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13. ABSTRACT (Maximum 200 words)
THE INVESTIGATION DISCUSSED IN THIS REPORT WAS CONDUCTED IN SUPPORT OF A CONCURRENT STUDY ONGOING AT RMA TO DETERMINE THE APPLICABILITY OF ACTIVATED ALUMINA ADSORPTION FOR THE REMOVAL OF FLUORIDE FROM GROUND WATER CROSSING THE NORTHERN BOUNDARY. THE APPLICABILITY STUDY IS BEING CONDUCTED BY RUBEL & HAGER, INC. THEIR ASSISTANCE & TRANSFER OF INFORMATION IS ACKNOWLEDGED. THE ACTIVATED ALUMINA BEDS MUST BE PERIODICALLY REGENERATED WHEN THE BED BECOMES EXHAUSTED. THIS REGENERATION PROCESS RESULTS IN A CAUSTIC WASTEWATER CONTAINING A HIGH CONCENTRATION OF FLUORIDE. AN ENVIRONMENTALLY ACCEPTABLE TREATMENT/DISPOSAL PROCESS IS REQUIRED FOR PROCESSING OF THIS WASTEWATER DURING THE ACTUAL OPERATION OF THE PROPOSED ACTIVATED ALUMINA SYSTEM. THE OBJECTIVES OF THIS STUDY ARE:
1. TO REVIEW THE EXISTING LITERATURE CONCERNING THE DISPOSAL CONCENTRATED FLUORIDE WASTEWATER, AND 2. TO ASSESS, ON A LABORATORY SCALE, THOSE TREATMENT PROCESSES HAVING THE GREATEST POTENTIAL FOR SUCCESS IN TREATING THE REGENERATION

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TREATMENT AND DISPOSAL OF REGENERATION WASTEWATER FROM ACTIVATED ALUMINA COLUMNS USED FOR FLUORIDE REMOVAL FROM GROUNDWATER AT ROCKY MOUNTAIN ARSENAL

by

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PREFACE

This investigation was conducted during the period March - November 1979 by the Environmental Laboratory (EL) of the U. S. Army Engineer Waterways Experiment Station (WES) for Rocky Mountain Arsenal (RMA). Funding for this study was authorized by IAO No. RM 59-79, dated 4 January 1979.

This report was prepared by Mr. Douglas W. Thompson, WES, Dr. Purush K. Terkonda, University of Missouri-Rolla, and Dr. Leale E. Streebin, University of Oklahoma, the Water Supply and Waste Treatment Group (WSWTG), EL, WES, under the direct supervision of Mr. Norman R. Francingues, Chief, WSWTG, and the general supervision of Mr. Andrew J. Green, Chief, Environmental Engineering Division (EED), and Dr. John Harrison, Chief, EL.

The investigation discussed in this report was conducted in support of a concurrent study ongoing at RMA to determine the applicability of activated alumina adsorption for the removal of fluoride from groundwater. The applicability study is being conducted by Rubel and Hager, Inc., Tucson, Arizona. Their assistance and transfer of information is hereby acknowledged.

Special acknowledgement is extended to the following individuals for their assistance and encouragement during the course of this work: Messrs. Ed Berry and Carl Laven (RMA); Mr. Don Campbell, U. S. Army Toxic and Hazardous Materials Agency (USATHAMA); Mr. Jack Dildine (WES); and also the personnel of the Material Analysis Laboratory Division (MALD), RMA, and the Analytical Laboratory Group, WES.

Directors of WES during the preparation of this report were COL J. L. Cannon, CE, and COL N. P. Conover, CE, respectively. Technical Director was Mr. F. R. Brown.

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TREATMENT AND DISPOSAL OF REGENERATION WASTEWATER FROM ACTIVATED ALUMINA COLUMNS USED FOR FLUORIDE REMOVAL FROM GROUNDWATER AT ROCKY MOUNTAIN ARSENAL

PART I: INTRODUCTION

Background

1. An anticipated requirement for the removal of fluoride from groundwater crossing the northern boundary of Rocky Mountain Arsenal (RMA) has resulted in pilot studies at RMA using activated alumina as the treatment process. Optimization studies on this process are currently being conducted onsite. The activated alumina beds must be periodically regenerated when the bed becomes exhausted. This regeneration process results in a caustic wastewater containing a high concentration of fluoride. An environmentally acceptable treatment/disposal process is required for processing of this wastewater during actual operation of the proposed activated alumina system.

Objective

2. The objectives of this study were:

   a. To review the existing literature concerning the disposal of concentrated fluoride wastewater.

   b. To assess on a laboratory scale those treatment processes having the greatest potential for success in treating the regeneration wastewater from the activated alumina system.

Methodology

3. The literature review strategy adopted was to evaluate the available information for data from theoretical and research studies to determine what means of treatment would prove to be most applicable. The areas of consideration were divided into chemical, physical, and biological processes. Since the biological area provided no treatment

possibilities due to the regeneration water's constituents and pH, the findings and recommendations for only the chemical and physical areas are presented in this report.

4. The criteria used in evaluating the potential of the various methods or processes found in the literature included: the anticipated ability of the process to remove significant quantities of fluoride from the highly concentrated regeneration waste, the engineering feasibility of the process (i.e., perceived operating difficulties, the relative cost of the process), and the impact of the process on the environment (particularly the potential for introducing any pollutants to the groundwater).

5. Certain chemical precipitation processes with a high potential for success were evaluated in the laboratory using standard jar tests. Cost estimates for these processes were made based on chemical dosages determined in the laboratory studies. Cost estimates for other processes were made based on the available literature and current material, construction, and energy costs.

Scope

6. This report includes the results of the literature review, the results of the laboratory studies conducted to date, and preliminary cost estimates based on these results. In addition, a recommended treatment system for the regeneration wastewater is presented for consideration.

PART II: LITERATURE REVIEW

Chemical Processes

7. Most of the studies on chemical defluoridation of water were conducted in the 1930's and 1940's. More stringent Public Health Drinking Water Standards brought about a renewed interest in the late 1950's and 1960's. Recent emphasis upon the environment and industrial wastes disposal has again brought this topic up for further investigation in the past years.

8. Early studies of the removal of fluorides from water involved many different chemicals and chemical complexes. The more recent studies however, have confined themselves to those more promising chemicals and chemical complexes and the variation of aspects of the treatment process or to the sequence of process series. A literature survey of the area of fluoride reduction reveals that certain treatment processes and chemicals may be currently regarded as more applicable to full-scale systems. These are: (a) coagulation-precipitation, (b) ion-exchange, (c) adsorption, and (d) reverse osmosis.

9. Other processes which involved a series of these methods (i.e., lime treatment followed by two or more polyelctrolytes (Rabosky and Miller, 1974), or foam stripping (Wilson, 1977), or specialized mechanical patents (Gunnarsson, 1972; Kabara, 1978; Lee, 1975) were considered; however, these proved to be unsatisfactory for the treatment of this particular wastestream. This was due to the complexity of, or perceived operating difficulties associated with the treatment process, or the cost of the method.

Coagulation-precipitation

10. Although many compounds may be utilized to either form a coagulant or precipitate of the fluoride molecule, by far the more widely used are alum coagulation and lime treatment. Both of these processes involve the respective chemical complexations which result in the production of an insoluble fluoride complex that may be removed from the water as a sludge.

11. As with any type of chemical treatment process, the selection of one such process versus another is highly dependent upon the chemical characteristics of the wastestream itself. Studies have shown that the most effective pH range for lime treatment exists at pH 8-9 or above 12 (Paulson, 1977). This pH adjustment of the wastestream by lime is possible in a combination neutralization-precipitation step if the existing wastestream is acidic. However, consideration must also be given to other chemical constituents of the wastestream, the final discharge pH, and the total water treatment process to be performed. Rabosky and Miller (1974) stated that pH should not be the sole determining parameter in lime precipitation, due to the large amounts of hydroxyl ion required for corresponding pH increases at high pH levels.

12. Lime addition for the removal of fluoride was reported to be the most widely used method at high fluoride concentrations. Therefore, it should be given strong consideration as a candidate for the treatment of the regeneration water from the activated alumina column. However, the studies indicated that large amounts of lime would be necessary for adequate reduction of a highly concentrated fluoride wastestream. Stoichiometrically, 1.06 lb of calcium removes 1 lb of fluorides (Paulson, 1977). The required reaction time varied from 30 min (usual) to 24 hr depending upon the type of wastewater being treated. Lime addition generally reduced the fluoride concentration to 12-30 mg/ℓ. If greater reduction was desired, other processes were utilized.

13. Some correlation has been found between fluoride removal and magnesium hardness removal in the lime water softening process. The mechanism was determined to be adsorption of the fluoride ion onto the magnesium hydroxide floc formed (Finkbeiner, 1938; Maier, 1947 and 1958; Scott, 1937). Scott and his associates (1937) found the following relationship to hold for their work:

$$F_r = F_i - (0.07\ F_i \times \sqrt{Mg})$$

where

F_r = residual fluoride concentration

F_i = initial fluoride concentration

Mg = magnesium removed

If magnesium is not present in the water to be treated, (as in the case of the regeneration wastewater) it must be added to accomplish the desired fluoride reduction (Sorg, 1978). The requirement for supplementary addition of magnesium generally makes this process economically unfeasible. The addition of magnesium also results in additional sludge volume being formed (Lowder, 1971). Also, the resulting sludge is generally not as compact as sludge resulting from only lime addition.

14. Alum coagulation was first investigated as a means of defluoridation by Boruff (1934). Culp and Stoltenberg showed that 250 mg/ℓ of alum was required to bring about a reduction of fluoride levels to 3.6-1.5 mg/ℓ in groundwater. The addition of 350 mg/ℓ was required to reduce it to 1.0 mg/ℓ. They concluded that this method should not be overlooked for the treatment of soft, high-fluoride water supplies. The pH range required for this process was found to be 6.5 to 7.5. Exact chemical requirements are difficult to estimate, since various studies reported data which varied greatly with respect to raw-water pH, mixing, and commercial products utilized.

15. Alum is much more expensive than lime. Alum flocs are generally fluffy and often require flocculant aids (polyelectrolytes) to increase precipitation efficiency.

16. Coagulation-precipitation processes require process trains generally including chemical addition, rapid mix, slow mix for flocculation, precipitate settling, and dewatering. The process can be conducted in a batch or continuous mode. Sludge produced in the process must be ultimately disposed of. Such sludges can be landfilled as produced or can be stabilized or fixed prior to landfilling to minimize leaching of contaminants.

Ion-exchange

17. The most successful ion-exchange media for fluoride removal are bone char (natural), tricalcium phosphate (a synthetic bone char),

and activated alumina.* In the ion-exchange process, contact beds are packed with calcium phosphates or aluminum salts and fluoride in wastewater passing through these beds is removed as a result of the anion exchange properties of these salts.

18. Bone char (consisting principally of tricalcium phosphate) has been reported to have an exchange capacity of approximately 450 grains/cu ft (Savinelli and Black, 1958). Arsenic has also been found to be removed by bone char, but unlike fluoride, arsenic adsorption results in an irreversible alteration in the chemical structure of the bone char precluding regeneration and lowering the fluoride removal as the removal/regeneration cycle progresses (Bellack, 1971).

19. In the ion exchange process, the media becomes exhausted when most of the exchange sites are occupied by the ion being removed. At this time, the media must be replaced or regenerated. In most cases, replacement costs are high and therefore, regeneration techniques are used.

20. The ion-exchange processes are not generally used on wastewaters with high concentrations of fluorides. Also, since this study is concerned with the disposal of a regeneration waste, it is illogical to produce another one.

Adsorption

21. Potential adsorbents discussed in the literature include silica gel, activated carbon, Fuller's earth, bentonite, diatomaceous earth, and activated alumina. The adsorption of fluoride on these media generally require acidic environments. Activated carbon has been found to adsorb fluoride at a pH of 3.0 or below (McKee and Johnston, 1934).

22. As in ion-exchange processes, adsorption processes are not generally used on wastewater with high concentrations of fluoride. The various adsorption processes require regeneration or replacement upon exhaustion making them illogical choices for treatment of regeneration wastewater.

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* Activated alumina can also be considered an adsorptive process depending on regeneration techniques and wastestream pH.

Reverse Osmosis

23. There are various reverse osmosis membranes available commercially with some potential for applicability for fluoride removal. Little information on fluoride removal by reverse osmosis is available in the literature. However, one study did indicate that fluoride concentrations were lowered from 58.5 to 1.0 mg/ℓ (Sorg, 1978). It appears that the membranes operate best in a pH range of 5.5 to 7.0 where small volumes of brackish water are to be treated.

24. Suitable membranes are usually determined by a trial method. Many membranes are susceptible to fouling and must be occasionally backwashed. Reverse osmosis processes are generally expensive and used mainly in situations where contaminants cannot be removed by less expensive techniques. The reverse osmosis process results in a concentrated brine which must be disposed of.

Physical Processes

25. Physical processes found applicable to the regeneration wastewater were primarily evaporation and drying. These processes involve the addition of energy to change water from the liquid phase to the vapor phase. In a closed system, the water vapor can be condensed resulting in water which is virtually free of all nonvolatile contaminants. Evaporation and drying may be achieved using mechanical or solar processes.

Mechanical Evaporation

26. A variety of mechanical evaporators are available, however, the single effect and multi-effect designs are the most common in industrial applications (Blackburn, 1977). Energy requirements for evaporation can be altered by manipulating the pressure such that boiling occurs at a certain temperature.

27. As indicated, the nonvolatile impurities remain in the concentrated brine. Continued evaporation and concentration of this brine results in the saturation limits of the contaminants being reached and the formation of undesirable scale on the heat transfer units. Such

scale can be extremely hard and may require mechanical or chemical removal (Blackburn, 1977; _____, 1973). Therefore, evaporators are generally used to produce a concentrated brine. If additional drying is required, the brine is generally processed using a mechanical dryer, such as a spray dryer or drum dryer.

28. In a closed system, the water vapor from the evaporator can be recovered but not from the dryer. Mechanical evaporators and dryers are energy intensive operations and generally require a high level of maintenance. The concentrated brine from the evaporator or the salt from the dryer must be disposed of.

Solar Evaporation

29. Solar evaporation is generally feasible in regions having net evaporation rates of at least 20 in./year (Blackburn, 1977). In Denver, Colorado, the 50 percent exceeded net evaporation (exceeded in one-half the years in a study of the past 21 years) is 45.8 in./year (Appendix A). Thus, the climatological conditions in Denver are favorable for solar evaporation.

30. In the solar evaporation process, generally a lagoon or basin is constructed so as to maximize the surface area. Wastewater is discharged to the lagoon and allowed to evaporate. Evaporation can be enhanced by mechanical agitation. The lagoon or basin must be suitably constructed so as to prevent any leakage from the lagoon entering the environment. At appropriate times, the resulting sludge from the lagoon or basin must be removed and disposed of. Water evaporated during the process is lost and cannot be returned to the process cycle.

PART III: EVALUATION STUDIES

31. Based on the literature review, additional studies were conducted on those processes found to be applicable to the regeneration wastewater. These included laboratory studies and cost evaluations on coagulation-precipitation processes; cost evaluations on mechanical evaporation and drying processes; and size and cost evaluations on the solar evaporation process. These processes were compared based on costs, flexibility, and potential environmental impact to determine the most cost-effective process for treating the regeneration wastewater.

Coagulation-Precipitation

32. Several laboratory studies were conducted to determine the applicability of different coagulants generally used for fluoride removal based on chemical addition and coagulation-precipitation. The coagulant addition processes investigated included: lime addition, neutralization followed by lime addition, neutralization followed by alum-polymer addition, calcium chloride addition, neutralization followed by calcium chloride addition, and simultaneous calcium chloride addition and pH adjustment. A detailed discussion of the studies conducted follows.

Materials and Methods

33. Regeneration wastewater used in the study was produced during the first and third regeneration of the activated alumina column at RMA. Time constraints of the study program prevented the use of wastewater generated during later runs of the alumina column. During the regeneration procedure, the wastewater was collected in consecutive 50-gal volumes. A sample for analysis and a 1-gal sample for use in laboratory treatment studies were collected from each 50-gal volume. The samples for the laboratory studies were composited and transported to WES along with a portion of each individual sample collected for analysis from each 50-gal volume. Additional analyses of the regeneration wastewater samples beyond those done at RMA were conducted at WES. For informational

purposes, the WES analytical results on samples from the first, second, and third regenerations are presented in Tables 1-3. The data indicate that the wastewater from the first regeneration has a higher concentration of aluminum than wastewater from later regeneration cycles. This is a result of the charging of the column with virgin alumina prior to the first experimental run. It was found that upon allowing the samples to set, a white precipitate developed. This precipitate was predominant in samples from the first regeneration. The fluoride concentration tended to vary with the amount of precipitate formed indicating that fluoride ions were being incorporated into or adsorbed upon the aluminum hydroxide precipitate.

34. The coagulation-precipitation studies were conducted using standard jar test procedures. The samples to be tested were placed in 2-ℓ beakers under a six-place gang stirrer. The appropriate chemicals were then added. All samples were then rapidly mixed for 1 to 2 min, followed by a slow mix period of 10 min and then allowed to settle for a minimum of 30 min. A sample for analysis was carefully removed from each beaker after the appropriate settling period so as to prevent the introduction of any precipitated material to the sample. Fluoride analyses were conducted using an Orion specific ion electrode for fluoride. A buffer solution, TISAB IV (as recommended by Orion), was added to each sample prior to analysis to prevent interference by the aluminum ions remaining in solution. Other analyses were conducted using procedures recommended in Standard Methods.

Precipitation with Lime Only

35. Laboratory precipitation studies using hydrated lime only were conducted on wastewater samples from the first regeneration. The results are presented in Table 4 and illustrated in Figure 1. A lime dose of 4000 mg/ℓ was required to reduce the fluoride concentration to 20 ppm from an initial concentration of 66 ppm. Lime addition in excess of 4000 mg/ℓ produced little additional removal of fluoride. Based on the results of these studies, a residual fluoride concentration of 20 ppm was taken as a reference concentration for comparison with other coagulation-precipitation processes. Comparable chemical cost data were developed on this basis.

