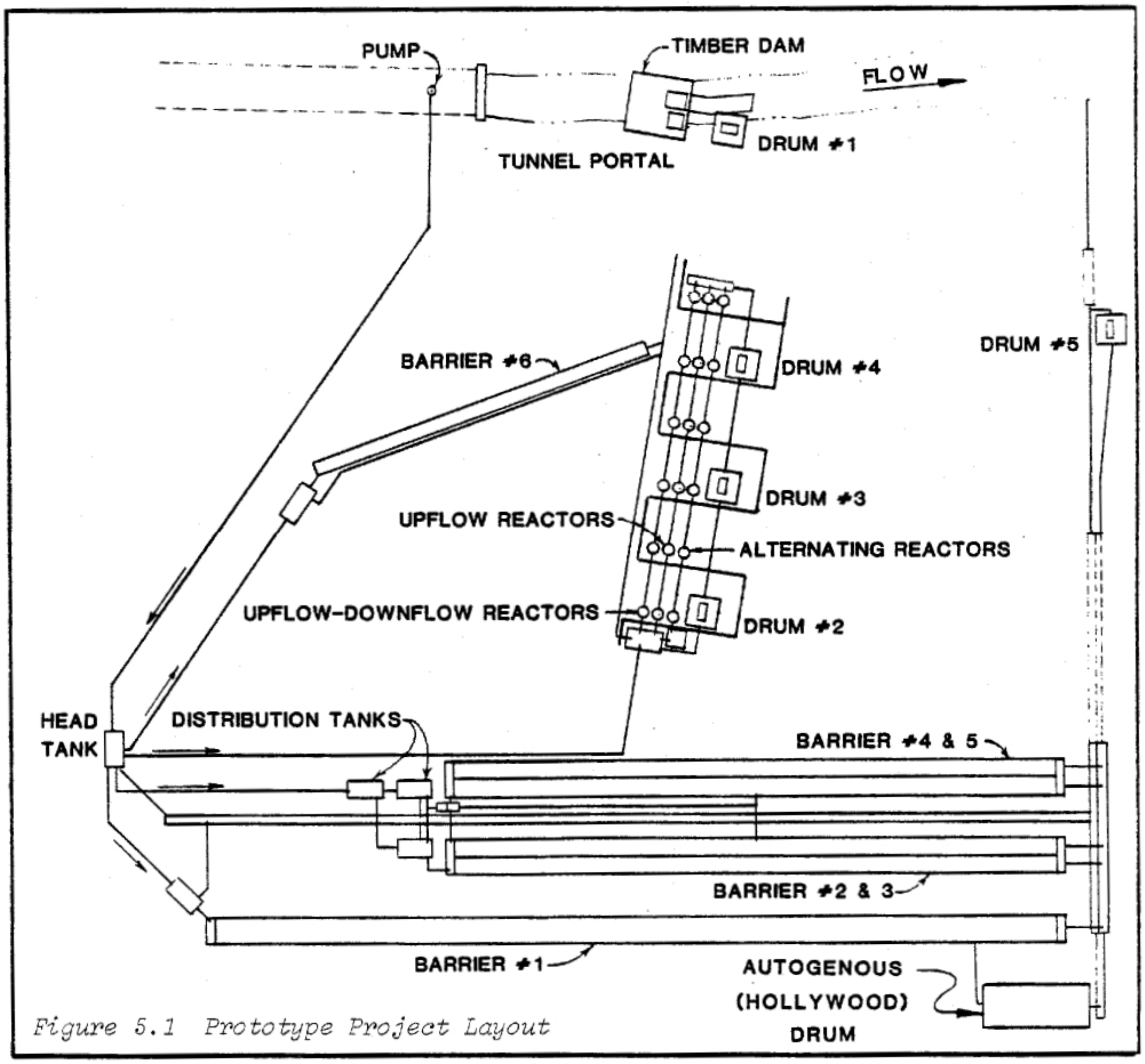


Figure 5.1 Prototype Project Layout

Limestone: Crushed limestone for the demonstration project was obtained from two sources. A high calcium limestone from the Bethlehem Mines Millard Quarry in Annville, PA, was selected for use in all the prototypes. In addition, a high magnesium limestone was obtained from local sources for comparative use in the tumbling drums. Three sizes of the high calcium stone were used. The chemical and physical properties for both limestones are as shown below.

TABLE 5.2 - CHEMICAL AND PHYSICAL CHARACTERISTICS OF PROCESS LIMESTONES

Characteristic	High Calcium Limestone			High Magnesium Limestone		
	Mean	Min.	Max.	Mean	Min.	Max.
Chemical Composition % Wt.						
Calcium Carbonate $CaCO_3$	97.0	96.9	97.2	62.2	59.5	66.2
Magnesium Carbonate $MgCO_3$	1.12	0.92	1.28	34.3	30.2	36.8
Silica SiO_2	0.98	0.76	1.29	2.64	2.46	2.73
Aluminum Oxide Al_2O_3	0.76	0.68	0.87	0.85	0.82	0.89
Iron Oxide Fe_2O_2	0.22	0.20	0.27	0.41	0.39	0.43
L.A. Abrasion %	43	39	45	25	-	-
Specific Gravity	2.72	2.72	2.73			
Bulk Density, Pcf						
Loose 5mm Stone (1/4")	88.6	88.1	90.1			
Rodded 5mm Stone	96.9	96.5	97.8			
Loose 13mm Stone (1/2")	83.7	81.7	85.2			
Rodded 13mm Stone	92.2	90.6	94.6			