Table 1

Analysis of Regeneration Wastewater from Activated Alumina Column

Sample No.	pH	Alkalinity (ppm as $CaCO_3$) P	Alkalinity (ppm as $CaCO_3$) Total	F (ppm)	Al (ppm)	B (ppm)	TOC (ppm)
1-U	8.1	----	500	17.7	29.0	0.450	45
2-U	10.7	1450	1750	218	625	0.674	200
3-U	11.1	2275	3475	245	520	0.621	160
4-U	10.9	975	1825	157	205	0.440	62
5-U	10.7	650	1425	102	205	0.389	25
6-U	10.4	450	925	72.8	64.5	0.311	
7-U	10.3	325	725	53.9	40.5	0.285	
8-U	10.3	250	625	41.9	30.0	0.280	
9-U	10.0	200	550	33.3	22.5	0.255	
10-U	9.6	150	550	27.8	14.0	0.259	
11-U	9.4	175	500	23.9	14.0	0.272	
12-D	10.0	175	550	24.5	11.0	0.280	
13-D	11.2	4175	6250	308	1950	2.28	
14-D	12.6	7725	9075	186	2050	1.21	
15-D	12.3	1975	2350	28.7	520	0.330	
16-D	12.0	950	1200	4.86	100	0.155	
17-D	11.8	650	875	4.28	66.5	0.117	
18-D	11.6	500	775	3.82	49.0	0.116	
19-D	11.5	450	675	3.38	31.5	0.092	
20-D	11.3	375	600	2.97	22.5	0.086	
21-D	11.2	325	575	2.56	17.0	0.100	
22-D	11.0	325	550	2.20	11.5	0.087	
23-D	10.9	300	500	1.84	8.0	0.088	
24-D	10.4	425	650	1.51	3.0	0.093	
25-D	10.2	175	425	1.25			

Table 2

Analysis of Wastewater from Regeneration No. 2

Sample No.	Parameters		
	Al, mg/ℓ	B, mg/ℓ	TOC, mg/ℓ
1	--	--	--
2	205	0.602	102
3	262	0.580	95.5
4	103	0.431	49.0
5	62.3	0.375	21.0
6	41.1	0.329	9.5
7	32,8	0.275	
8	17.4	0.281	
9	12.9	0.250	
10	10.5	0.247	
11	9.6	0.242	
12	8.8	0.238	
13	8.2	0.229	
14	7.9	0.224	
15	1250	1.95	
16	525	0.981	
17	87.7	0.202	
18	--	--	
19	25.8	0.081	
20	17.6	0.068	

Table 3

Analysis of Wastewater from Regeneration No. 3

Sample No.	Parameters		
	Al, mg/ℓ	B, mg/ℓ	TOC, mg/ℓ
1	37.7	0.382	42.0
2	105	0.525	93.5
3	168	0.584	86.0
4	75.8	0.463	40.0
5	43.3	0.390	17.0
6	24.0	0.332	8.0
7	15.3	0.299	
8	8.9	0.277	
9	6.6	0.258	
10	5.9	0.242	
11	4.8	0.231	
12	3.6	0.228	
13	3.1	0.226	
14	2.7	0.225	
15	2.4	0.229	
16	915	1.7	
17	383	0.641	
18	58.6	0.174	
19	27.8	0.090	
20	18.9	0.075	

Table 4

Regeneration Wastewater Treatment - Lime Precipitation

Lime Dosage* Percent Excess of Stoichiometric Dose	mg/ℓ	Residual F^-, ppm	Final pH After Lime
0	1300	49	12.1
62	2100	48	12.3
100	2600	39	12.3
200	3900	21	12.4
300	5200	21	12.5
400	6500	21	12.5
500	7800	19	12.5
545	8400	18	12.5

Note: Initial F^- = 66 ppm, pH = 10.6, and total alkalinity = 1800 mg/ℓ as $CaCO_3$.
* Hydrated lime.

36. Chemical requirements and costs for each process were calculated on a per day basis although the alumina columns will not be regenerated every day. The alumina column study indicated that regeneration wastewater will be produced at a rate of approximately 2 percent of the influent raw water to the alumina columns. Based on an estimate of 600 gpm influent flow, approximately 17,280 gpd of regeneration wastewater will be produced.

37. The daily lime requirement for the lime only process based on the above flow was calculated as follows:

$$(4{,}000\ \text{mg}/\ell)\left(\frac{\text{gm}}{1{,}000\ \text{mg}}\right)\left(\frac{\text{lb}}{453.6\ \text{gm}}\right)(17{,}280\ \text{gpd})\ (3.785\ \ell/\text{gal}) = 577\ \text{lb/day}$$

Using commercial lime with a purity of 99.6 percent as $Ca(OH)_2$, the amount of commercial lime required would be 579 lb/day. At a cost of $56 per ton (based on available vendor information), the cost would be

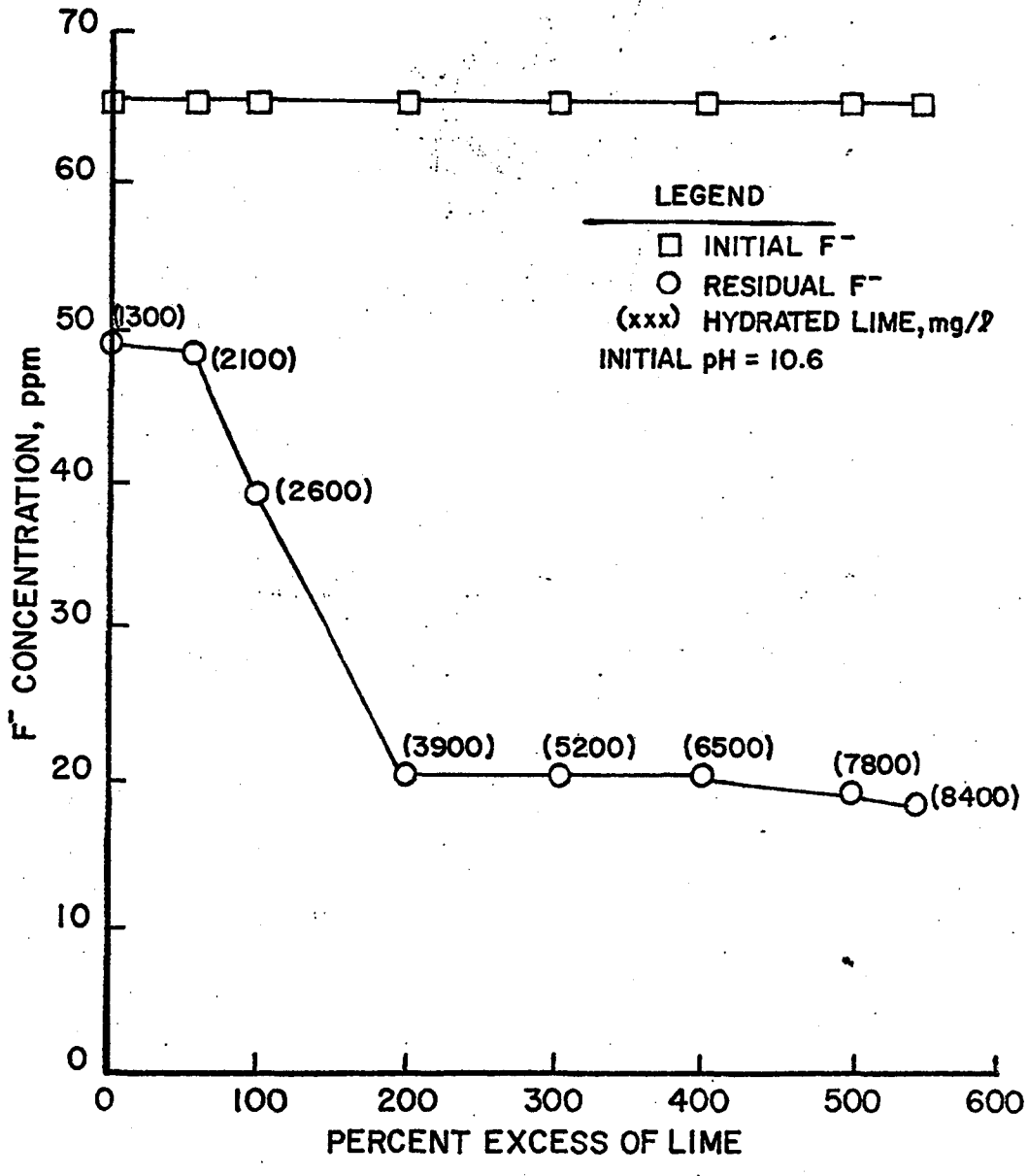


Figure 1. Treatment of regeneration wastewater with lime

$16.20 per day. This can also be expressed as $0.94 per 1000 gal of regeneration wastewater treated or as $0.019 per 1000 gal of raw influent water to the alumina column.

Lime Addition After Neutralization

38. Since high doses of hydrated lime were required to significantly reduce the fluoride concentration in the regeneration wastewater, an investigation was conducted on the effect of reducing the alkalinity of the wastewater by sulfuric acid addition. The initial study was conducted on wastewater from the first regeneration. First, jar tests were conducted using sulfuric acid only. A white aluminum hydroxide precipitate formed upon the addition of acid. Samples were collected after the precipitate settled and fluoride analyses were conducted. The results are presented in Figure 2 expressed as residual fluoride concentration versus pH. The greatest reduction in fluoride concentration (to 20 ppm) occurred in a narrow pH range between 6 and 7. This is also the range of minimum solubility of aluminum hydroxide which is amphoteric. Therefore, the fluoride ions were probably being incorporated into or absorbed upon the aluminum hydroxide precipitate.

39. As a result of this investigation, additional studies were conducted to determine the effect of lime addition after neutralization. It was found that the residual fluoride concentration in the water standing above the aluminum hydroxide precipitate tended to increase with time. For this reason and to prevent resolubilization of the aluminum hydroxide, the water was decanted immediately after the aluminum hydroxide precipitate settled. Jar tests were then conducted on this water using lime addition.

40. Initially, wastewater from the first regeneration was dosed with hydrated lime based on the residual fluoride concentration. The results of the test are presented in Table 5 and illustrated in Figure 3. As indicated, the lime addition resulted in little additional fluoride concentration reduction.

41. The test was repeated using lime doses based on the residual alkalinity after neutralization. The results of the test are presented in Table 6 and illustrated in Figure 4. In this test, much higher doses

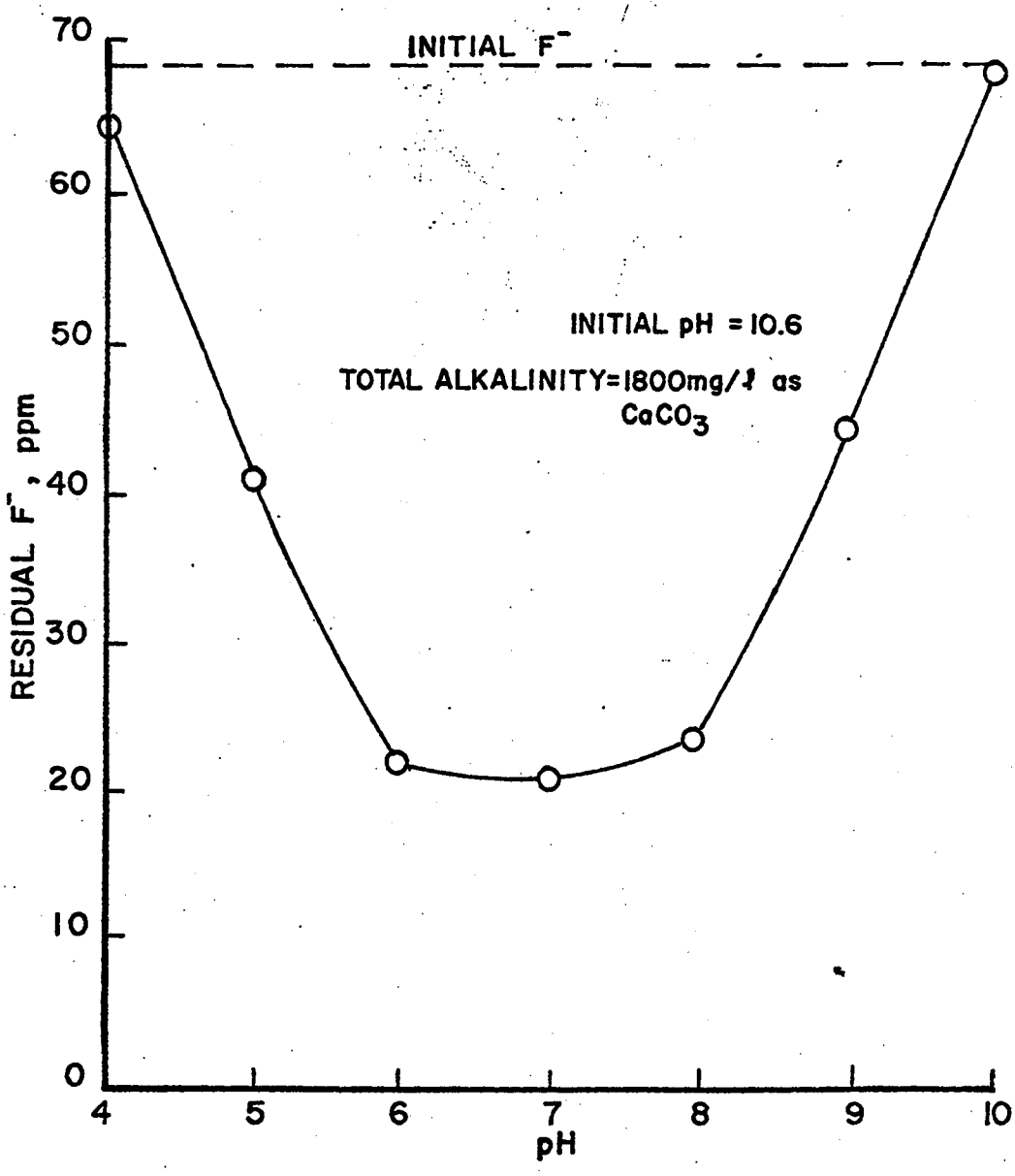


Figure 2. Fluoride reduction by neutralization with H_2SO_4

Table 5

Regeneration Waste Treatment - Lime* Addition

Following Neutralization to pH 6.5

Lime Dosage, mg/ℓ*	F^- at pH 6.5 ppm	Residual F^-, ppm	Final pH After Lime
30	15.4	15.1	8.6
135	16.8	15.5	9.5
160	16.0	15.3	9.6
190	15.7	15.3	9.6
270	15.8	15.0	10.2
350	15.7	14.9	10.6

Note: Initial fluoride = 67 ppm and pH = 11.2.
* Hydrated lime based on F^- levels at pH 6.5.

Table 6

Regeneration Waste Treatment - Lime* Addition

Following Neutralization to pH 6.5

Lime Dosage				
% Excess	mg/ℓ	F^- at pH 6.5 ppm	Residual F^-, ppm	Final pH After Lime
0	210	16	13.5	9.9
400	1050	18.6	11.6	11.9
800	1890	14.9	10.9	12.0
1000	2310	15.0	10.1	12.1
1500	3360	14.6	9.3	12.1
2000	4400	15.1	10.0	12.1

Note: Initial fluoride = 61 ppm, pH = 11.5 and total alkalinity = 1625 mg/ℓ as $CaCO_3$.
* Hydrated lime based on residual alkalinity at pH 6.5.

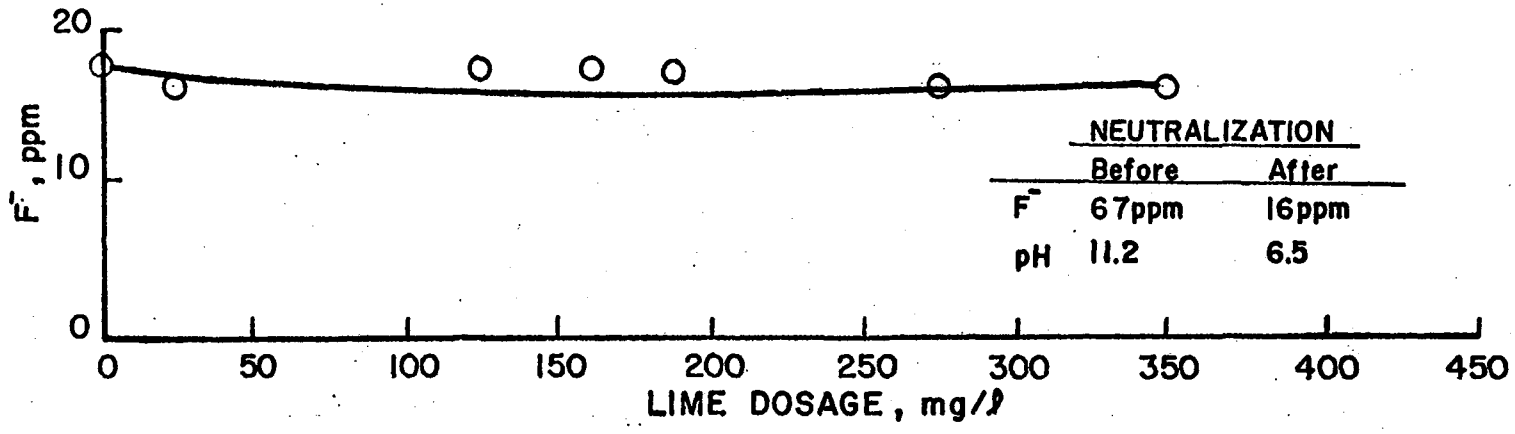


Figure 3. Treatment of regeneration wastewater - Neutralization followed by lime
(Lime dosage based on F^- level after neutralization)

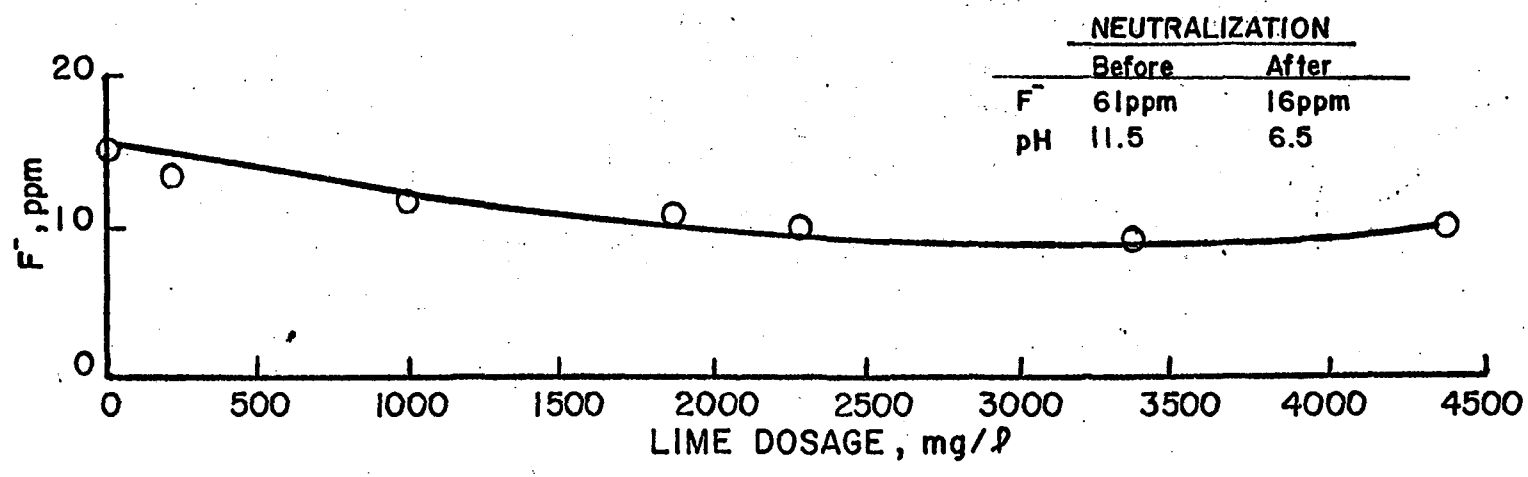


Figure 4. Treatment of regeneration wastewater - Neutralization followed by lime
(Lime dosage based on alkalinity after neutralization)

of lime were used than in the previous test. The residual fluoride concentration was reduce to as low as 9.3 ppm.