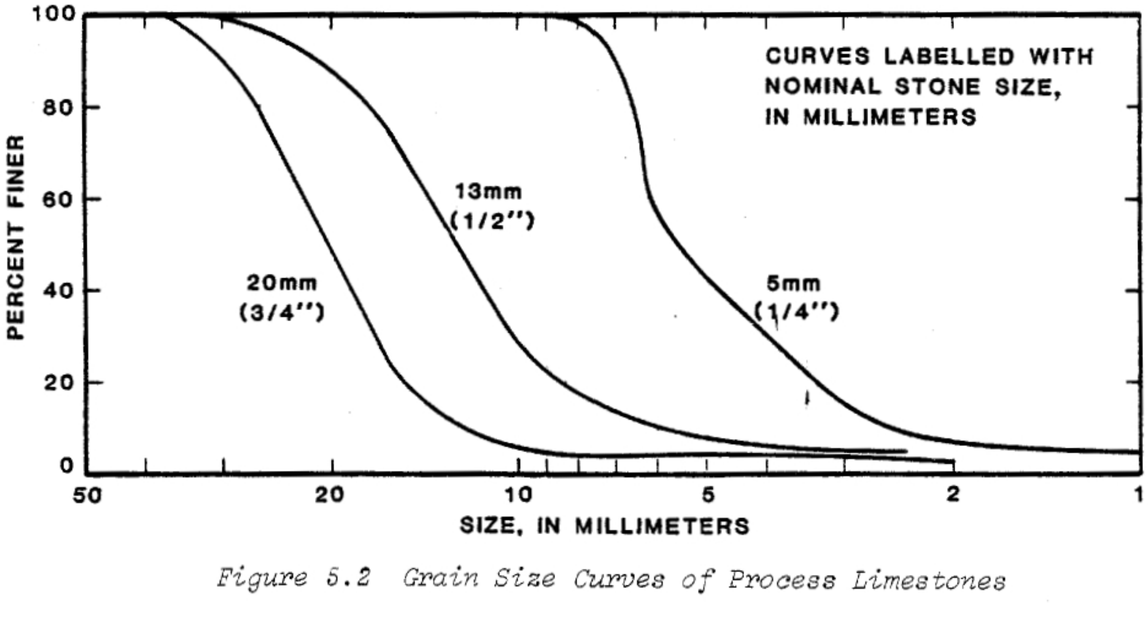
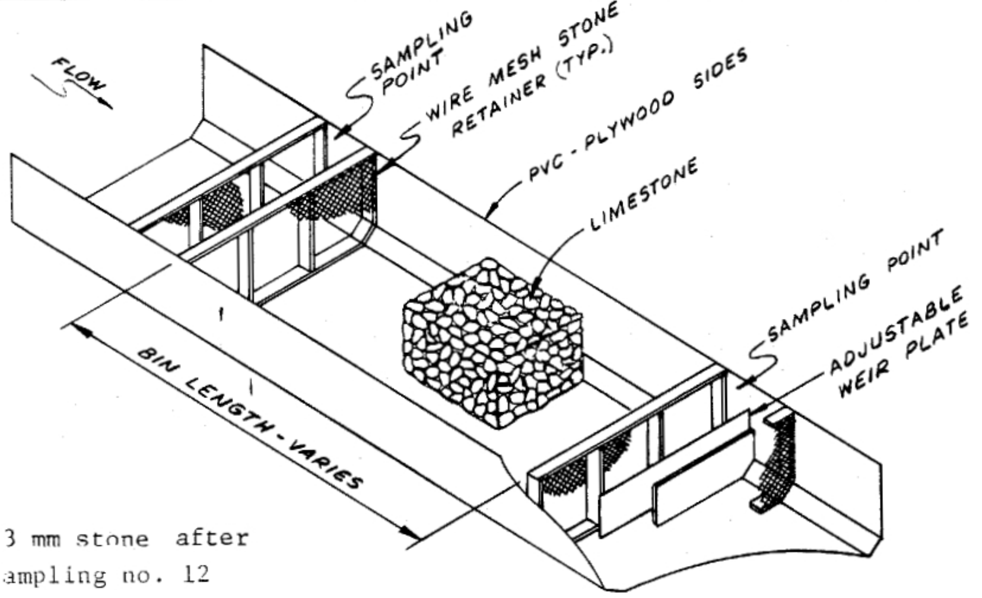


Figure 5.2 Grain Size Curves of Process Limestones



CONSTRUCTION DETAIL	BARRIER NO. 1	BARRIERS 2 THRU 5	BARRIER NO. 6
STONE SIZE (mm)	20	5 *	5 *
TOTAL LENGTH (ft.)	199	143	85.7
BIN LENGTH (ft.)	12	10	6
WIDTH (ft.)	6	4	3
STONE DEPTH (ft.)	2'-4"	2'-4"	3'-6"
NUMBER OF BINS	14	10	10
STONE (tons per bin)	6.8	4.5	3.1
BED SLOPE	-5.00%	-1.00%	-30.00%

* 13 mm stone after sampling no. 12

Figure 5.3 Limestone Static Barrier Construction

Static Barriers: Ideally, the problem of neutralizing an acid stream might be solved by the simple method of placing a sufficient amount of limestone as a bed or barrier, directly in the stream. However, during previous attempts to implement this method, the limestone became coated with metal complexes and the stone became clogged by stream sediments. These problems could have been partially the result of design deficiencies since both laboratory studies and evaluation of the Trough Creek Limestone Barrier Project (14, 15, 17) indicated that the use of instream barriers was feasible under certain conditions. The conditions which favor the use of limestone beds are low stream discharge variations, low sediment load and low iron content. These criteria were used in the selection of the Quakake Tunnel Project site. Also, the diversion of a constant amount of flow to the prototypes in the demonstration project eliminated flow variations. Standard sanitary septic tanks were used as combination diversion/sedimentation tanks. They were designed to remove sediment sizes greater than the sizes which would theoretically be carried through the stone voids by the flowing water.

Previous research identified the parameters considered to govern the neutralization process. They include the following:

Stone and AMD composition,
Available Limestone Surface (stone size and shape),
Contact time, Streamflow and Temperature,
Water Turbulence - Hydraulic Shear Forces, and
C02 Exsolution Subsequent to Neutralization.

The prototype limestone barriers were designed to explore the response of the process to variations in stone size and hydraulic characteristics. Prior studies indicated that under barrier conditions of near constant flow and low iron and sediment loads, the reduction in reactivity due to fouling of the limestone surfaces did not fall below 20% of that for fresh clean stone. Accordingly, all the barriers were sized to provide 5 times the limestone surface area per unit flow of AMD (Load Factor) above that required by theory to achieve the desired degree of neutralization using clean crushed stone.

Each barrier was subdivided into individual units, (bins) within which limestone was placed. This provided convenient sampling points along the treatment path and allowed adjustment of hydraulic gradient through the barrier. The use of adjustable weir plates between the bins provided control of stone submergence and hydraulic gradient through the stone. The limestone barriers were constructed in plywood channels lined with 20 mil. PVC. Divisions were created within the barriers by using wooden frames covered with heavy diamond wire mesh and 1/4 inch hardware cloth. Figure 5.3 shows construction details of the six barriers. The flow to the inlet of each barrier was measured using a 90^0 v-notch with a plywood stilling box. The dissipation of flow energy into the stilling boxes was accomplished by using slotted PVC pipes fitted with end caps.

Filter -Type Units: The filter-type processes consisted of the installation of three parallel sets of six filter units. The units were designed to operate in three modes; downflow, upflow and alternating downflow-upflow. Construction details are illustrated in Figure 5.4.

An upflow method of operating was reported to have been successful in the treatment of steel pickling liquors (7,8). In upflow process, abrasion of the limestone particles is created by maintaining the bed in a constant fluidized condition. In the downflow design, the beds act as a static barrier but they have the capability of being backwashed to remove the buildup of sediments and coatings. Backwashing is initiated by closing the bottom gate valves and operating the units in the fluidized upflow mode. The alternating flow units were designed as downflow units with automatic backwashing capabilities.