42. Since a residual fluoride concentration of 20 ppm was achieved with the addition of sulfuric acid only, chemical requirements and costs were calculated for sulfuric acid only. Based on 17,280 gpd of regeneration wastewater, the sulfuric acid (66°Be H_2SO_4 with 93.2 percent purity) requirement using a 1.5 g/ℓ dose was calculated as follows:

$$(1.5\ g/\ell)\left(\frac{lb}{453.6\ gm}\right)\ (17{,}280\ gpd)\ (3.785\ \ell/gal)\ \left(\frac{1}{0.932}\right)$$

$$= 232\ lb/day$$

Using a bulk cost of $60 per ton, the total cost was calculated to be $7.00 per day. This can also be expressed as $0.40 per 1000 gal of regeneration wastewater treated or as $0.008 per 1000 gal of raw influent water to the alumina column.

43. The aluminum concentration in the wastewater from the first regeneration was higher than in wastewater from later regenerations. Since the initial aluminum concentration affected fluoride removal in this process, an additional test was conducted using wastewater from the third regeneration. The initial fluoride concentration in this wastewater was 101 ppm. The fluoride concentration was reduced to 73 ppm by acid neutralization to a pH of 6.5. Lime was then added in various doses to the decanted water. The results of this study are presented in graphical form in Figure 5. A lime dose of 2500 mg/ℓ was required to reduce the fluoride concentration to 20 ppm. The residual fluoride concentration continued to decrease somewhat with increasing lime dosage.

44. Chemical requirements and costs were calculated on the basis of a 20 ppm residual fluoride concentration as follows:

a. Sulfuric Acid -

$$(1.5\ g/\ell)\left(\frac{lb}{453.6\ gm}\right)\ (17{,}280\ gpd)\ (3.785\ \ell/gal)\ \left(\frac{1}{0.932}\right)$$

$$= 232\ lb/day\ @\ \$60\ per\ ton = \$7.00\ per\ day$$

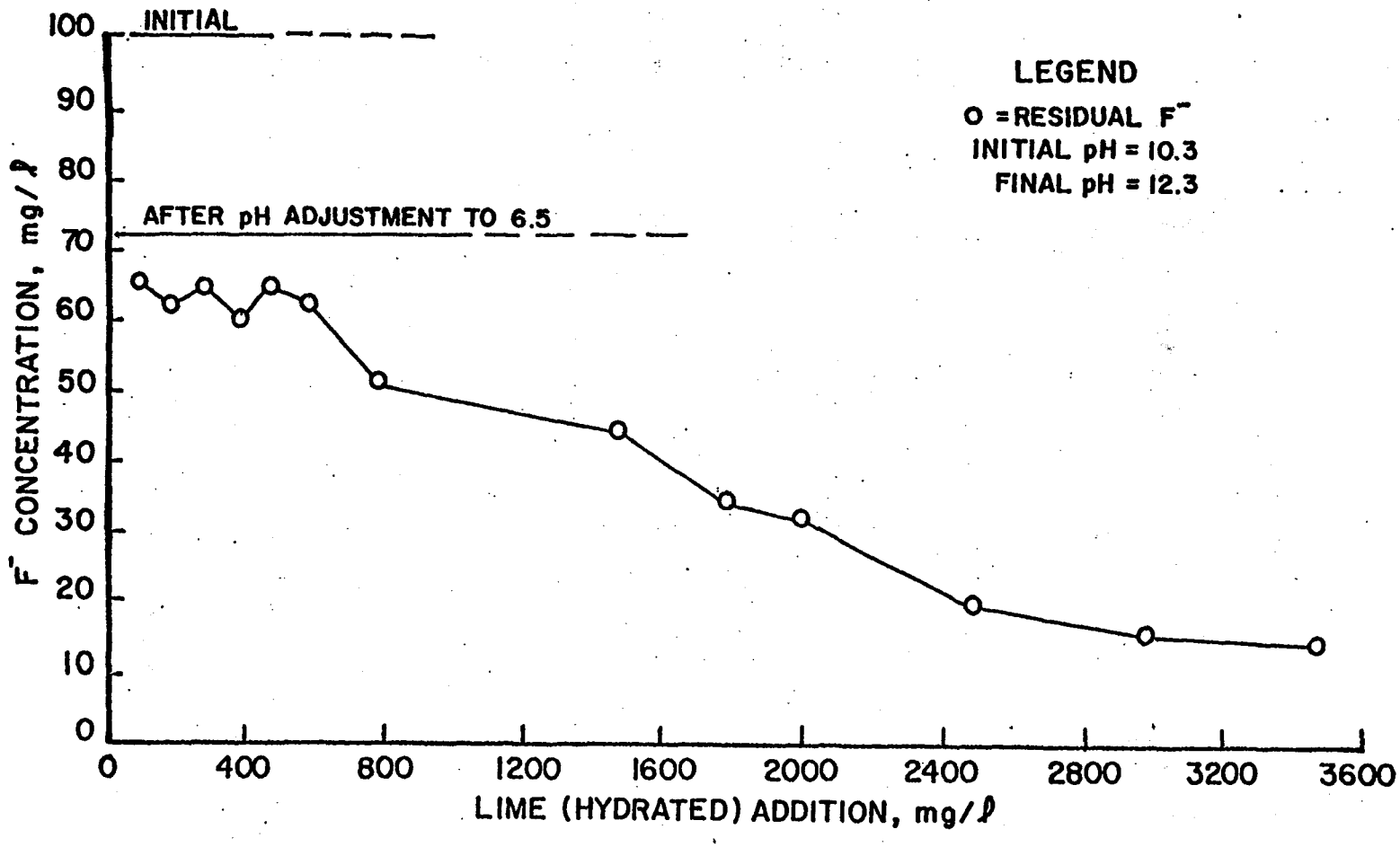


Figure 5. Residual fluoride concentration following pH adjustment, decantation, and lime addition

b. Lime -

$$(2.5\ \text{gm}/\ell)\left(\frac{1\text{b}}{453.6\ \text{gm}}\right)\ (17{,}280\ \text{gpd})\ (3.785\ \ell/\text{gal})\left(\frac{1}{0.932}\right)$$

$$= 362\ \text{lb/day @ \$56 per ton} = \$10.10\ \text{per day}$$

This total cost is therefore $17.10 per day. This can also be expressed as $0.99 per 1000 gal of regeneration wastewater treated or as $0.02 per 1000 gal of raw influent water to the alumina column.

Neutralization Followed
by Alum/Polymer Addition

45. Laboratory precipitation studies using neutralization followed by alum and polymer addition were conducted on wastewater samples from the first regeneration. The samples were first neutralized to pH 7 with sulfuric acid. The aluminum hydroxide formed was allowed to settle and the decanted water was then dosed with alum and a polymer (Magnifloc 577C). Alum was added in doses from 0 to 1600 mg/ℓ while the polymer dosage was held constant at 5 mg/ℓ. The results of the test are presented in Figure 6. Alum doses of over 400 mg/ℓ tended to reduce the pH which resulted in higher fluoride residual concentrations with increasing dosages. Therefore, the addition of alum is limited to this dose unless additional measures are taken to control the pH.

46. Using wastewater from the first regeneration, an alum dose of 400 mg/ℓ resulted in a residual fluoride concentration of 9 ppm. As in the previous study, neutralization of the wastewater from the first regeneration resulted in a significant fluoride concentration reduction down to below 20 ppm. Therefore, the alum/polymer addition produced a reduction in fluoride of approximately 10 ppm. Since the study indicated that alum addition in excess of 400 mg/ℓ resulted in a decrease in fluoride removal and since polymer addition was required as a coagulant aid, the requirements and costs for both of these chemicals were calculated even though the residual fluoride concentration was well below 20 ppm. The chemical requirements and costs were calculated as follows:

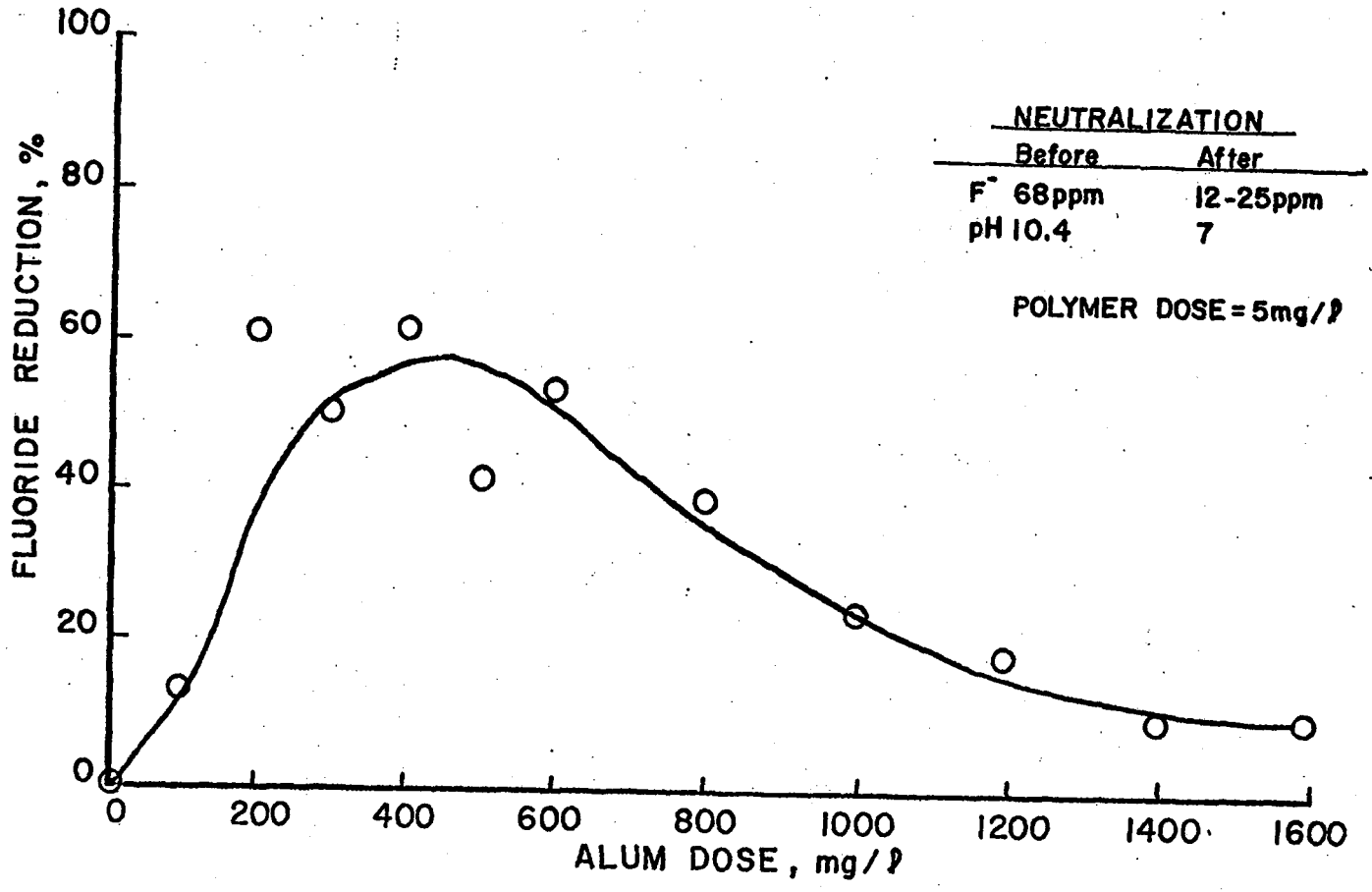


Figure 6. Treatment of regeneration wastewater - Neutralization and alum-polymer addition

a. Sulfuric acid -

$$(1.5\ g/\ell)\left(\frac{lb}{453.6\ gm}\right)(17{,}280\ gpd)(3.785\ \ell/gal)\left(\frac{1}{0.932}\right)$$

$$= 232\ lb/day\ @\ \$60\ per\ ton = \$7.00\ per\ day$$

b. Alum -

$$(0.4\ gm/\ell)\left(\frac{lb}{453.6\ gm}\right)(17{,}280\ gpd)(3.785\ \ell/gal) = 58\ lb/day$$

58 lb/day @ $15 per 100 lb = $8.70 per day

c. Polymer -

$$(0.005\ gm/\ell)\left(\frac{lb}{453.6\ gm}\right)(17{,}280\ gpd)(3.785\ \ell/gal) = 0.7\ lb\ day$$

0.7 lb/day @ $0.80 per 1 lb = $0.60 per day

The total cost is therefore $16.30 per day. This can also be expressed as $0.94 per 1000 gal of regeneration wastewater treated or as $0.019 per 1000 gal of raw influent water.

Calcium Chloride Addition

47. Due to the low solubility of lime at the high pH, characteristic of the regeneration wastewater, a study was initiated using a more soluble calcium salt; hydrated calcium chloride. The initial tests were conducted on wastewater from the third regeneration using calcium chloride only. Calcium chloride was added to the wastewater in doses ranging from 750 to 2500 mg/ℓ. The results of this test are presented in Figure 7. The addition of 2500 mg/ℓ of calcium chloride resulted only in a reduction of fluoride concentration from 101 ppm to 51 ppm. Addition of calcium chloride at higher doses was deemed impractical based on previous tests using lime addition. Calcium chloride costs at that point were approaching those calculated for lime addition after neutralization. Therefore the study was terminated.

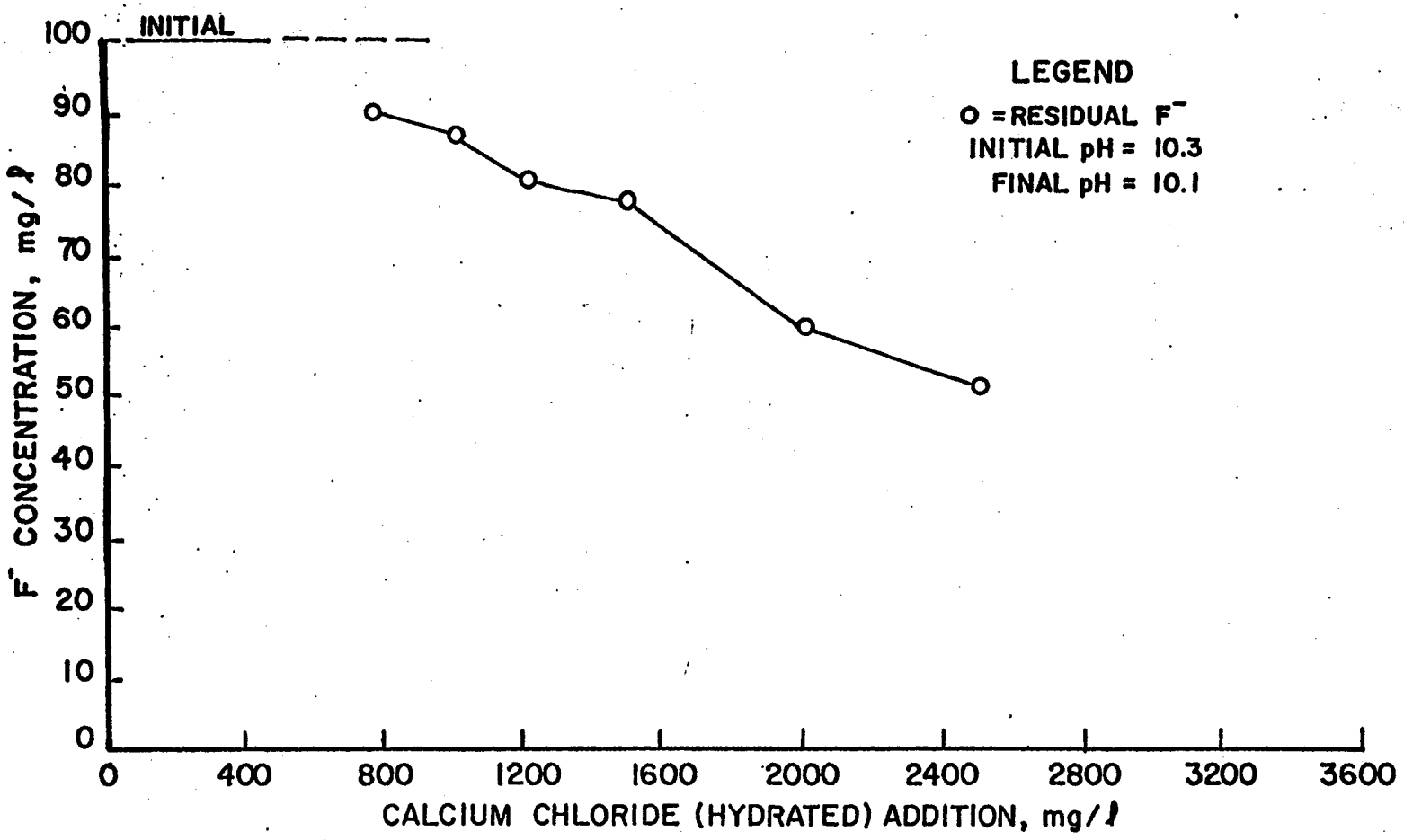


Figure 7. Residual fluoride concentration following calcium chloride addition

Calcium Chloride
Addition After Neutralization

48. As a result of the success of previous tests using lime addition following neutralization, a test was conducted using calcium chloride addition after neutralization. Sulfuric acid was added to wastewater from the third regeneration and the aluminum hydroxide precipitate formed was allowed to settle. The fluoride concentration was found to be 73 ppm after neutralization. The decanted water was then dosed with calcium chloride in a range from 100 to 1600 mg/ℓ. The results of this test are presented in Figure 8. A dose of 1600 mg/ℓ resulted in a residual fluoride concentration of 44 ppm. Upon comparing this data with that from the previous lime addition study (Figure 5), it was found that calcium chloride addition produced no better results than did lime addition. Since calcium chloride is more expensive than lime, and no additional justification for calcium chloride use was found, the study was terminated.

Calcium Chloride
Addition with pH Adjustment

49. Since aluminum hydroxide precipitation upon neutralization resulted in a significant reduction in fluoride concentration, and calcium fluoride precipitation upon the addition of excess calcium resulted in a reduction in the residual fluoride concentration, it was decided to investigate the potential for these two reactions occurring simultaneously. Therefore a study was initiated on wastewater from the third regeneration using calcium chloride addition followed immediately by pH adjustment to 6.5 with sulfuric acid. This eliminated the need for an intermediate decantation step in the process. The wastewater was dosed with calcium chloride in a range from 100 to 3500 mg/ℓ followed by sulfuric acid addition until the pH reached 6.5. The wastewater was then rapidly mixed, followed by a slow-mix period for precipitate formation, and finally the precipitate was allowed to settle.

50. The results of the study are presented in Figure 9. The fluoride concentration was reduced from 101 to 50 ppm upon the addition of 100 mg/ℓ of calcium chloride. The plot of fluoride concentration

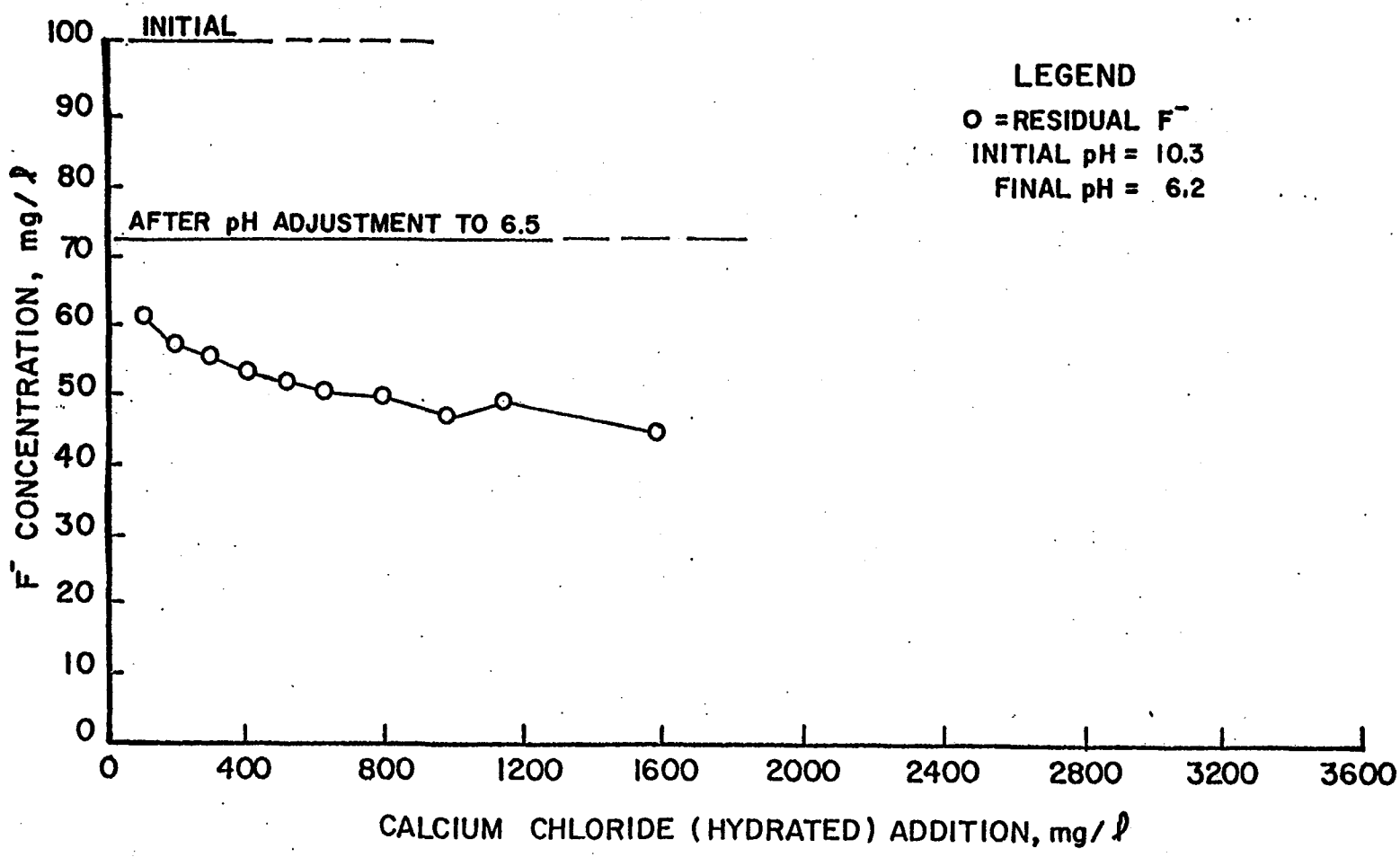


Figure 8. Residual fluoride concentration following neutralization, decantation, and calcium chloride addition

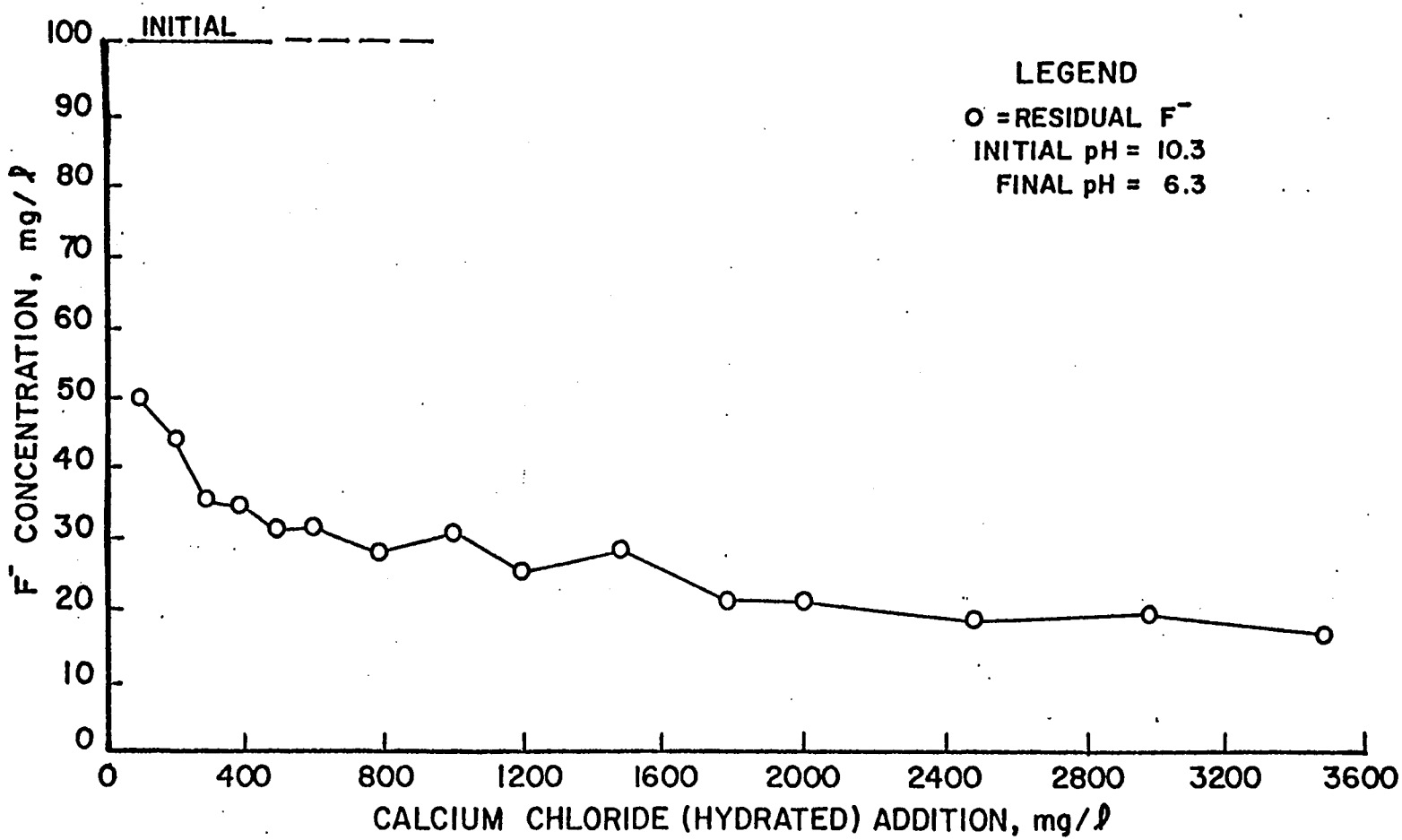


Figure 9. Residual fluoride concentration following calcium chloride addition, pH adjustment

versus calcium chloride dose decreases rapidly to a flouride concentration of 30 ppm at 600 mg/ℓ of calcium chloride. The slope of the plot then increases (from a negative value) and becomes more gradual. A calcium chloride dose of 1800 mg/ℓ resulted in a residual fluoride concentration of 20 ppm. The lowest fluoride residual found was 15 ppm at a calcium chloride dose of 3500 mg/ℓ. Upon comparing these results with the data from the tests using lime addition following neutralization, it was found that the calcium chloride process was more efficient with respect to chemical addition than was the lime addition process.

51. Chemical requirements and costs were calculated as follows:

a. Calcium chloride -

$$(1.8\ \text{gm}/\ell)\left(\frac{1\text{b}}{453.6\ \text{gm}}\right)(17{,}280\ \text{gpd})(3.785\ \ell/\text{gal})\left(\frac{1}{0.98}\right) = 265\ \text{lb/day}$$

265 lb/day @ $80 per ton = $10.60 per day

b. Sulfuric acid -

$$(1.3\ \text{gm}/\ell)\left(\frac{1\text{b}}{453.6\ \text{gm}}\right)(17{,}280\ \text{gpd})(3.785\ \ell/\text{gal})\left(\frac{1}{0.932}\right) = 201\ \text{lb/day}$$

201 lb/day @ $60 per ton = $6.00 per day

The total cost is $16.60 per day. Expressed on a per 1000 gal basis, this would be $0.96 per 1000 gal of regenerated wastewater treated or $0.019 per 1000 gal of raw influent water to the alumina column.

Discussion of Results

52. The coagulation-precipitation studies were conducted on wastewater from the first and third regenerations of the alumina column. It was found that fluoride removal from the wastewater could be enhanced by precipitating the aluminum in the wastewater as aluminum hydroxide in a pH range between 6 and 7. Fluoride ions are either incorporated into or adsorbed onto the precipitate and thus removed. The optimum treatment processes are those that utilize this effect along with calcium fluoride precipitation for fluoride removal.

53. Since the aluminum concentration was higher in wastewater from the first regeneration than would normally be found in wastewater from later regenerations, the results from the tests conducted on wastewater from the third regeneration should be considered more typical. The results of these studies indicate that two processes, neutralization followed by lime addition and calcium chloride addition with pH adjustment, are effective and have associated with them comparable low chemical costs with respect to the other process evaluated. The use of the calcium chloride process instead of the lime process would eliminate the need for an intermediate decantation step which would result in lower capital and operating costs. Otherwise, the two process would require the same equipment train. In addition, the lower chemical requirements of the calcium chloride process would result in less sludge being produced and therefore the cost of sludge treatment and disposal would be less. As a result, the process using calcium chloride addition with pH adjustment was judged to be the most cost-effective. Hence, additional process design calculations were made using the results of the calcium chloride process study.

54. The calculations and conclusions presented in this report are based on the results of limited laboratory studies. Coagulation-precipitation process efficiencies are often significantly affected by the chemical characteristics of the wastewater. If the characteristics of the wastewater from later regenerations vary from those found in this investigation, the results of these process studies should be verified using the more typical wastewater.

Sludge Production

55. Sludge volume production requiring disposal was estimated on the basis of aluminum hydroxide precipitation, and fluoride removal as a result of both co-precipitation with aluminum hydroxide and calcium fluoride precipitation. The sludge produced on a dry weight basis was calculated as follows:

a. Aluminum hydroxide - 35 lb/day

b. Fluoride ion - 5 lb/day

c. Calcium fluoride - 16 lb/day

d. Others - 4 lb/day

The total sludge production for a wastewater flow of 17,280 gpd is 60 lb/day. Assuming that the sludge concentrates 1.5 percent by weight and assuming a specific gravity of 1.0, the total volume for disposal was found to be 480 gpd.

Recycle of Treated
Regeneration Wastewater

56. The use of a coagulation-precipitation process would allow for the recycle of much of the regeneration wastewater back to the groundwater treatment system. The use of pH adjustment in the calcium chloride process produces an effluent with a pH near that of the groundwater. The supernatant from the clarifier used in the process could be recycled to the head-works of the groundwater treatment system where the multi-media filters would remove any residual precipitate. The recycle of the supernatant would result in an increase in the overall fluoride concentration in the influent water. This increase was calculated as follows:

$$600(3.4) + 0.02(600)(20) = [600 + 0.02(600)]\ x$$

$$x = 3.73 \text{ ppm}$$

where

3.4 ppm = fluoride concentration in the groundwater

20 ppm = fluoride concentration in the effluent from the regeneration wastewater treatment process

600 gpm = flow rate through the treatment system

2 percent or 0.02 = quantity of regeneration wastewater produced expressed as percentage of total flow

x = resulting fluoride concentration in influent

This represents a small increase of 0.33 ppm in fluoride concentration.

57. The present reduction in total flow time before exhaustion of the column due to the increased fluoride concentration was determined by setting equal the total amount of fluoride that can be removed by the alumina bed as follows:

$$3.4(600)(T) = 3.73\ [600 + 0.02(600)]\ (T - t)$$

where

T = flow time before regeneration at a fluoride concentration of 3.4 ppm

t = reduction in flow time

Solving:

$$t = 0.106T \text{ or } 10.6 \text{ percent}$$

Therefore, the increase in fluoride concentration in the influent due to recycle of the treated regeneration wastewater will result in a 10.6 percent reduction in the flow time before exhaustion of the alumina bed.

Mechanical Evaporation

58. As stated previously, no studies were conducted on the applicability of various types of mechanical evaporation processes to the regeneration wastewater. The information presented in this report was obtained from the literature. A review of the literature indicated that wastewater with characteristics similar to the regeneration wastewater had been successfully processed using mechanical evaporation equipment. The particular type of equipment used was found to vary. For purposes of this report, three types of evaporators were considered. Energy requirements (Blackburn, 1977) and costs for the evaporators are presented in Table 7. Since evaporators are not generally used to remove all the water from a wastestream, the energy costs were calculated on the basis of evaporation of 95 percent of the wastewater in the evaporator. The rest of the water would be removed in a dryer such as spray dryer or drum dryer.

59. Energy requirements for spray dryers range from 250-3500 KWh/1000 gal (Perry and Chilton, 1973). Using the scenario indicated above where 95 percent of the water is removed by the evaporator and 5 percent by a spray dryer, a calculation of total energy requirements and cost

Table 7

Energy Requirements and Costs for Evaporators

Type	Energy Required	Form of Energy	Cost/Day*
Multi-stage flash	90-420 kwh/1000 gal	Steam	$75-$345
Multi-effect	100-699 kwh/1000 gal	Steam	$85-$495
Vapor compression	75-90 kwh/1000 gal	Electrical	$62-$75

* Based on 95 percent of 17,280 gpd with an energy cost of $0.05/kwh.

Table 8

Total Minimum Energy Requirements and Costs for Mechanical Evaporation

Process	Energy Required	Cost/Day
Evaporation of 95 percent of water by vapor compression	1300 kwh	$65
Evaporation of 5 percent of water by spray dryer	250 kwh	$15
Total	1550 kwh	$80

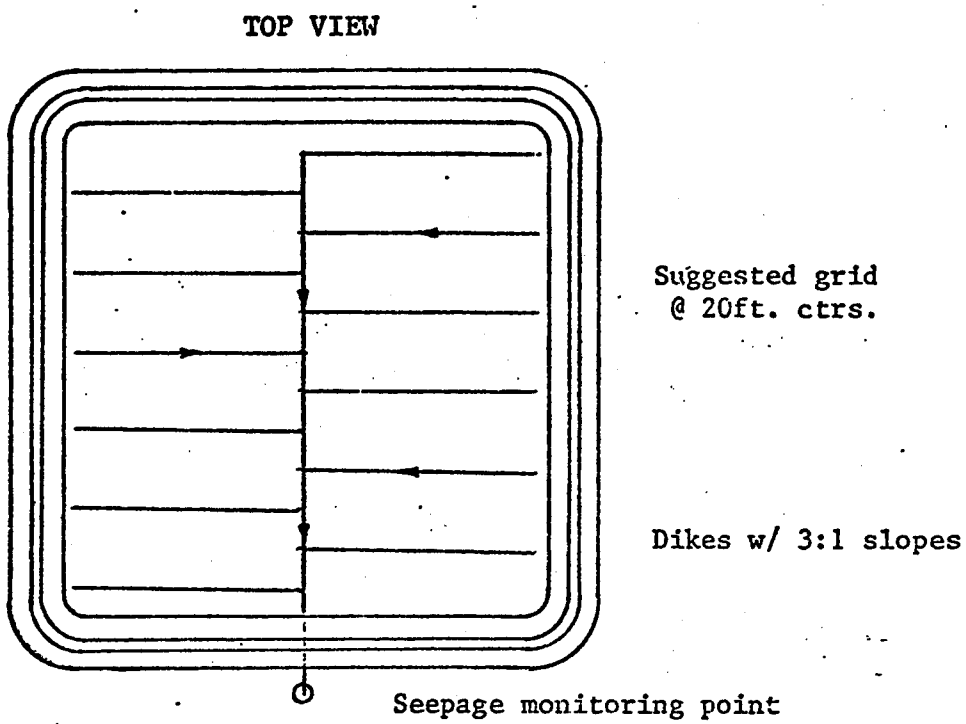
was made using a flow of 17,280 gpd, minimum energy requirements, and an energy rate of $0.05/KWh. The results are presented in Table 8. Capital and operating costs will be presented later in this report.

60. The condensate from the evaporator would be essentially free of contamination and could be discharged to the effluent stream from the groundwater treatment system at RMA. Water vapor from the dryer would be lost to the atmosphere. The salt from the drying process could be stored or disposed of in a landfill. Pretreatment of the salt (i.e. fixation) prior to landfilling would probably be required since the salt has a high potential for leaching due to its solubility.

Solar Evaporation

61. A preliminary design for an evaporative lagoon for disposal of the regeneration wastewater was developed using information from the literature and climatological data for the Denver area (1979). This lagoon would be constructed at RMA. The lagoon design incorporates a double liner as specified in proposed Federal regulations to prevent leakage and contamination of the groundwater under the site. Capital and operating costs for the evaporative lagoon will be presented later in this report.

62. The proposed lagoon design is presented in Figure 10. The double-lined lagoon would have a primary liner of polyvinyl chloride or hypalon followed by a secondary liner of clay at least 5 ft thick with a permeability of not greater than 10^{-7} cm/sec. If a suitable source of clay is not available, the lower liner could also be constructed of the same artificial material as the top liner. In addition, the design includes a network of 4-in. perforated PVC pipes (drains) surrounded by gravel located between the liners which drain to a common location outside the lagoon dike perimeter. This serves as a monitor of the integrity of the top liner. The artificial liner is placed on a bed of sand which acts as a cushion to prevent damage to the liner. The dikes are also lined to prevent seepage through them.



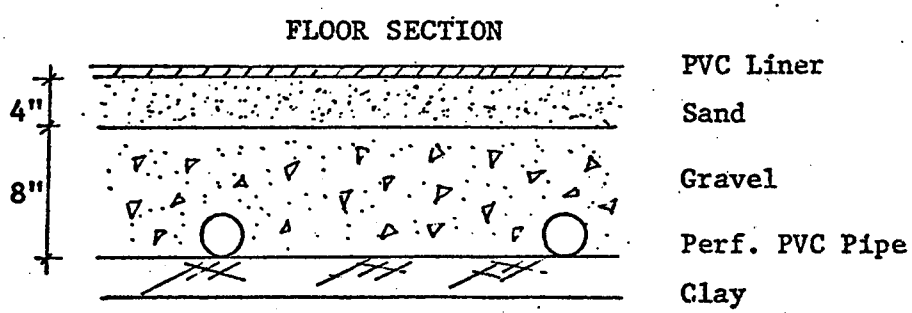


Figure 10. Idealized evaporative lagoon

Lagoon Size

63. Using a regeneration wastewater flow of 17,280 gpd and a net evaporation of 45.77 in./year (50 percent exceeded, Table A1), the required surface area was calculated as follows:

a. Inflow volume = (17,280 gpd)(0.1337 ft^3/gal)(365 days/year) = 843,000 ft^3/year.

b. Net evaporation = 45.77 in./year = 3.81 ft/year.

c. Required surface area = (843,000 ft^3/year)/(3.81 ft/year).
= 221,300 ft^2
= 5 acres

d. Dimensions of lagoon = $(221{,}300\ ft^2)^{1/2}$ = 471 ft

Therefore, a square lagoon 471 by 471 ft would provide the required surface area.