Downflow operation was achieved by opening the bottom gate valve allowing AMD to percolate downward through the stone and through the gate valve to the next unit. By closing the bottom gate valve, the operation converted to the upflow mode, wherein AMD entered the bottom chamber, flowed upward to fluidize the stone, and then passed through the slotted control valve to the base of the next unit downstream. For operation in the alternating flow mode the slotted control valve was replaced by a siphon. The bottom gate valves were partially operated and the unit operated in a down flow mode. The siphon discharged to the base of the next downstream unit causing an upflow flushing of the downstream unit.

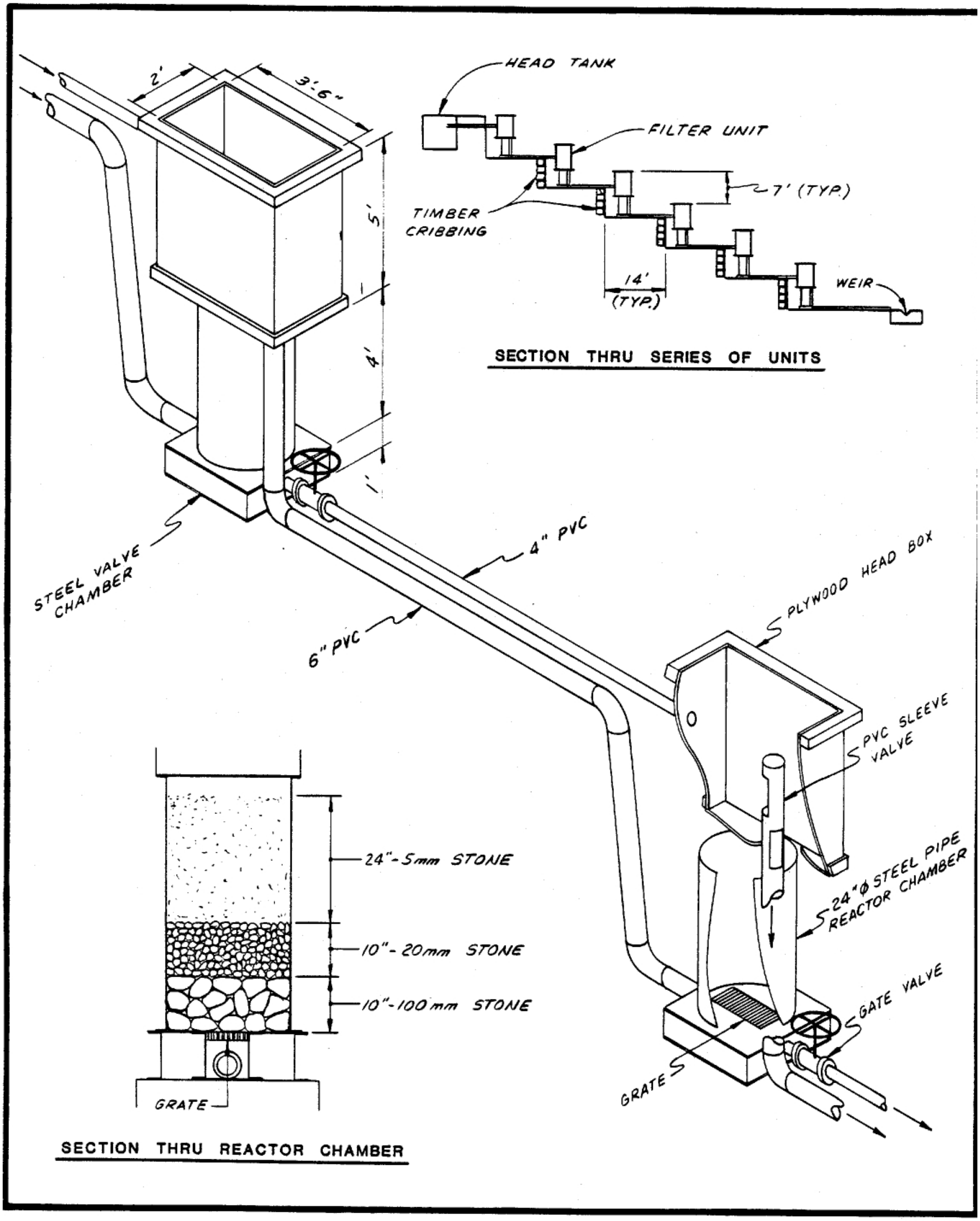


Figure 5.4 Construction Details of Filter-Type Units

Tumbling Drums: Rotating drums containing crushed limestone act as grinding mills to produce fine limestone particles which are highly reactive with AMD. Motor powered tube mills and limestone filled water wheels for neutralization of AMD and slightly acid streams have been successfully demonstrated (10, 19, 20, 21). The success of the unique drums demonstrated by Zurbuch, coupled with the subsequent analysis of the chemical and hydraulic/mechanical processes of the drums by Pearson and McDonnell led to the design and installation of similar units at the Quakake Tunnel site.

Of the five drums installed at Quakake, three drums (Drums 2, 3 and 4) were installed in series as an integrated treatment unit. One drum (No. 5) placed separately to treat the effluent from the static barriers provided data on combining the two methods. The remaining drum (No. 1) located in the stream channel, below the diversion dam, provided information on flows exceeding the capacity that could be delivered through the pumped distribution system (1+ cfs). A typical drum installation is illustrated in Figure 5.5.

The five drum installations were constructed identically. Drum bays were constructed of 6 inch cinder block walls placed on 6 feet, 8 inch square by 8 inch thick concrete pads. The front bay walls were erected 4 feet high for splash containment. The bay side walls were 2 feet high in order to facilitate loading and unloading and periodic checks of the drum contents.

The drum shell was constructed from 3/8 inch thick steel pipe with an inside diameter of 3 feet and a length of 18 inches. Welded to both ends were 3/8 inch thick, 4 feet 8 inch diameter end plates. Welded between each end plate were sixteen curved water wheel vanes, having a 10 inch radius, which functioned as water containing buckets. The curved metal vanes were cut from standard steel pipe. Half-inch diameter holes were drilled through the inner drum at the base of each bucket to allow water to enter the drum and wash out the limestone fines generated by the tumbling stone in the drums. Baffles of 1/4 inch thick by 2 inch angle iron were bolted to the inside of the drum surface at the base of each vane to prevent slippage of the stone mass. A hinged door, bolted shut during operation, allowed loading of limestone into the drum. The drums were supported by 2 inch steel axles seated in pillow blocks with sealed ball bearings which rested on structural steel angle tripods.