64. The lagoon storage requirements for the winter months when inflow exceeds net evaporation were calculated on the basis of 50 and 90 percent exceeded net evaporation. For 50 percent exceeded net evaporation (Table 9):

a. (24.51 percent)(17,280 gpd)(365 days/year)
= 1,546,000 gal/year.

b. Depth required = (206,700 ft^3/year)/(221,300 ft^2)
= 0.93 ft/year.

Providing a lagoon capacity for five consecutive years of 50 percent exceeded net evaporation, the required lagoon depth would be:

(5 years)(0.93 ft/year) + 3 ft [freeboard] = 7.7 ft

Therefore, use a lagoon depth of 8 ft. For 90 percent exceeded net evaporation (Table 10):

a. (50.36 percent)(17,280 gpd)(365 days/year)
= 3,176,000 gal/year.

b. Depth required = (424,700 ft^3/year)/(221,300 ft^2)
= 1.92 ft/year.

Providing a lagoon capacity for five consecutive years of 90 percent exceeded net evaporation, the required lagoon depth would be:

(5 years)(1.92 ft/year) + 3 ft [freeboard] = 12.6 ft

Table 9

Lagoon Storage Requirements - 50 Percent Exceeded

Month (1)	Backwash Water Production (2)	Evaporation -Precipita. 50 Percent Exceeded* (3)	Backwash - Net of Evap & Preci. (2) - (3) (4)	Lagoon Storage Required (5)
November	8.2**	5.06	3.14	3.14
December	8.47	5.50	2.97	6.11
January	8.47	2.81	5.66	11.77
February	7.92	3.05	4.87	16.64
March	8.47	3.34	5.13	21.77
April	8.2	5.46	2.74	24.51
May	8.47	8.52	-0.05	24.46
June	8.2	2.89	-4.69	19.77
July	8.47	15.29	-6.82	12.95
August	8.47	16.12	-7.65	5.30
September	8.2	12.08	-3.88	1.12
October	8.47	9.83	-1.36	0.06

* See Table A1.
** Values are expressed as percent of annual.

Table 10

Lagoon Storage Requirements - 90 Percent Exceeded

Month (1)	Backwash Water Production (2)	Evaporation -Precipita. 50 Percent Exceeded* (3)	Backwash - Net of Evap & Preci. (2) - (3) (4)	Lagoon Storage Required (5)
November	8.22**	4.74	3.46	3.46
December	8.47	3.07	5.4	8.86
January	8.47	-4.74	13.21	21.07
February	7.92	-2.95	10.87	32.94
March	8.47	1.29	7.18	40.11
April	8.2	3.63	4.57	44.68
May	8.47	2.79	5.68	50.36
June	8.2	15.07	-6.87	43.49
July	8.47	20.09	-11.62	31.87
August	8.47	29.69	-21.22	10.65
September	8.2	15.07	-6.87	3.78
October	8.47	12.27	-3.8	-0.02

* See Table A1.
** Values are expressed as percent of annual.

Therefore, use a lagoon depth of 13 ft. A lagoon with dimensions of 471 by 471 by 13 ft was chosen for use in developing cost data for comparison with the other processes.

Discussion of Alternatives

65. The literature review and evaluations made on the three treatment processes found to be most applicable to the regeneration wastewater indicated positive and negative factors associated with each process. The coagulation-precipitation process is economical and provides for recycle of most of the regeneration wastewater to the system. It also produces a sludge which must be disposed of in an environmentally acceptable manner. The mechanical evaporation process allows for the return of most of the wastewater to the system but the process is energy intensive and therefore expensive and produces a residue which must be disposed of. The solar evaporation process requires little maintenance but results in an undesirable loss of water from the groundwater treatment system.

66. In order to provide for additional evaluation of the processes, estimated capital and operating costs for each process were developed and are discussed below. An additional sludge pretreatment step was added to the coagulation-precipitation process in order to dewater the sludge to facilitate use of a fixation process on the sludge prior to disposal. A small evaporative lagoon (78 x 78 x 10 ft) was included in the process design. This would allow for both drying of the sludge and accumulation of the sludge making the fixation process more economical. With the inclusion of this pretreatment step, all three processes provided for treatment of the regeneration wastewater to the point of sludge or residue disposal which was common to all. A comparable cost evaluation of the three processes was then made.

67. The estimated capital and operating costs for the three processes are presented in Table 11. The coagulation-precipitation process design includes a package type flocculator - clarifier, chemical storage and feed equipment, a building, supporting hardware, and a sludge

Table 11

Estimated Costs for Treatment and Disposal of Regeneration Wastewater

Process	Capital ($1000)	O and M ($1000/year)	Total* ($1000)
Coagulation-precipitation	250	30	1203
Mechanical evaporation	800-1000	80-150	3340-5770
Solar evaporation	800	8	1054
Sludge fixation and disposal	--	5	159

Note: These costs were developed using information from the literature and past experiences of the authors.

* Includes 10-percent inflation over a period of 15 years.

basin. The effluent from the clarifier is returned to the headworks of the groundwater treatment system and the sludge is transferred to the sludge basin. These items along with installation were included in the calculation of capital cost for the system. The yearly operation and maintenance cost covers energy, labor, chemicals, and system maintenance.

68. The capital cost of the mechanical evaporation system covers the evaporation and drying equipment, supporting hardware, a building, and installation. The dried salt would be stored onsite. The yearly operating and maintenance cost includes energy, labor, and equipment maintenance. The total cost of the system varies depending on the type of equipment used.

69. The solar evaporation process design includes an evaporative lagoon with a double artificial liner containing a leachate detection and monitoring system. The capital cost covers materials and installation. The yearly operating and maintenance cost includes monitoring and labor. The solids produced as the water evaporates would remain in the basin until such time as the volume of the basin was significantly reduced.

70. The sludge or residue produced in the various processes would be stored until sufficient quantities were produced to economically justify fixation and disposal. The fixation and disposal could be accomplished by a vendor under a service contract. The cost of such a service was estimated to be $5000 per year as indicated in Table 11.

71. The sum of the costs for each process over an operational period of 15 years was calculated and is presented in Table 11. An inflation rate of 10 percent per year was used for the operation and maintenance cost. As indicated, the total costs of the coagulation-precipitation process and the solar evaporation process become comparable as the operational period increases. The total cost of the mechanical evaporation process for the same period is much higher. For this reason, the mechanical evaporation process was eliminated from further consideration.

72. An evaluation of the remaining two processes was made based on the positive and negative factors associated with each process. The selection of the coagulation-precipitation process to treat the regeneration wastewater was found to be advantageous for several reasons.

First, the coagulation-precipitation process allows for recycle of the wastewater back to the groundwater treatment system except for a small amount lost in the sludge disposal process. All of the wastewater would be lost in the solar evaporation process. The loss of this water from the groundwater system could be considered as an adverse environmental impact by regulatory agencies. For this reason, it is advantageous to return as much water as possible to the groundwater system.

73. Next, the total cost of the coagulation-precipitation process is more dependent on variations in wastewater quantity and quality than is the cost of the solar evaporation process. This results from the total cost of the coagulation-precipitation process being composed primarily of operational costs while the total cost of the solar evaporation process is primarily a capital cost. The capital costs of both processes are essentially fixed since each process system must be designed on the basis of the predicted maximum flow rate and wastewater chemical characteristics. However, if over the operational life of the system, the groundwater flow rate decreases and/or the concentration of fluoride in the groundwater decreases (which is likely to occur as the fluoride is flushed from the groundwater system), the regeneration wastewater flow rate will decrease. As a result, the operational cost associated with the coagulation-precipitation process would decrease from the predicted value while the operational cost of the solar evaporation process would not. In summary, the coagulation-precipitation process would prove to be more economical over the operational period than the solar evaporation process.

74. Finally, at the end of the operational period, the coagulation-precipitation process equipment could be dismantled and sold or scrapped. The small sludge storage basin could be easily cleaned, filled, and covered. This would eliminate any potential environmental impact. Closing procedures for the evaporative lagoon would be more involved and potentially more costly. If the residue was allowed to remain in the basin, monitoring of the leachate detection systems and the surrounding groundwater would have to be continued indefinitely. Otherwise, the salt residue would have to be removed, fixed, and disposed of in an

environmentally acceptable manner. The lagoon could potentially then be used for other purposes.

75. Based on the results of the laboratory studies and process evaluations, it is recommended that the coagulation-precipitation process be used to treat the regeneration wastewater from the activated alumina fluoride removal process at RMA. The recommended process design includes a package flocculator-clarifier, chemical storage and feed equipment, and a sludge basin for storage and volume reduction. This system would provide sufficient flexibility to allow for the use of several different coagulant addition processes, although the technique using calcium chloride addition with pH adjustment is recommended based on the results presented in this report. In summary, the regeneration wastewater would go to the flocculator - clarifer where the chemicals would be added, mixing would occur, and the precipitate formed allowed to settle. The supernatant would be recycled to the headworks of the groundwater treatment system. The sludge would be placed in the sludge basin for storage and volume reduction. At the appropriate time (perhaps annually), the sludge would be removed, fixed or stabilized using a commercial process, and landfilled. This system would require relatively low capital expenditures, be economical to operate, provide for flexibility in operation, and provide an environmentally acceptable method for disposal of the regeneration wastewater.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

76. Based on the results of the literature review and the laboratory studies conducted in this study, the following conclusions and recommendations have been made:

a. Treatment processes found in the literature to be applicable to the high fluoride concentration regeneration wastewater include coagulation-precipitation, mechanical evaporation and drying, and solar evaporation.

b. The chemical characteristics of regeneration wastewater from the first several regenerations of the column containing virgin alumina were found to vary. The chemical requirements for coagulation were found to be dependent on the wastewater characteristics. Since the laboratory studies on coagulation-precipitation discussed in this report were conducted on wastewater from the first several regenerations, the results of these studies should be verified using wastewater produced during later regenerations.

c. During the laboratory studies on the coagulation-precipitation process, it was found that fluoride removal from the regeneration wastewater could be enhanced by precipitating the aluminum in the wastewater as aluminum hydroxide. This was achieved by reducing the pH of the wastewater to approximately 6.5, where precipitation of aluminum hydroxide occurred. The most effective coagulation techniques for fluoride removal were those which incorporated both aluminum hydroxide precipitation and calcium fluoride precipitation.

d. The coagulation-precipitation process using calcium chloride and pH adjustment was found to be the most cost-effective process for use in treating the regeneration wastewater. The capital cost for this process is estimated to be $250,000 while the operation and maintenance cost is estimated at $30,000 per year. The sludge produced could be chemically fixed and disposed of at a cost of $5000 per year.

e. The mechanical evaporation process was eliminated because of high capital and operational costs. The solar evaporation process was eliminated after evaluation because it does not allow for recycle of the treated regeneration wastewater to the groundwater system. In addition, the coagulation-precipitation process proved to be potentially more economical.

f. The coagulation-precipitation process system should include a package flocculator-clarifier, chemical storage and feed equipment, and a sludge basin for storage and volume reduction.

g. The supernatant from the clarifer should be recycled to the headworks of the groundwater treatment system. At a residual fluoride concentration of 20 ppm in the supernatant, the total flow time before exhaustion of the alumina column would be reduced by 10.6 percent.

h. The sludge from the process should be stored in a sludge basin, the water allowed to evaporate, and the solids removed periodically, fixed or stabilized, and landfilled.

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APPENDIX A: CLIMATALOGICAL DATA FOR DENVER, COLORADO

Table A1

Summary of Probability Graphs

Month	Net Evaporation for Denver, Colorado = Evaporation - Precipitation				
	10% Exceeded in./month	50% Exceeded in./month	90% Exceeded in./month	% of Annual 50% of Exceeded	% of Annual 90% of Exceeded
January	1.78	1.29	-0.85	2.81	-4.74
February	2.37	1.4	-0.53	3.05	-2.95
March	3.1	1.53	0.23	3.34	1.29
April	3.8	2.5	0.65	5.46	3.63
May	6.16	3.9	0.5	8.52	2.79
June	7.3	5.9	2.7	12.89	15.07
July	8.28	7.0	3.6	15.29	20.09
August	8.14	7.38	5.32	16.12	29.69
September	6.85	5.53	2.7	12.08	15.07
October	5.5	4.5	2.2	9.83	12.27
November	2.97	2.32	0.85	5.06	4.74
December	3.38	2.52	0.55	5.50	3.07
Monthly Mean	4.96	3.81	1.58	8.32	8.82
Standard Deviation	2.33	2.20	1.74		
Annual Evap.	59.63	45.77	17.92	100	100.02

Table A2

Climatalogical Statistics for Denver, Colorado

Month	Mean Monthly Air Temp. F°	Standard Deviation	Variance	Mean Precip.	Standard Deviation	Variance
January	29.34	4.39	18.38	0.540	0.394	0.148
Feburary	33.10	4.45	18.89	0.70	0.450	0.193
March	37.95	4.25	17.19	1.21	0.61	0.359
April	47.48	3.03	8.76	1.86	0.98	0.91
May	57.52	2.61	6.49	2.22	1.86	3.30
June	66.51	2.74	7.177	1.78	1.38	1.81
July	73.01	2.26	4.87	1.80	1.388	1.83
August	71.26	1.91	3.48	1.12	0.825	0.648
September	61.76	3.10	9.18	1.44	1.187	1.34
October	51.60	3.96	14.9	0.96	0.988	0.93
November	38.97	2.49	5.78	0.75	0.436	0.18
December	31.7	3.80	13.76	0.65	0.69	0.45
Annual Average	50.01					

The following graphs represent the net evaporation values for each of the 12 months of the year for the past 21 years, plotted by order of magnitude.

Note: For the months of February-April and December, one inch was added to the calculated net evaporation and later subtracted to avoid the plotting of negative numbers on the probability graphs. Two inches were added to January.

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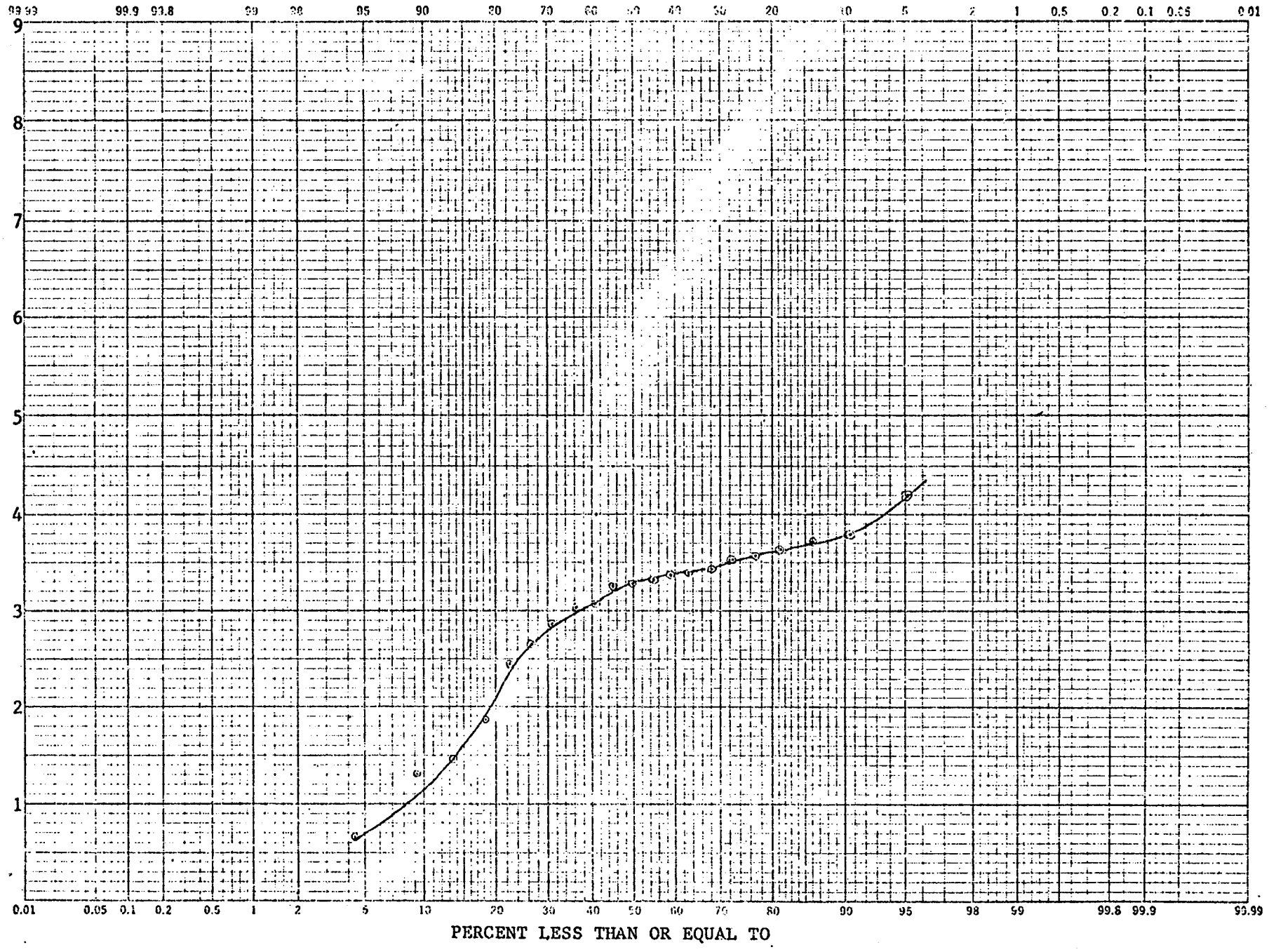