Lovell (21) noted that noise is a drawback associated with operation of the drums. Zurbuch (19) significantly reduced this problem by lining his drums with a steel reinforced rubber mat. The Quakake drums were provided with a similar liner. Consequently noise levels created by the drums were not objectionable.

Autogenous Mill: The method of passing AMD through motorized rotating tubes partly filled with crushed limestone has been used to neutralize AMD. One such installation was transferred from its original Hollywood, Pennsylvania location to the Quakake Tunnel site prior to the third sampling period! The mill, shown in Figure 5.6, is a steel drum 5 feet in diameter and 20 feet long. The drum which rests on idlers is rotated by a 25 HP electric motor. The operation of this unit as an autogenous mill has been previously reported (21).

The mill was used at Quakake to investigate the concept of mechanically cleaning a static bed. The drum was used as a stationary limestone bed with periodic revolutions to achieve stone cleaning, rather than the production of fines. The bed was turned through two revolutions every four or eight hours. The drum was filled approximately one-half of its capacity with 5mm (1/4 inch) limestone.

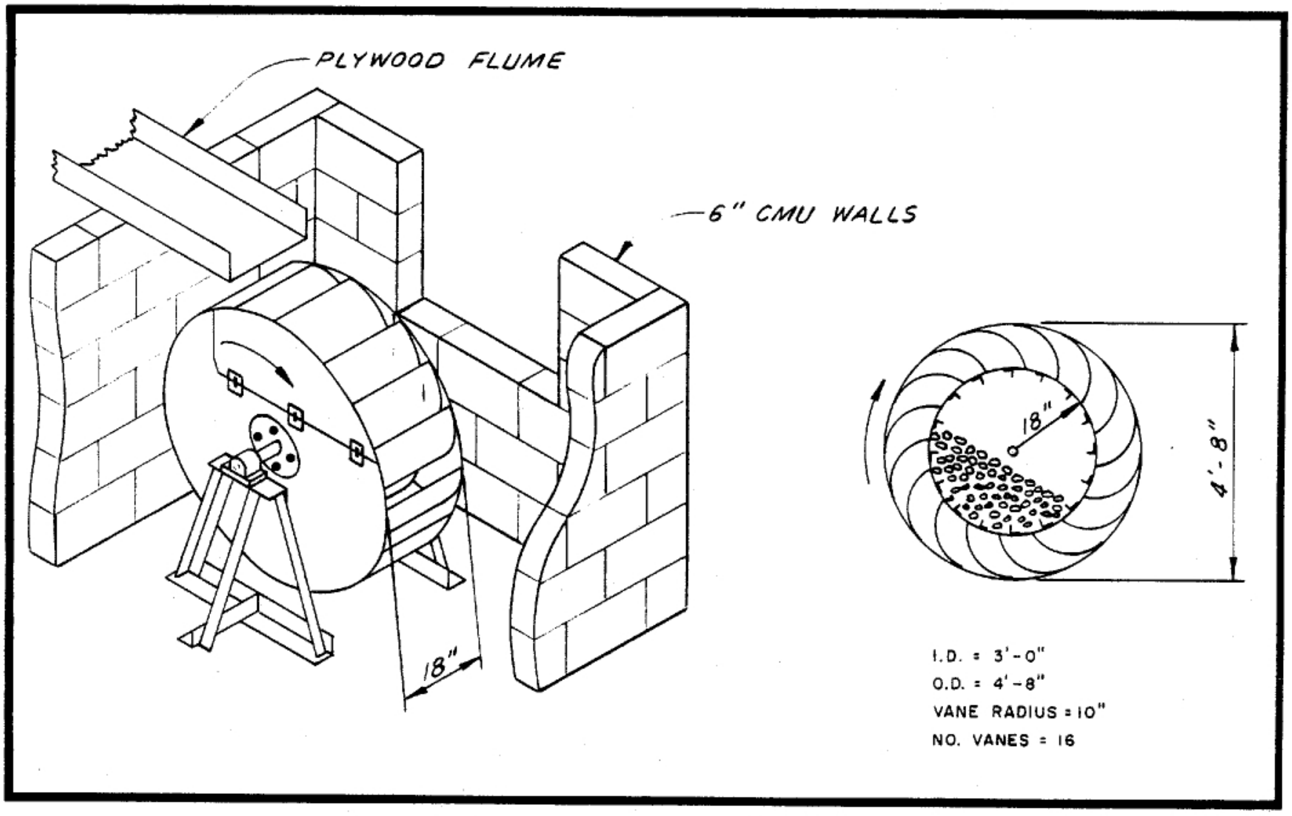


Figure 5.5 Construction Details of Tumbling Drum Units

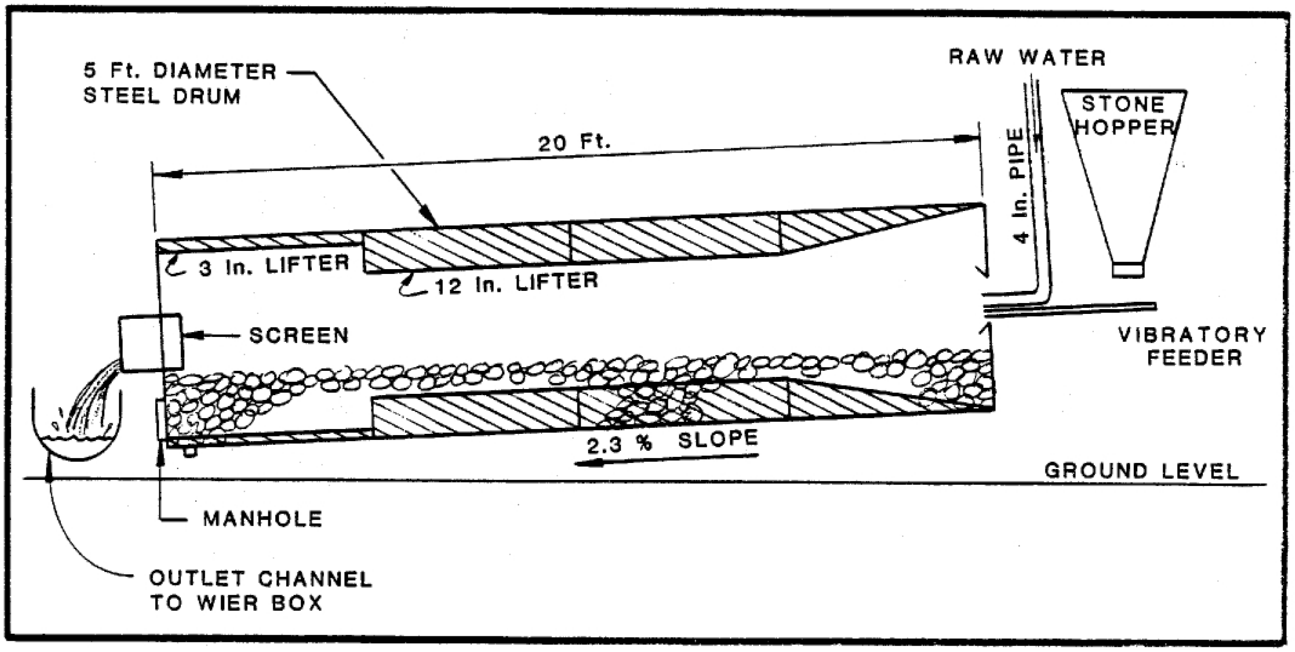
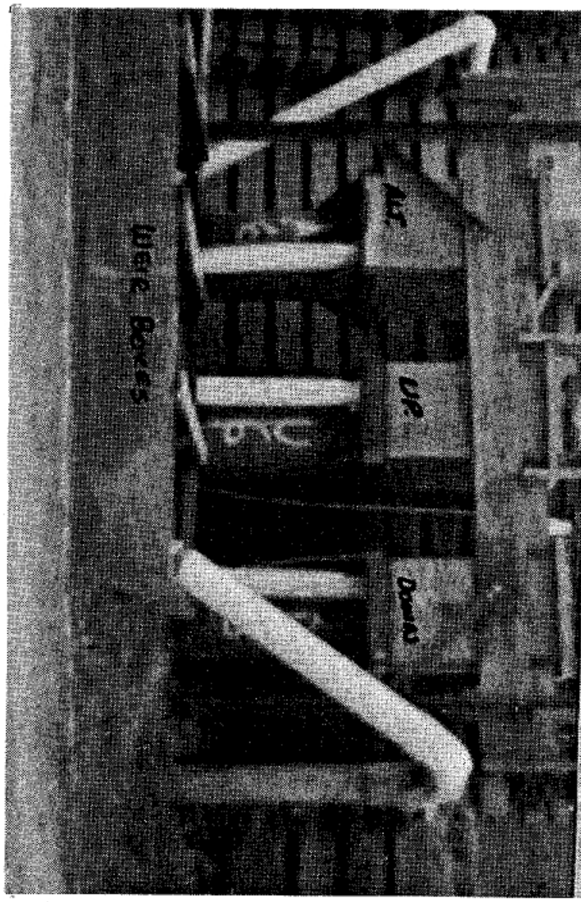
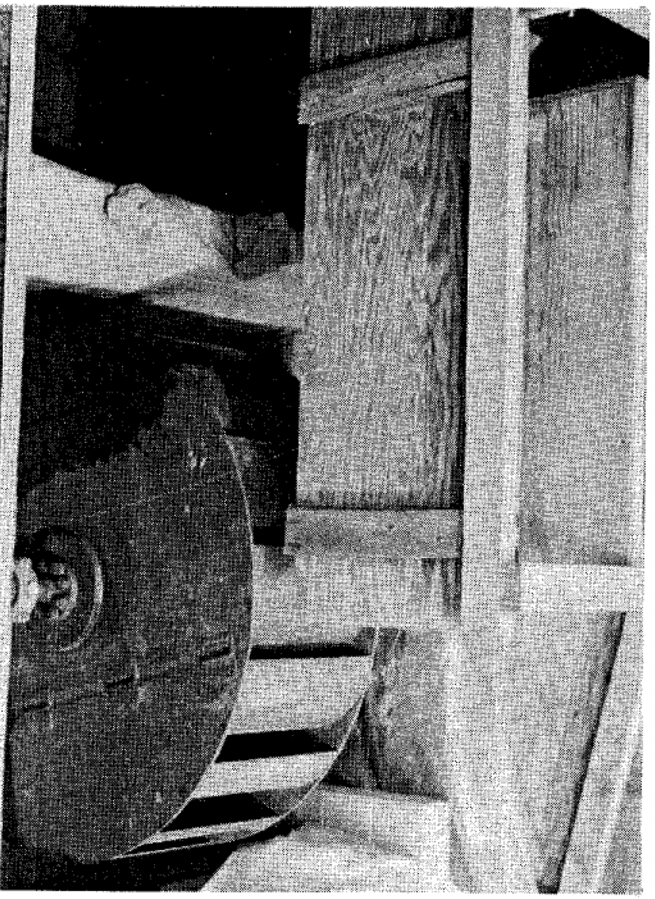


Figure 5.6 Section Through The Autogenous Mill


UPFLOW/DOWNFLOW UNITS


AUTOGENEOUS MILL


TUMBLING DRUM

6. PROTOTYPE OPERATION

The Quakake Tunnel prototypes were operated periodically over a 2-year period. The facility was operated for four separate sampling periods (runs) as follows:

Run No.	Sampling No.	Begin-End Dates
1	1 thru 12	7/10 - 10/4/79
2	13 thru 39	11/12- 11/21/79
3	40 thru 65	5/19 -5/21/80
4	66 thru 83	7/20 - 7/25/81

The non-operating periods were used for the chemical analysis of samples, evaluations of results, planning subsequent runs, and modification or repair of the plant.

Monitoring and Analytical Procedures: For samplings 1 thru 65, a 500 mL sample and a 125 mL acidified sample were taken at each sampling point. Bottles were rinsed before filling, capped underwater and stored at 9^{0}C until shipping to the laboratory in ice-packed containers. Chemical analyses were performed at the Harrisburg Laboratory of the Pennsylvania Department of Environmental Resources. All samples were tested for the following parameters:

pH;
free acidity
total acidity;
alkalinity;
iron (total and ferrous);
sulfate;
aluminum;
calcium.

Occasional determinations were also made of:

manganese;
magnesium;
sodium;
potassium;
silica;
chloride; solids (total and suspended).

The following field measurements were also made at each sampling:

pH;
temperature (water and air);
flow rate (by weirs); hydraulic head; and
stone load and RPM for tumbling drums

During Run No. 4, the pH, alkalinity and acidity were determined on site.

Results of the monitoring program are presented in Appendix "C".

Run No. 1: Initially, the plan of operation for the demonstration project anticipated a 6-month operating period with twice-weekly samplings. This procedure was followed for samplings 2 through 12. Sampling No. 1 was a false start as the project operation was halted by a malfunction of the generator which supplied power to the pump. Figure 6.1 shows the operation schedule for Run No. 1.

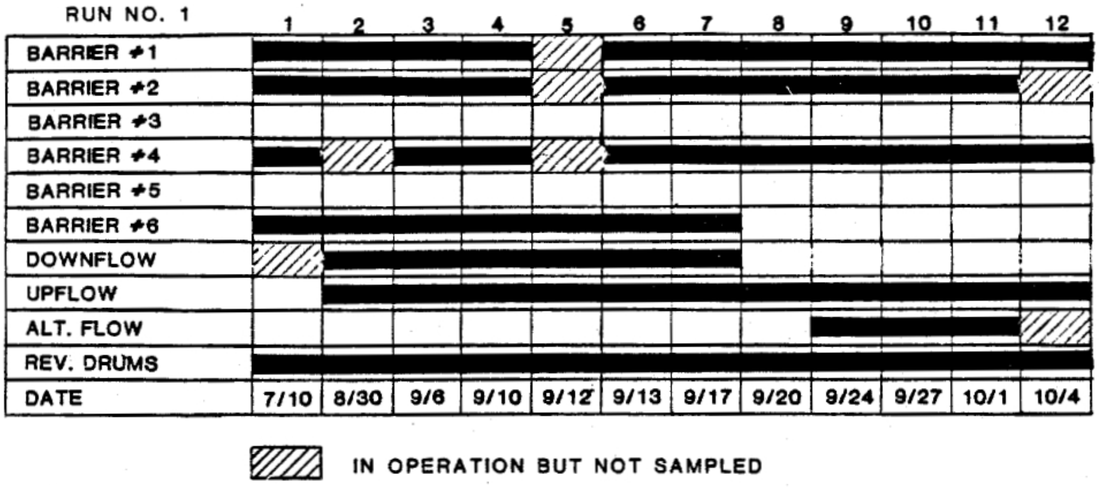


Figure 6.1 Operation Schedule - Run No. 1

During Run No. 1, several problems developed which required correction. The siphon units in the alternating filter units did not function because they were unable to develop sufficient head to purge the air in the pipes between the units. To correct the situation, the siphon in the upper unit was replaced with a mechanical flusher, while the siphon in the third unit was replaced by a commercial sanitary siphon with non-pressure discharge. Both modifications worked satisfactorily, although the modification of the backwashing equipment required the removal of some of the stone, thereby reducing neutralization capability. Having demonstrated the feasibility of automatic backwashing on some of the units, the remaining filter-type units were backwashed manually.

Major problems were encountered in the units containing the 5mm (1/4") stone. The rate at which the limestone fouled was much greater than had been originally anticipated. The front face of the stone beds of barriers 2, 4a and 6 became clogged which reduced the permeability of the stone bed to the point that the AMD ran over the tops of the beds rather than through them. This was particularly problematic in barrier No. 6 which was on a 30% slope.

The permeability of the filter units was also seriously reduced by clogging. The original design of these units used an 1/8-inch screen to retain the stone at the base of each bin. These screens became almost totally clogged after 3 weeks of operation. In several instances, the upper one foot of the downflow units was actually "cemented" by the fouling coat and could not be backwashed. Mechanical prodding was necessary to break the "cemented" layer so that the stone could be cleaned. After sampling No. 8, the stone and screens were removed from the upflow and downflow units and a graded filter was placed in lieu of the screening. Also the monitoring of barrier No. 6 was halted at this time.

Evaluation of the results from the first sampling run indicated that the monitoring procedures would have to be revised in order to adequately investigate the rate of limestone consumption and fouling. It was clear that an increased sampling rate would be required because the rate at which the stone reactivity decreased necessitated hourly rather than daily measurements as had been originally anticipated. Similarly, the filter units required more frequent backwashing to maintain reactive limestone surfaces. In addition, the three to four day sampling intervals did not allow gathering of sufficient data to describe the short term operations of the tumbling drums. The refilling cycle for the drums coincided with the sampling frequency approximately 3 to 4 days. As a result, the data gathered was primarily for freshly filled or nearly empty drums. Another problem associated with the drum operations noted during this run was that the detention time provided by the units was insufficient. It was observed that the AMD leaving the process units was milky colored, indicating that the reaction of the limestone fines with the AMD was not complete.

Run No. 2: The operation of the units during Run No. 2 was planned in a manner which would supplement the data gathered during Run No. 1 by utilizing shorter sampling intervals. The monitoring frequency was increased to 3 samplings per day with continuous 24-hour operation of the units.

Run No. 2, consisting of samplings 13 through 39, started on November 12, 1979. Figure 6.2 shows the operation schedule for Run No. 2.

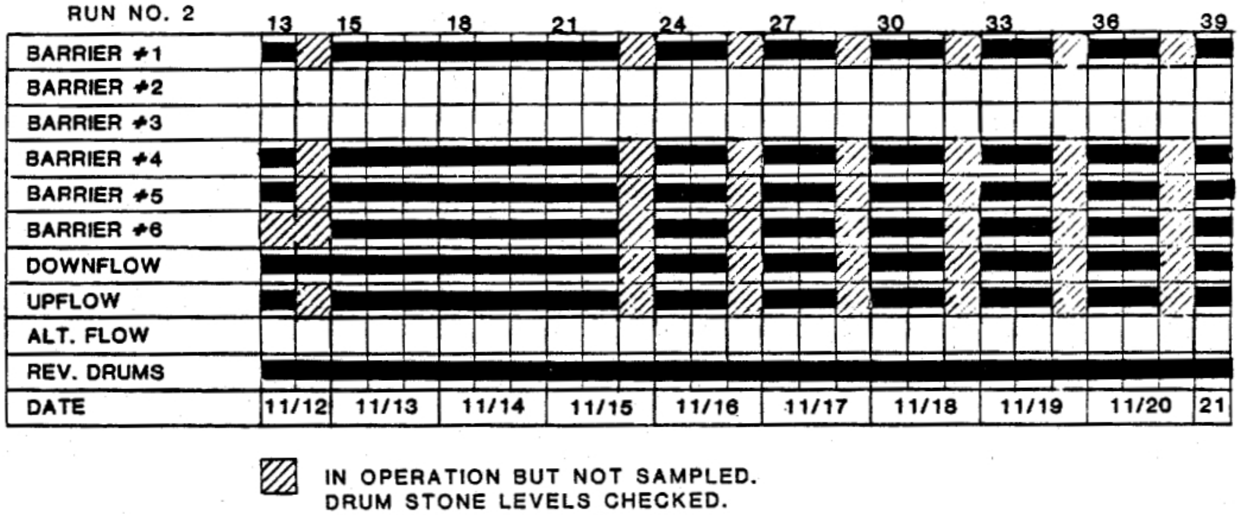


Figure 6.2 Operation Schedule - Run No. 2

On completion of the laboratory testing of samples for Run No. 2, the monitoring results were evaluated with respect to the design theories. At this point, more than 2000 samples and measurements had been collected. Analysis of the data indicated that although design processes could be described emperically, the results did not correlate with the initial theoretical derivations. Part of this problem is related to the random nature of the data itself which is illustrated in Table 2.1 by the wide chemical variations of the AMD influent itself. The lack of agreement between the theoretical and experimental results was related to buffering effects observed in the pH 4.5 to 6.0 range. Additional correlation problems were encountered while trying to relate the measured drum operation parameters - RPM, flow and stone load, to the observed neutralization process.