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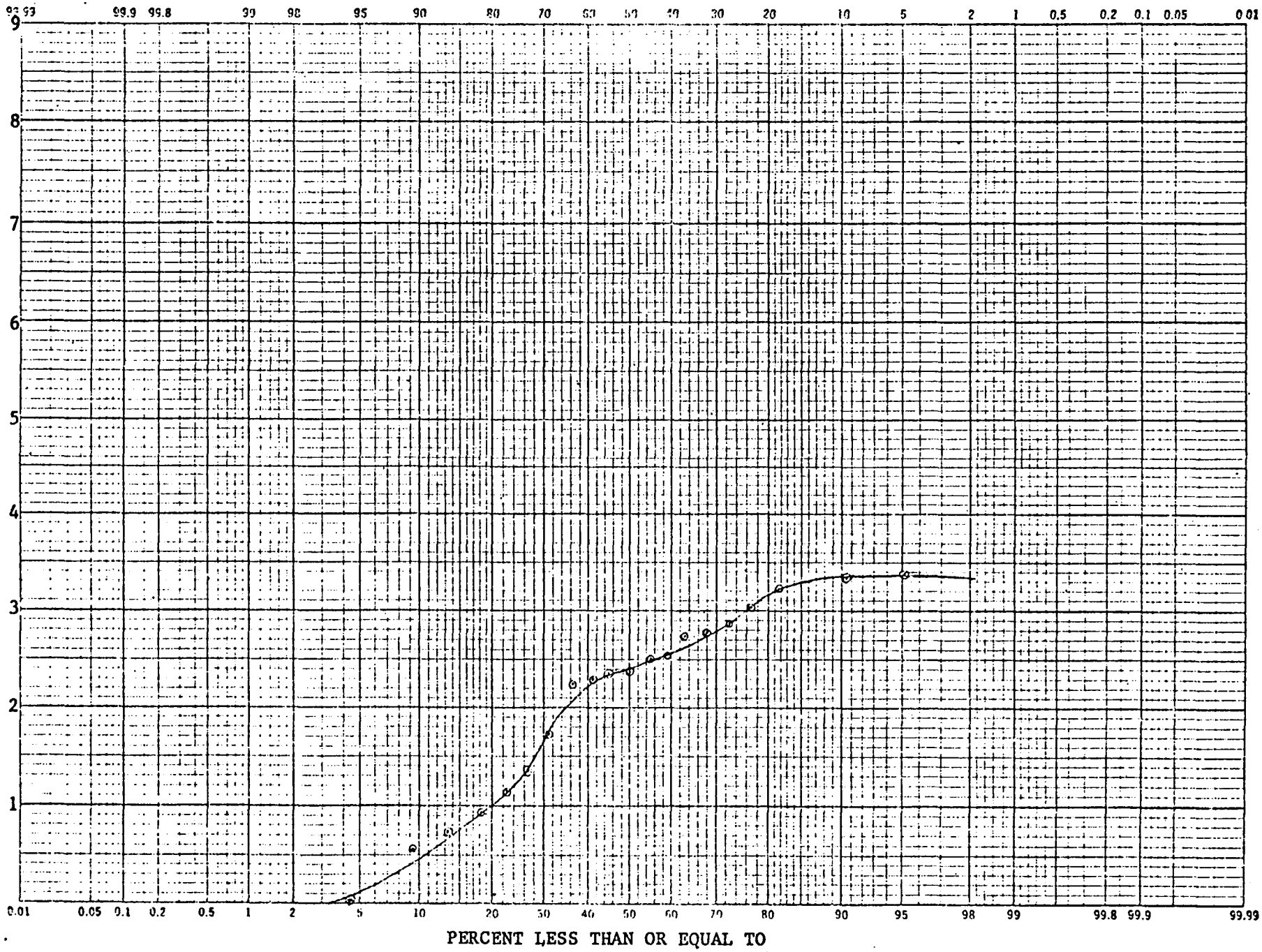
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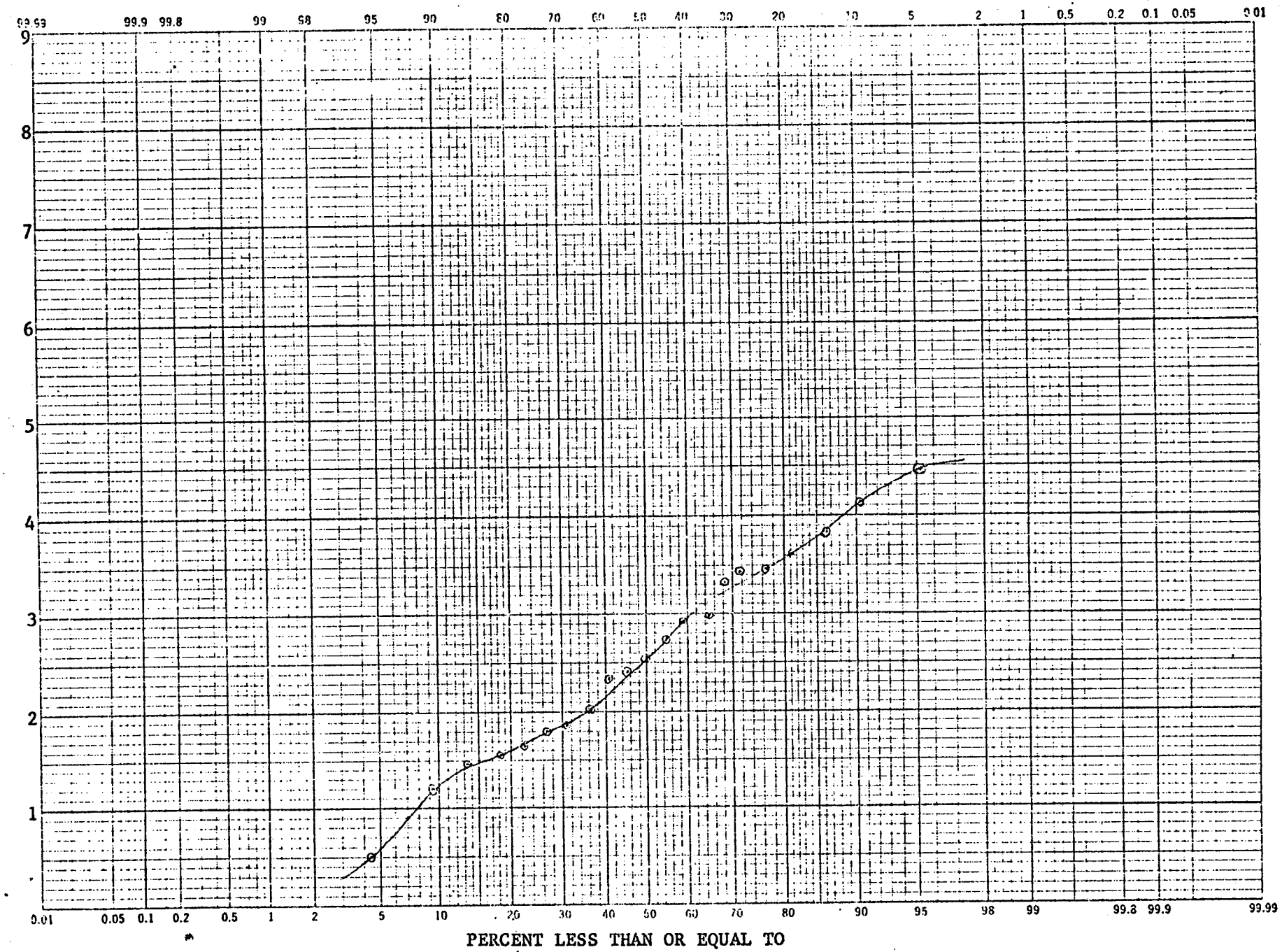
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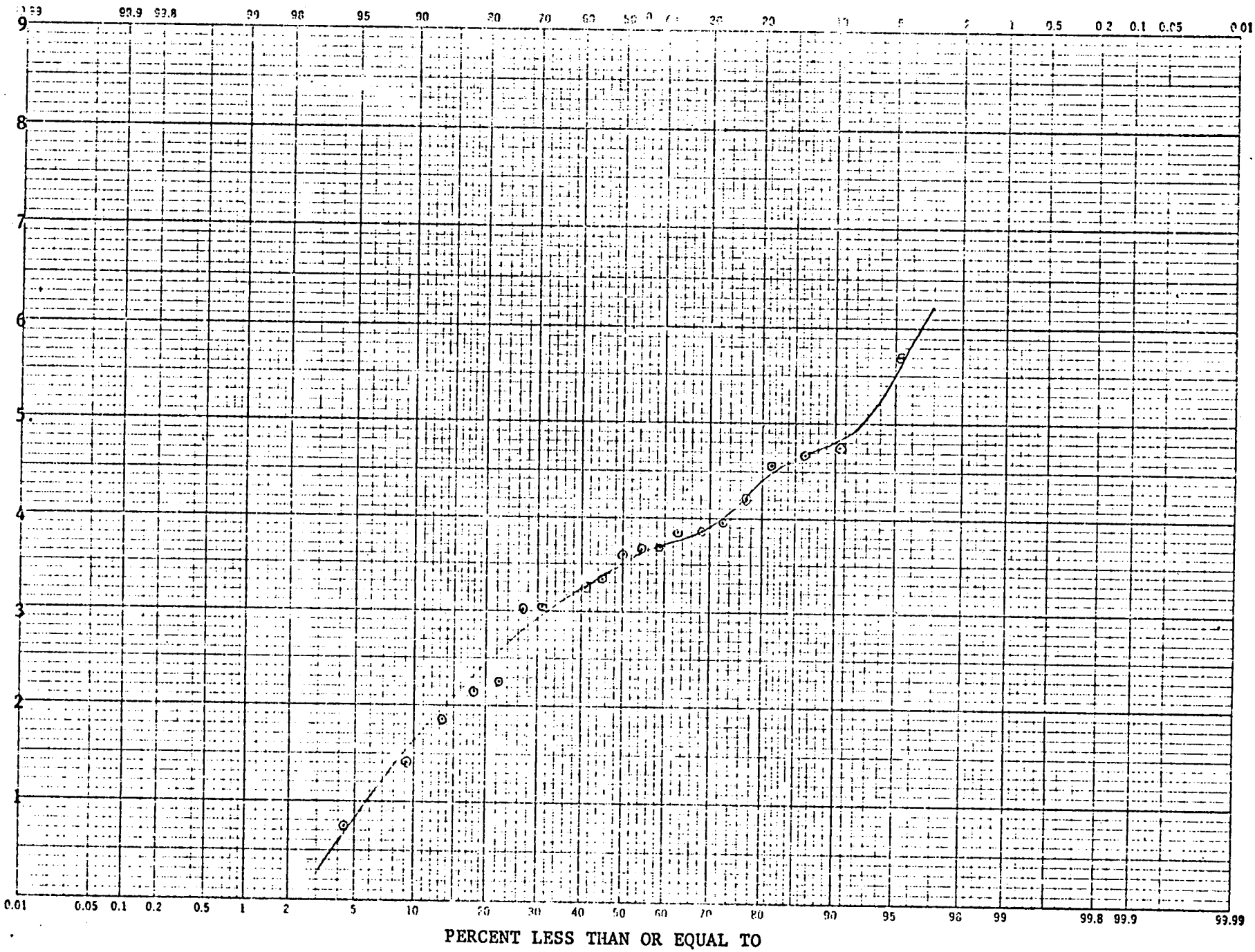
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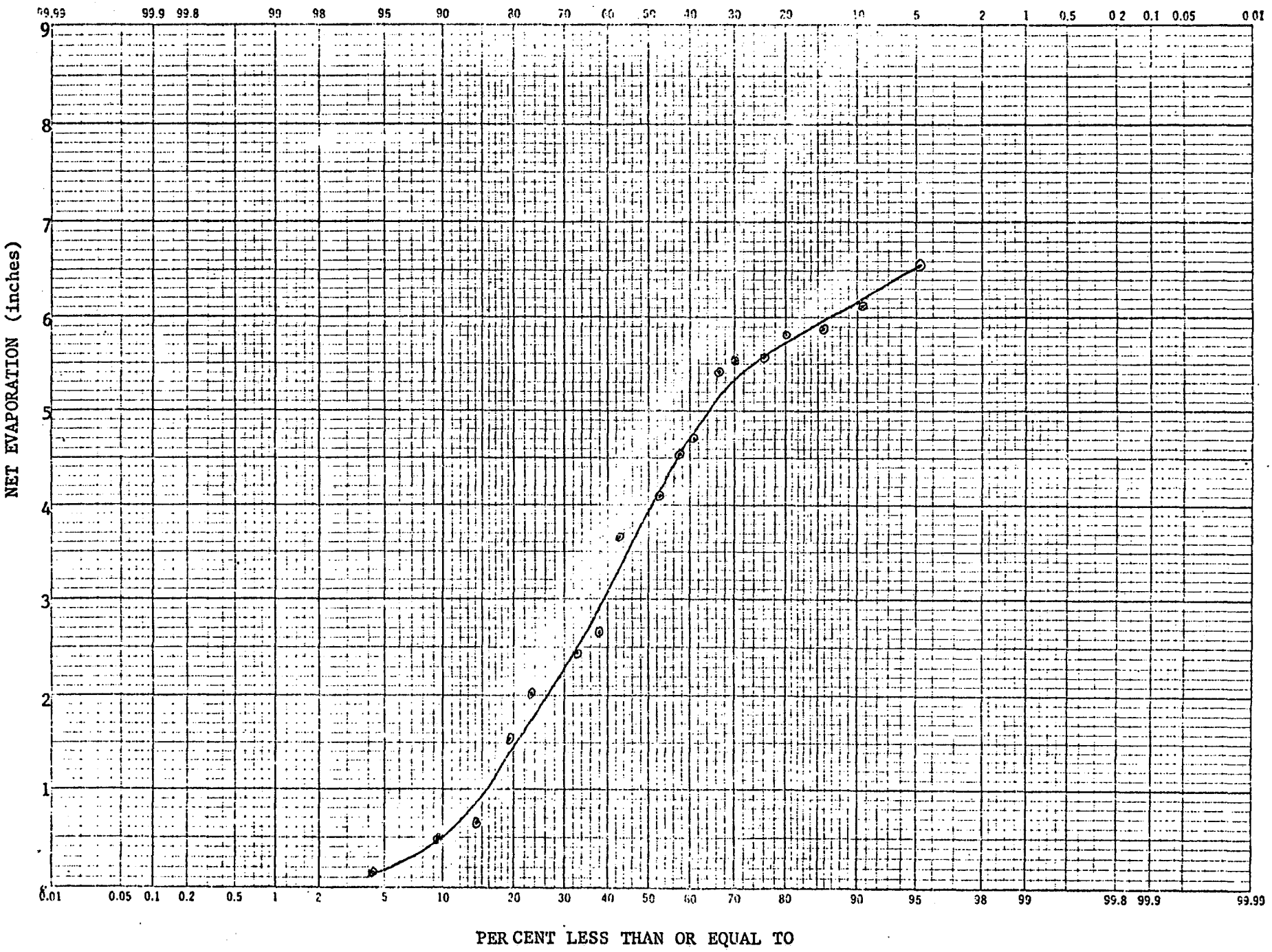
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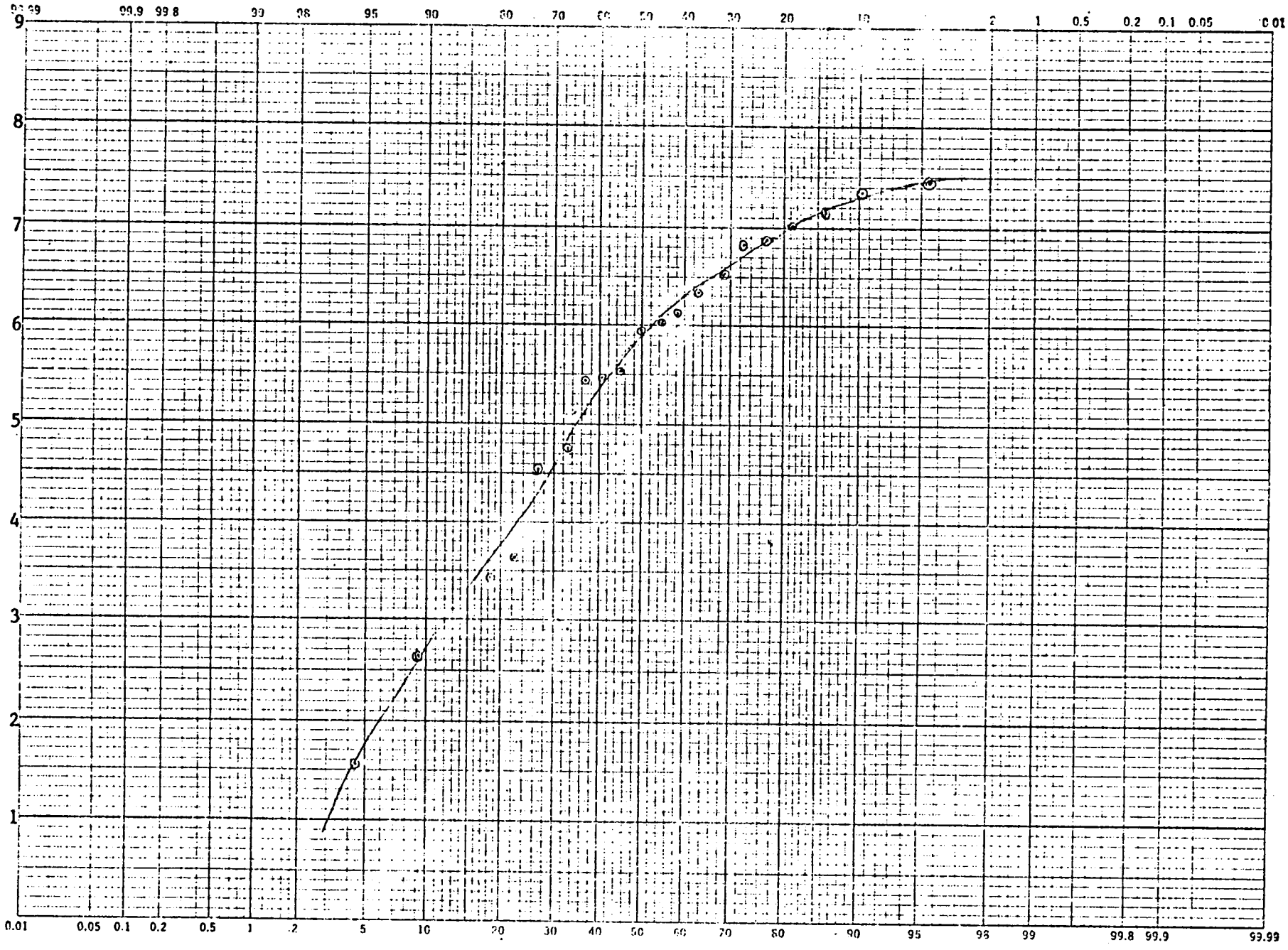
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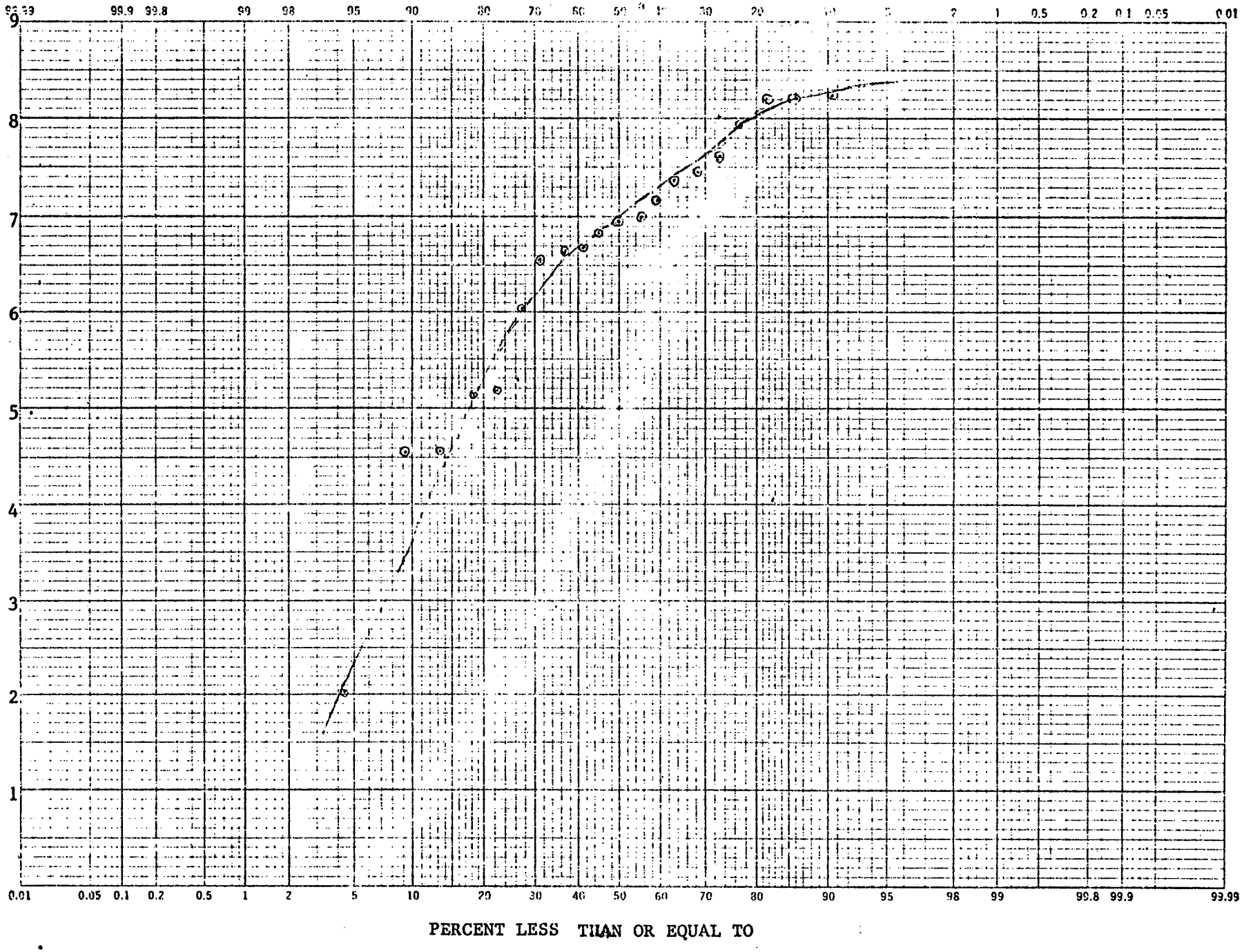
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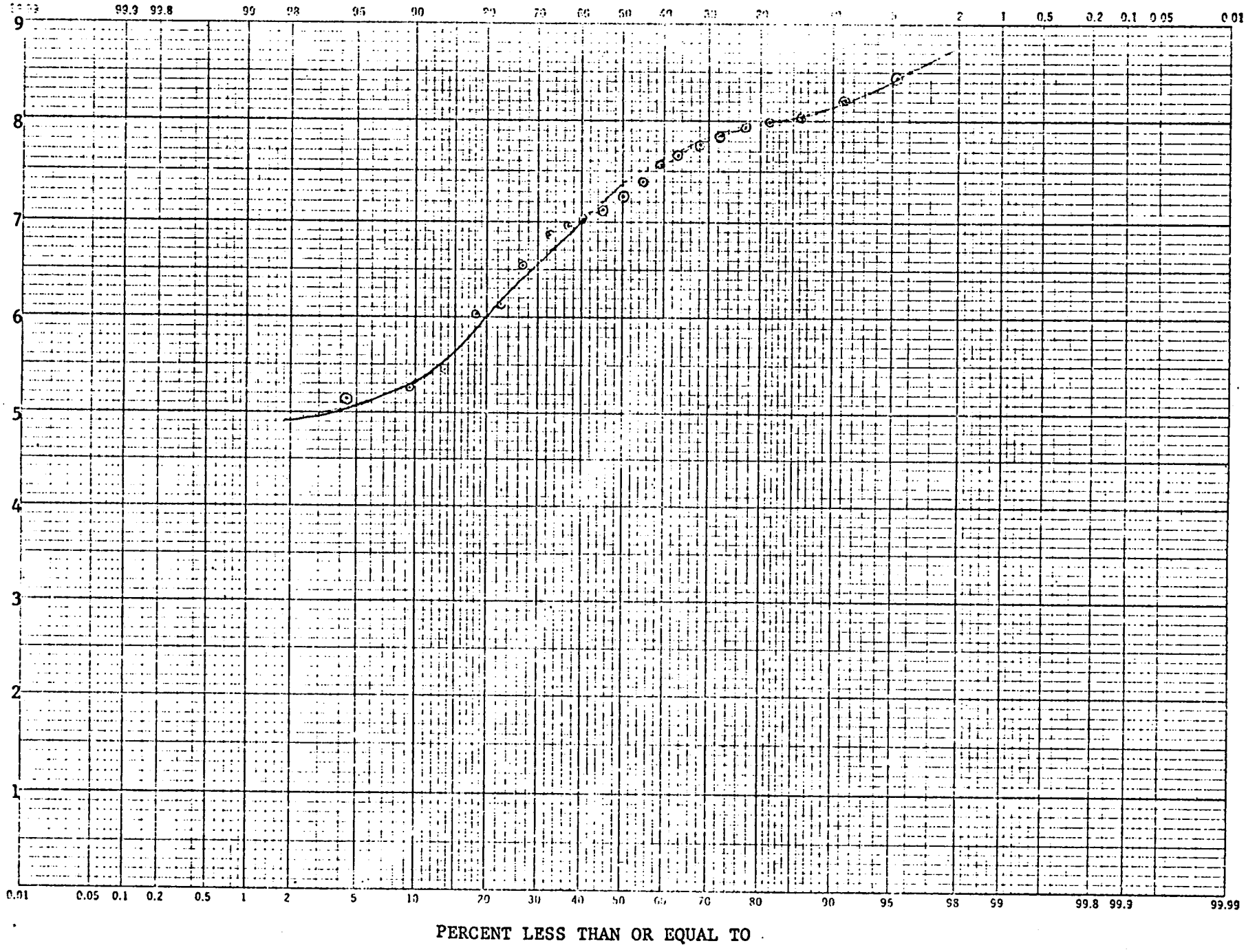
AUGUST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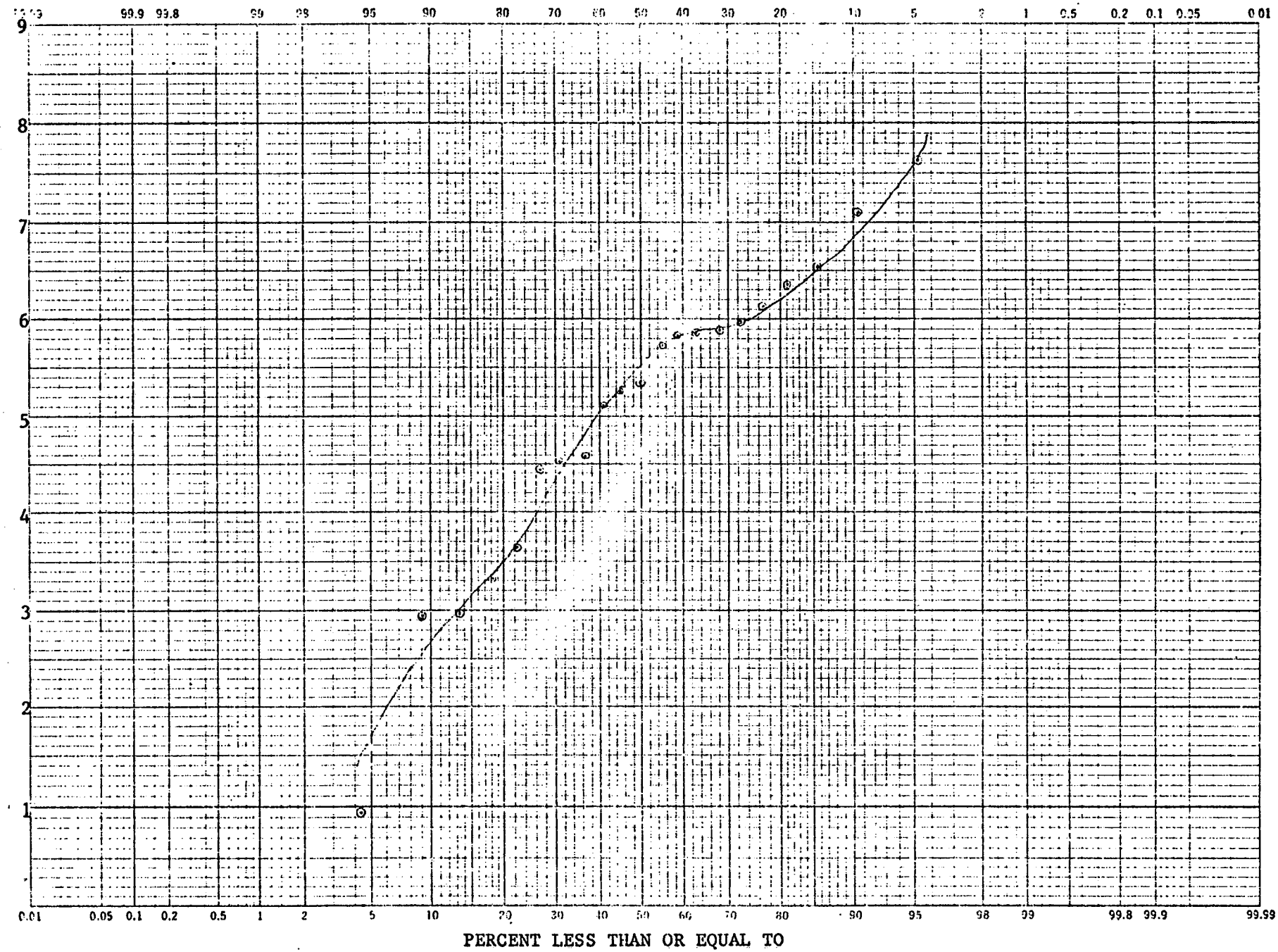
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OCTOBER

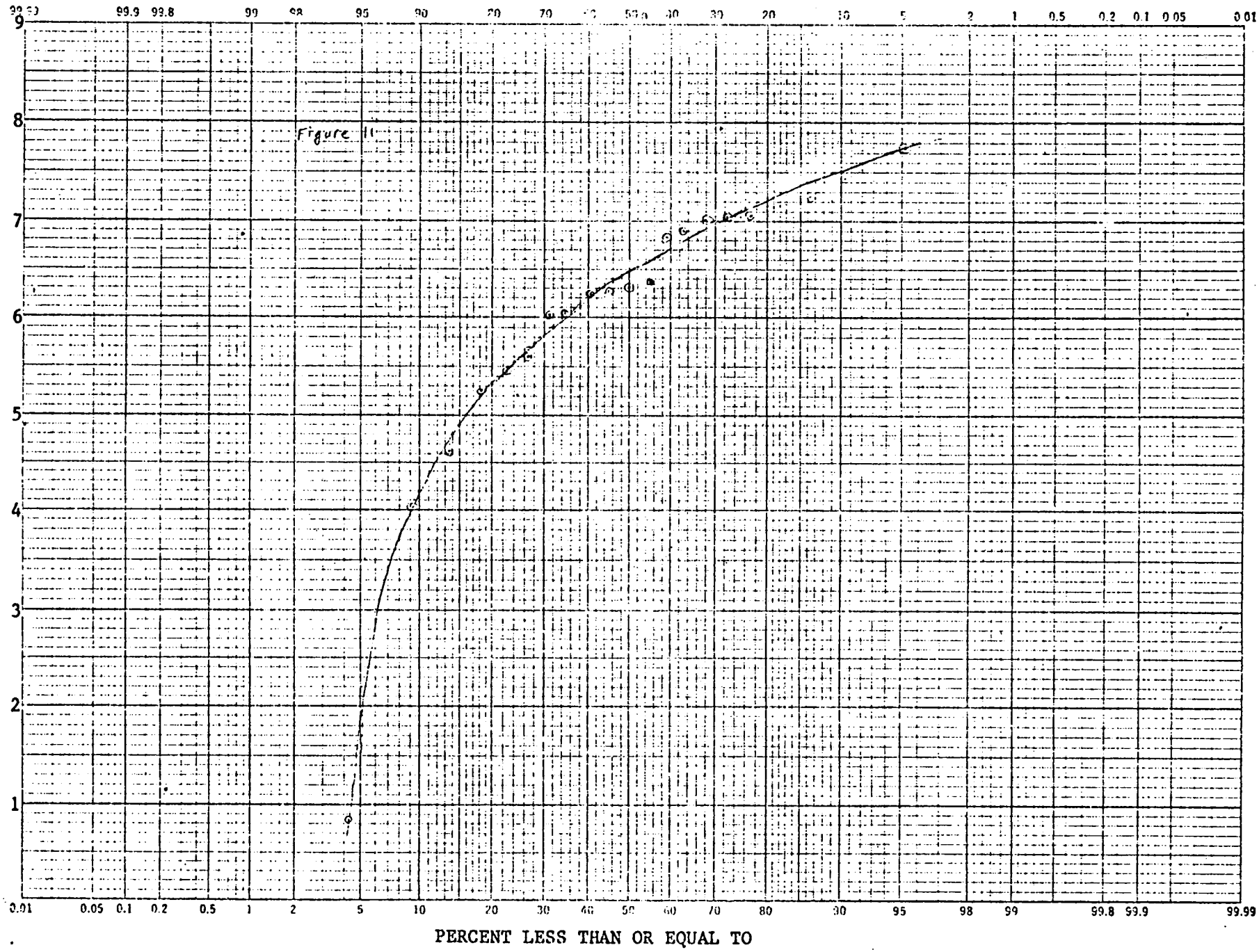
Figure 11
NET EVAPORATION (inches)
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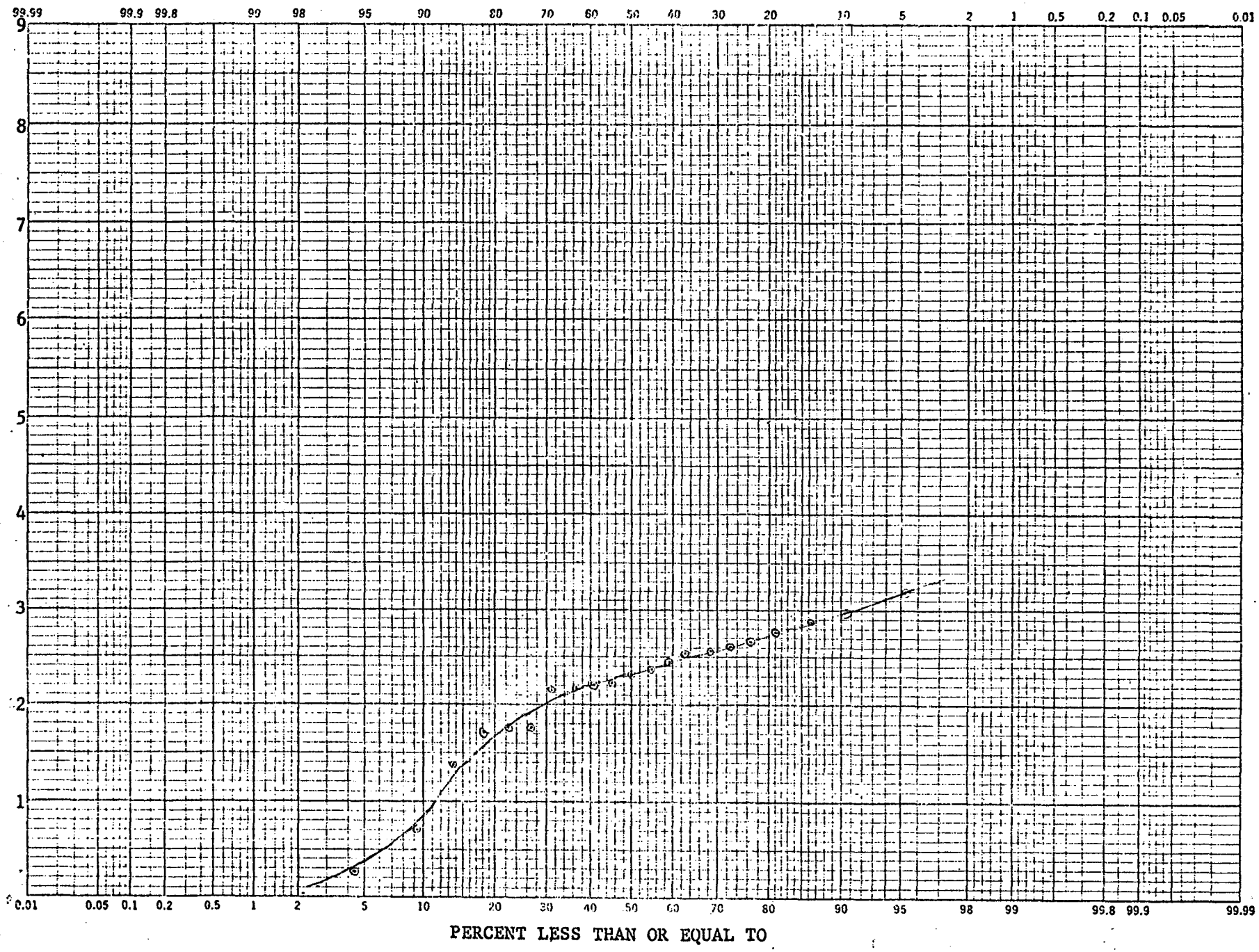
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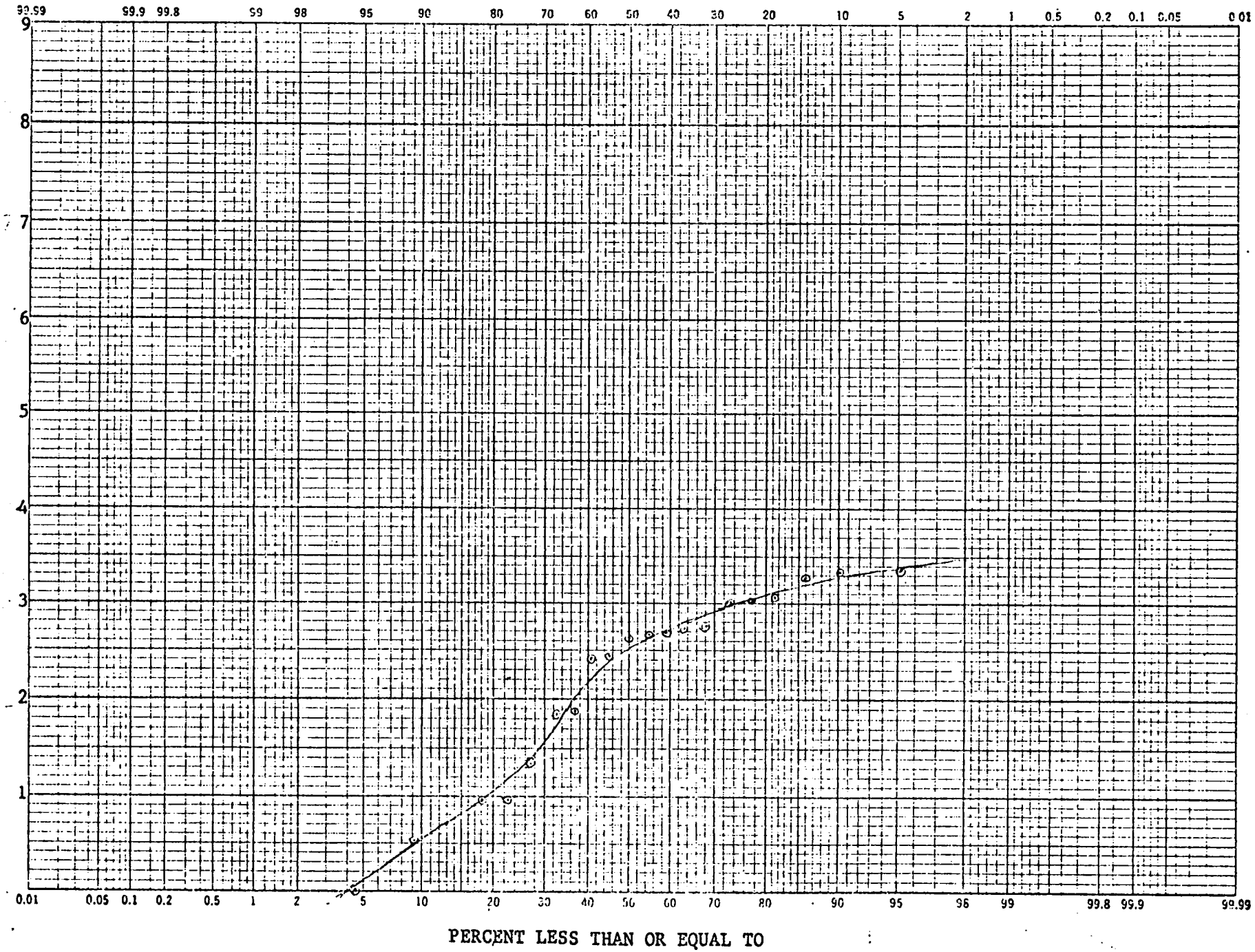
NET EVAPORATION (inches)
PERCENT LESS THAN OR EQUAL TO