As a result of the evaluations of Runs 1 and 2, the following measures were taken in preparation for Run 3:

Fresh 5 mm (1/4") limestone was placed in the filter type units after removal of the used stone.

The 5 mm (1/4") limestone in barriers 5 and 6 was replaced with 13 mm (1/2") limestone.

Facilities were added to provide detention of a portion of the effluent from the drum series 2, 3, and 4. This was achieved by diversion of 1 to 3 gallons per minute into two 55 gallon drums, providing up to 1 hour detention time for the process to continue.

Run No. 3: The third sampling run concentrated on the operation of the downflow units and revolving drums. The operation schedule is shown in Figure 6.3. The evaluation of the data from Runs 1 and 2 indicated that these processes were the most promising treatment methods. As it was felt at this time that the likely cause of the buffering problem was the carbon dioxide being generated by the neutralization process, aeration equipment was provided for the drum detention units. The autogenous mill from the Hollywood Plant was also installed at this time.

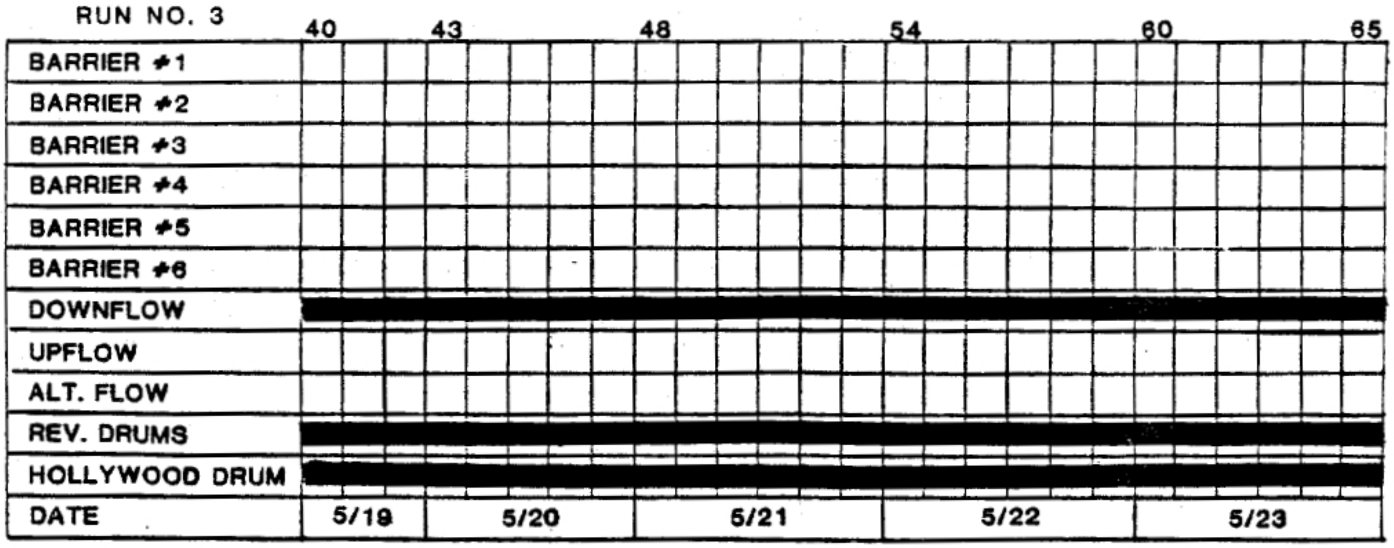


Figure 6.3 Operation Schedule - Run No. 3

Following the evaluation of Run No. 3, a draft report was prepared and tentative design procedures were proposed. The design procedures were based almost entirely on empirical data as the relationships between the observed neutralization processes and theory were not established. A fourth run was proposed in an attempt to establish this link. Marked differences between laboratory pHs and field pHs were noted in all the samplings as illustrated in Figure 6.4. The pH, acidity and alkalinity relationships are fundamental descriptors of the chemical processes in, the reactions. It was questionable if the values obtained in the laboratory adequately describing the chemical process at the site. For example, the carbon dioxide content of the process effluent could not be determined in the laboratory. It was decided to attempt to solve these problems by testing the acidity and alkalinity on fresh samples in the field during a fourth run.

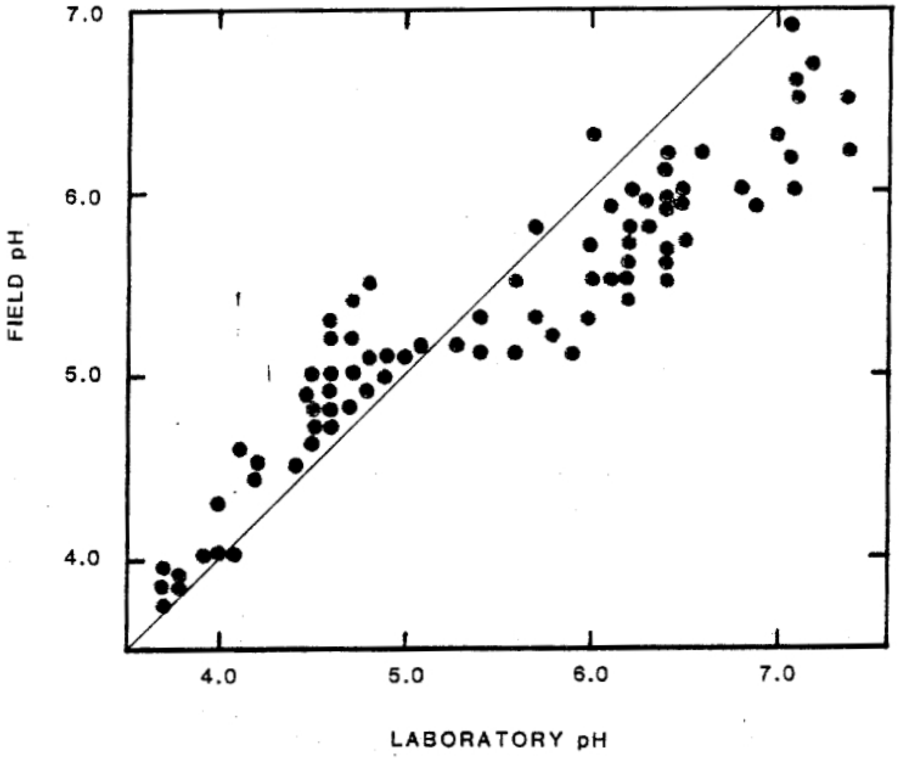


Figure 6.4 *Field pH Determinations Compared with Lab pH The differences between lab and field values are consistant with pH levels. This suggests the chemistry of the sample has been altered between testing periods. Loss of CO_2 and continued $CaCO_3$ dissolution could contribute to these changes.*