DECEMBER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0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
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Raw Climatological Data (1979)
for Denver, Colorado

Equation used for evaporation in terms
of Temperature for Denver, Colorado (Ward 1977)

$$E = -0.00868 + 0.000431T$$

where $T = {}^{o}F$ and

E = evaporation (ft/day)

YEAR 1958	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	46.5	19.3	32.9	0.73	2.00	1.27
February	50.1	24.6	37.4	1.00	2.50	1.5
March	42.5	23.1	32.8	1.48	2.03	0.55
April	55.8	33.3	44.6	1.73	3.79	2.06
May	74.3	49.1	61.7	4.46	6.66	2.20
June	81.8	54.4	68.1	1.47	7.44	5.97
July	83.3	57.3	70.3	3.50	8.04	4.54
August	87.2	59.9	73.6	1.17	8.57	7.4
Septem.	78.7	50	64.4	1.51	6.86	5.35
October	67.6	40.1	53.9	0.37	5.41	5.04
November	55.1	26.1	40.6	0.74	3.17	2.43
December	48.1	23.5	35.8	0.64	2.51	1.87

YEAR 1959	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	42.8	17.2	30	0.70	1.58	0.88
February	41.2	19.2	30.2	1.31	1.45	0.14
March	49.7	25.5	37.6	2.85	2.79	-0.05
April	58.7	32.5	45.6	1.35	3.95	2.60
May	67.9	44.5	56.2	3.33	5.78	2.45
June	85.2	56.5	70.9	0.44	7.87	7.43
July	87.2	57.9	72.6	0.83	8.41	7.58
August	86.2	59.8	73.0	0.25	8.47	8.22
Septem.	74.8	47.4	61.1	1.82	6.35	4.53
October	61.1	35	48.1	2.46	4.48	2.02
November	53.1	22.1	37.6	0.40	2.74	2.39
December	49.6	23.4	36.5	0.26	2.62	2.36

YEAR 1960	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	39.9	15.3	27.6	0.77	1.19	0.42
February	35.7	13.8	24.8	1.66	0.67	-0.48
March	50.3	25.9	38.1	0.89	2.87	1.99
April	64.0	36.9	50.5	2.56	4.71	2.15
May	70.3	44.0	57.2	2.27	5.94	3.67
June	82.4	54.2	68.3	0.63	7.47	6.84
July	86.9	59.4	73.2	1.31	8.50	7.19
August	89.8	57.1	73.4	0.06	8.53	8.47
Septem.	80.8	49.2	65.0	0.38	6.96	6.58
October	66.1	37.8	52	2.46	5.10	2.64
November	54.3	24.6	39.5	0.49	3.00	2.51
December	38.9	14.1	26.5	1.50	1.01	-0.49

YEAR 1961	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	44	19.4	31.7	0.06	1.85	1.79
February	48.3	22.1	35.2	0.66	2.18	1.52
March	50.5	27.2	38.9	2.51	3.00	0.49
April	60.2	31.8	46	1.06	4.01	2.95
May	67.5	43.9	55.7	4.12	5.70	1.58
June	81	51.2	66.1	1.11	7.13	6.02
July	87.6	55.4	71.5	1.60	8.23	6.63
August	86.6	57.7	72.2	1.21	8.34	7.13
Septem.	64.4	43.2	56.3	4.67	5.61	0.94
October	65.2	34.8	50	0.77	4.78	4.01
November	47.4	22	34.7	0.93	2.32	1.39
December	40.6	21.2	30.9	0.23	1.72	1.49

YEAR	TEMPERATURE, °F					
1962	Maximum Average	Minimum Average	Average	Precip. Inches	Evapor. Inches	Evapor. - Precip.
January	33.4	5.5	19.5	1.33		-1.3
February	41.4	18.3	29.9	1.05	1.41	0.36
March	46.9	22.3	34.6	0.52	2.31	1.79
April	64.4	36.2	50.3	1.10	4.67	3.57
May	75.3	44.2	54.8	0.84	6.35	5.51
June	80.4	50.6	65.5	1.52	7.03	5.51
July	89.2	56.5	72.9	0.54	8.45	7.92
August	89.9	55	72.5	0.46	8.39	7.93
Septem.	79.2	45.6	62.4	0.19	6.55	6.36
October	70.6	36.2	53.4	0.05	5.33	5.28
November	55.5	27.0	41.3	0.68	3.28	2.60
December	49	18.5	33.8	0.17	2.19	2.02

YEAR 1963	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	33.1	5.1	19.1	0.7	0	-0.7
February	51.5	23.1	37.3	0.21	2.48	2.27
March	50.8	23.8	37.3	1.42	2.48	1.06
April	65.7	34.3	50	0.03	4.78	4.75
May	76.7	45	60.9	0.68	6.53	5.85
June	82.7	50.7	66.7	3.59	7.22	3.63
July	91.2	58.4	74.8	0.55	8.76	8.21
August	81.2	56.2	68.7	2152	7.78	5.26
Septem.	81.7	50.1	65.9	1.25	7.10	5.85
October	73.8	42	57.9	0.31	6.05	5.74
November	58	25.4	41.7	0.45	3.34	2.89
December	43.9	13.1	28.5	0.51	1.34	.83

YEAR 1964	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	45.5	15.6	30.6	0.26	1.67	1.41
February	39.6	15.1	24.4	1.04	0.61	-0.42
March	45.1	20.9	33	1.38	2.06	0.68
April	59.9	33.3	46.6	1.25	4.10	2.85
May	74.4	43.2	58.8	2.53	6.19	3.66
June	79.9	50.1	65	0.82	6.96	6.14
July	92.4	59.2	75.8	0.72	8.92	8.20
August	86.2	54.6	70.4	0.27	8.05	7.78
Septem.	78.9	46.1	62.5	0.41	6.57	6.16
October	68.5	42	55.3	0.17	5.61	5.44
November	52.3	27.6	40	0.88	3.08	2.20
December	46.1	20.3	33.2	0.40	2.09	1.69

YEAR 1965	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	48.8	21.2	35	1.0	2.38	1.38
February	40.8	14	27.4	1.27	1.05	-0.22
March	40.4	17.5	29	1.20	1.42	0.22
April	65.3	37.1	51.2	1.05	4.81	3.76
May	70.6	43.6	57.1	1.82	5.92	4.10
June	76.3	51.5	63.9	4.14	6.78	2.64
July	86.8	58.5	72.7	6.41	8.42	2.01
August	84.4	56	70.2	1.06	8.02	6.98
Septem.	68.1	43.2	55.7	2.58	5.51	2.93
October	71.8	38.3	55.1	0.45	5.60	5.15
November	59.2	27.4	43.3	0.39	3.54	3.20
December	49.4	20.6	35	2.0	2.38	0.38

YEAR 1966	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	44	13.1	28.6	0.3	1.35	1.05
February	42.2	14.6	28.4	1.28	1.19	-0.08
March	59	25.9	42.5	0.34	3.58	3.26
April	59.7	24.5	44.6	1.46	3.79	2.23
May	74.9	42.4	58.7	0.34	6.18	5.84
June	79.7	49.5	64.6	1.41	6.89	5.48
July	90.3	66.6	78.5	0.85	9.35	8.5
August	84.9	56.7	70.8	2.06	8.12	6.06
Septem.	79.3	50.6	65.0	1.15	6.96	5.81
October	68.4	36	52.7	0.96	5.22	4.26
November	56.9	26	41.5	0.32	3.31	2.99
December	45.7	18.0	31.9	0.17	1.88	1.71

YEAR 1967	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	48.9	19	34	0.84	2.22	1.38
February	50.3	19.9	35.1	0.39	2.18	1.77
March	58.5	27.3	42.9	0.79	3.64	2.85
April	63.9	32.5	48.2	3.95	4.35	0.40
May	66.0	39.2	52.6	4.77	5.20	0.43
June	72.8	48.4	60.6	4.69	6.27	1.58
July	82.4	55.8	69.1	3.25	7.84	4.59
August	82.9	53.5	68.2	0.83	7.70	6.87
Septem.	77.5	46.7	62.1	0.6	6.51	5.91
October	68.6	36.4	52.5	1.13	5.18	4.05
November	56.4	24.5	40.5	1.01	3.15	2.14
December	40.5	12.5	26.5	1.06	1.01	-0.05

YEAR 1968	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	44.1	15.3	29.7	0.51	1.53	1.02
February	47.2	21.2	34.2	0.74	2.03	1.29
March	55.8	25.4	40.6	0.85	3.28	2.43
April	57.8	28.1	43.0	2.39	3.54	1.15
May	68.6	39.2	53.9	0.71	5.41	4.7
June	84.6	50.9	67.8	0.5	7.39	6.89
July	86.4	56.9	71.7	1.34	8.26	6.92
August	82.1	54.1	68.1	2.53	7.68	5.19
Septem.	76.6	45.1	60.9	0.59	6.32	5.73
October	68.4	35.4	51.19	0.71	5.69	4.38
November	48.4	23	35.7	0.71	2.41	1.70
December	44.2	13.6	28.9	0.51	1.40	0.89

YEAR 1969	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	44.8	20.1	35	0.17	2.38	2.21
February	49.7	21	35.4	0.43	2.21	1.78
March	44.9	19.4	32.2	1.10	1.93	0.83
April	66.6	37.8	52.2	1.33	4.97	3.64
May	71.9	46.7	59.3	6.12	6.27	0.15
June	73.7	49.2	61.5	2.99	6.41	3.42
July	88.8	60.6	74.7	1.81	8.74	6.93
August	88.7	59.1	73.9	0.74	8.61	7.82
Septem.	74.0	49.9	64.5	1.67	6.88	5.21
October	49.5	28.4	39.0	4.17	3.02	-1.14
November	53.4	24.7	39.1	0.62	2.94	2.32
December	46.4	18.6	32.5	0.32	1.98	1.66

YEAR 1970	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	45.2	15.9	30.6	0.1	1.67	1.57
February	55.5	21.6	38.6	0.01	2.67	2.66
March	46.2	20.8	33.5	1.34	2.14	0.8
April	58.1	29.2	43.7	0.97	3.65	2.68
May	75	42.5	58.8	0.64	6.19	5.55
June	80.2	50.2	65.2	3.83	6.99	3.16
July	86.9	57	72	1.67	8.31	6.64
August	89.4	58.3	73.9	0.54	8.61	8.07
Septem.	75.3	43.7	59.5	2.47	6.10	3.63
October	60.5	31.2	45.9	.88	4.13	3.25
November	58.1	25	39.1	1.19	2.94	1.75
December	49.7	16.8	33.3	0.09	2.11	2.02

YEAR 1971	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	45.7	18.4	32.1	.35	1.91	1.56
February	43.4	17.7	30.6	.78	1.51	0.73
March	54	22.9	38.5	.53	2.91	2.4
April	62.2	33.4	47.8	1.98	4.29	2.31
May						
June	86.4	51.6	69.0	0.23	7.58	7.35
July	86.2	55	70.6	1.2	8.04	6.89
August	88.6	56.9	72.8	.85	8.44	7.59
Septem.	72.5	42.4	57.5	2.85	5.79	2.94
October	64.7	34	49.4	.44	4.69	4.25
November	54.2	24	39.1	0.16	2.94	2.78
December	46.4	17.3	31.9	0.25	1.88	1.63

YEAR 1972	TEMPERATURE, °F Maximum Average	Minimum Average	Average	Precip. Inches	Evapor. Inches	Evapor. - Precip.
January	45.9	15.0	30.5	.36	1.66	1.30
February	51.9	20.4	36.2	.44	2.32	1.88
March	61.2	28.3	44.8	.5	3.95	3.45
April	62.9	34.1	48.5	3.52	4.40	0.88
May	71.2	42.8	57	.49	5.90	5.41
June	82.8	53.7	68.3	2.94	7.47	4.53
July	85.7	54.7	70.2	.63	8.02	7.39
August	85.3	56.6	71	2.71	8.15	5.44
Septem.	76	48.1	62.1	2.07	6.51	4.41
October	65.8	38.3	52.1	.82	5.12	4.30
November	44.5	21.2	32.9	1.69	1.97	0.28
December	37.8	12.0	24.9	.7	0.76	0.06

YEAR 1973	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	39.8	14.8	27.3	1.31	1.14	-0.16
February	47.5	23.4	35.5	.16	2.22	2.06
March	50.4	29.3	39.9	1.76	3.16	1.40
April	55	31.4	43.2	3.73	3.57	-0.15
May	68.3	47.8	55.6	5.06	5.68	0.62
June	83.6	51.4	67.5	.20	7.34	7.14
July	85.7	56.2	71	2.47	8.15	5.68
August	88.8	58.1	73.5	1.28	8.55	7.27
Septem.	74.3	45.5	59.9	2.85	6.16	3.31
October	70.4	38.6	54.5	0.47	5.50	5.03
November	53.4	25.6	39.5	.83	3.0	2.17
December	45	18.1	31.6	2.84	1.83	-1.00

YEAR 1974	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	37.5	9.8	23.7	1.03	0.5	-0.52
February	49.0	21.3	35.2	0.82	2.18	1.36
March	58.5	27.8	43.2	1.32	3.69	2.37
April	62.4	33.3	47.9	2.28	4.30	2.02
May	79.1	44.1	61.6	.06	6.64	6.58
June	83.9	52.9	68.4	2.01	7.48	5.47
July	90.5	58.8	74.7	2.34	8.74	6.40
August	85.5	53.4	69.5	.16	7.91	7.75
Septem.	74.6	44.2	59.4	.98	6.09	5.11
October	67.2	37.6	52.4	1.68	5.17	3.49
November	51.1	24.8	38.	1.06	2.77	1.71
December	43.7	18.6	31.2	.29	1.77	1.48

YEAR 1975	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	46.4	16.9	31.7	0.23	1.62	1.85
February	45.2	16.0	30.6	0.37	1.14	1.51
March	50.4	24.1	37.3	1.19	1.56	2.75
April	58.3	27.0	42.7	2.25	1.25	3.5
May	68	40.5	54.3	2.8	2.67	5.47
June	79.5	49	64.3	2.11	4.74	6.85
July	87.2	58.2	72.7	2.78	5.64	8.42
August	86.2	55.3	70.8	2.0	6.12	8.12
Septem.	75.3	43.7	59.5	0.24	5.86	6.10
October	70.5	35.9	53.2	0.3	5.00	5.30
November	50.8	22.8	36.8	1.88	.70	2.58
December	50.5	24.5	37.5	0.47	2.31	2.78

YEAR 1976	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	46.3	18.3	32.3	0.19	1.75	1.94
February	54.1	24.4	39.3	0.54	2.23	2.77
March	51.7	22.4	37.1	1.34	1.37	2.71
April	62.9	35.4	49.2	1.27	3.23	4.5
May	70.3	43.0	56.7	1.34	4.52	5.86
June	82.0	50.6	66.3	0.63	6.53	7.16
July	89.1	61.4	75.3	2.31	6.53	8.84
August	84.6	55.8	70.2	1.48	6.54	8.02
Septem.	74.3	49.2	61.8	1.88	4.58	6.46
October	63.1	33.6	48.4	0.93	3.60	4.53
November	53.0	26.0	39.5	0.32	2.68	3.00
December	50.9	20.0	35.5	0.16	2.30	2.46

YEAR 1977	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	43.9	14.4	29.2	0.16	1.29	1.45
February	51.8	24.1	38.0	0.27	2.31	2.58
March	53.8	25.9	39.9	1.24	1.92	3.16
April	63.3	38.8	51.1	2.13	2.67	4.80
May	74.9	46.4	60.7	0.34	6.16	6.5
June	86.3	57.5	71.9	1.02	7.01	8.02
July	87.8	60.7	74.3	1.20	7.48	8.68
August	82.9	57.5	70.2	1.00	7.02	8.02
Septem.	82.3	50.8	66.1	0.1	7.10	7.20
October	69.4	37.1	53.3	0.48	4.83	5.31
November	53.7	26.8	40.3	0.59	2.53	3.12
December	49.1	21.0	35.1	0.3	2.09	2.39

YEAR 1978	TEMPERATURE, °F			Precip. Inches	Evapor. Inches	Evapor. - Precip.
	Maximum Average	Minimum Average	Average			
January	37.5	14.1	25.8	0.27	0.90	0.63
February	42.2	20.5	31.4	0.27	1.63	1.36
March	57.0	29.6	43.3	1.07	3.71	2.64
April	63.6	36.9	50.3	1.82	4.67	2.85
May	67.1	41.7	54.4	3.46	5.49	2.03
June	80.6	53.1	66.9	1.17	7.49	6.32
July	90.4	59.0	74.7	0.54	8.74	8.20
August	85.5	53.7	69.6	0.26	7.93	7.67
Septem.	81.2	48.7	65.0	0.07	5.96	6.89
October	68.2	37.9	53.1	0.32	5.28	4.96
November	49.8	25.7	37.8	0.50	2.74	2.24
December	36.9	12.3	24.6	0.82	0.71	-0.1