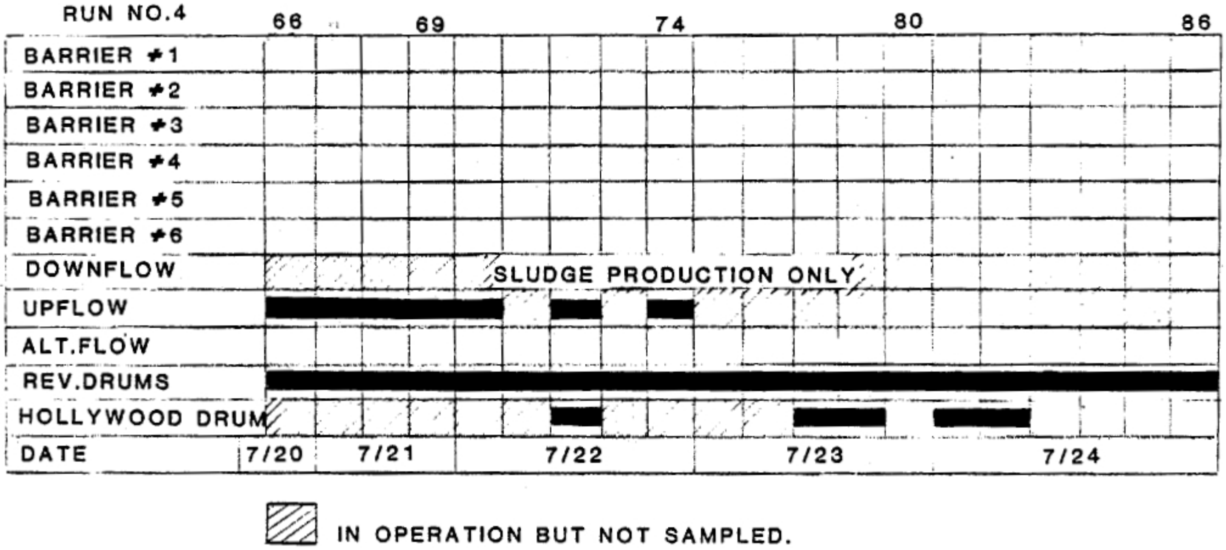


Figure 6.5 *Operation Schedule - Run No. 4*

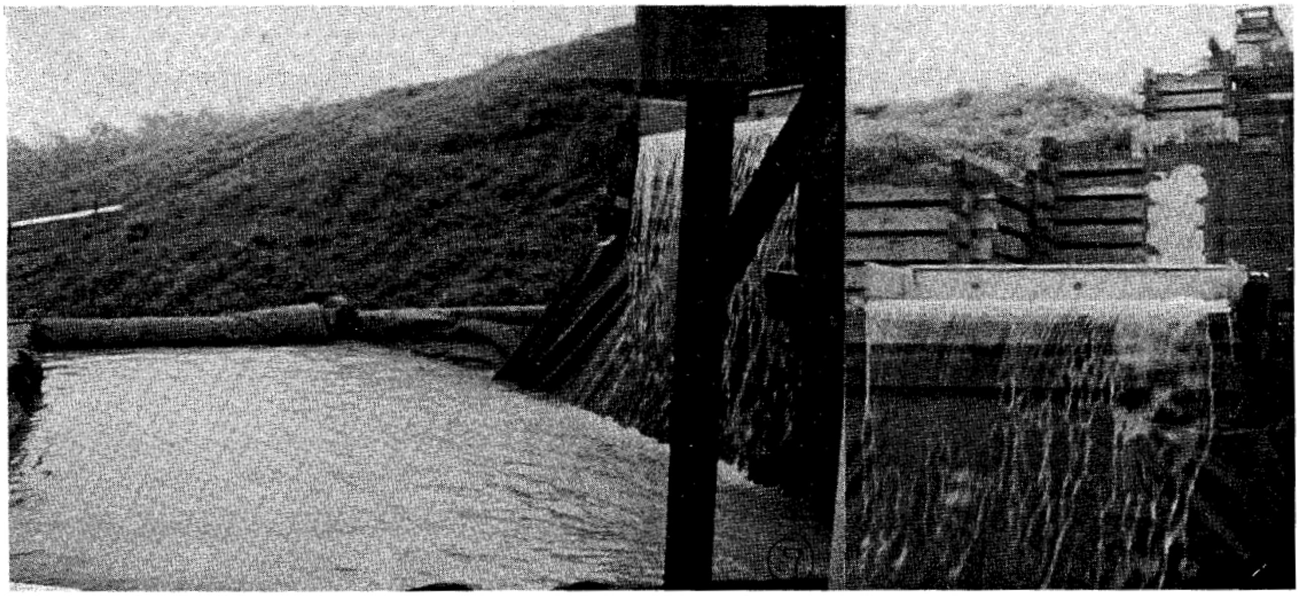
Run No. 4: Run No. 4 consisted of intense sampling of the drums and upflow units for one week as shown on Figure 6.5. A laboratory trailer was provided by the Department and the chemical tests for pH, acidity and alkalinity were performed onsite on fresh samples. In addition to the standard test for hot acidity, titrations on cold unoxidized samples were made. Comparison of the oxidized titrations with the unoxidized titrations allowed a rough estimate of the carbon dioxide to be made. Intermediate readings were taken during the tests to allow comparison of the entire titration curves.

Additional objectives of Run No. 4 were the gathering of additional data on carbon dioxide stripping by aeration, sludge production in the downflow units, and the effects of increased detention time on drum process series.

Two 500 gallon tanks with aeration equipment were installed for carbon dioxide stripping tests on the tumbling drum effluent. Both flow through and batch stripping tests were made.

An additional 200 gallon tank was used to settle sludge from the downflow backwash water. Dewatering tests were performed on the settled sludge. The tests were for the rapid sludge dewatering system of U.S. Environmental Products Inc. and the results are presented in Appendix "E."

A 2,500 gallon shallow detention pond was constructed between Drum No. 3 and Drum No. 4 in order to evaluate the effect of maintaining the ground limestone fines within the process. Partial aeration was provided by a seven feet high drop into the pond with a steel edged 8 feet long weir maintaining sheet flow.



DETENTION POND BETWEEN DRUMS 3 AND 4