

REMOVAL OF COLOR
FROM SOUTH KOHALA WATER: ISLAND OF HAWAII

by
Nathan C. Burbank, Jr.
Po Lau Chan
Reginald H. F. Young

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ABSTRACT

The waters of the streams in the South Kohala district of the island of Hawaii have long been noted for their extremely high color and at times a distinct peaty taste. Early attempts to treat this water have led to the conclusion that the color bodies occurring in the water were refractive in nature and very difficult to remove except with unusually large and uneconomic chemical treatment.

At the end of one year of research into the problem of removal of the color from water as typified by the water from Waikoloa stream, it has been found that the color bodies are predominantly organic and characteristic of humic and tannic acids of vegetable origin.

The color of the water has varied from a maximum value of 320 units to a minimum value of 22 units, the average value, based on present data, is 80 units. The zeta potential of the color colloid complex has varied from 36 mv to 18.5 mv.

Coagulation and removal of the color from the water can be achieved using either alum or ferric sulfate. Alum with an average dosage of 25 mg/l can reduce the color level from 140 to as low as 10 mg/l while ferric sulfate at an average dosage of 20 mg/l can reduce the color level of the water to as low as 5 color units over a wide range of pH values (6.0 to 8.5). Such color reduction permits the water to meet the U.S. Public Health Service standards for interstate carriers.

The use of coagulant aids holds great promise for successful color removals at lower coagulant dosage.

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INTRODUCTION

The presence of water in palatable form has always insured the habitation of an area by men and beasts. Until recent times, the quality of the water, other than palatability, was of secondary importance.

As man became more aware of the connection between disease and his water supply, a series of secondary standards of water quality arose which came to include freedom from objectionable materials which posed a threat to the health of man; among those were freedom from pathogenic organisms and objectionable physical and chemical constituents adverse to man's welfare. These requirements have reached a peak in the standards of the U.S. Public Health Service and the World Health Organization for potable water supplies approved for use on interstate and international carriers.

Traditionally on the island of Hawaii (southernmost and largest of the Hawaiian Islands), until the development of irrigation water supplies in the late nineteenth and early twentieth centuries for plantation use, the major source of water for all uses was surface water. This water, the result of rainfall, served the early populace and can serve to meet the future needs of many areas where ground water is scarce or difficult to develop.

SURFACE WATER RESOURCES

Most surface water in the area originates on the higher slopes of Kohala Mountain and on the windward Hamakua coast. The streams stemming from rainfall in the area are largely intermittent and flow only in times of heavy rainfall. The rest are perennial only in their upper courses. Among the perennial streams are those between Wailoa Stream in Waipio, north of Honokaa, and Pololu Stream in Kohala. The streams of major significance are Kawainui, Alokahi, Hauani, Wai-koloa, and Kohakohau Streams.

Site accessibility and development costs are limiting factors in the development of the water of the streams flowing to the ocean from the northeast side of Kohala Mountain. The streams on the southern flank of Kohala Mountain are deemed the most logical for development as surface water supply sources. The streams are perennial only on the

upper slopes of the mountain and lose their water to permeable rocks long before they reach the ocean. However, their flow is of a magnitude to warrant consideration for development as potential sources of water supply. On the basis of flow records, Waikoloa Stream has been selected as the most reliable water source.

Waikoloa Stream

Waikoloa Stream originates in the forested watershed of the forest reserve on state lands on the southeast slope of Kohala Mountain. This stream flows toward the south following the land contours of the saddle valley until it crosses Waimea town, then it runs to the west towards the ocean parallel to the Waimea-Kawaihae road. While the stream is perennial in its upper reaches much of the flow is diverted for stock use, domestic use, or lost to seepage before it reaches the town of Waimea.

Streamflow records at two gauging stations have been kept for nearly 20 years and provide an accurate record of the quantity and character of the flow.

The small drainage basin (1.19 square miles at the lowest gauging station) and the precipitation characteristics of the basin combine to show wide variations in instantaneous rates of discharge as well as daily mean discharge values, a variance of approximately 340 times being observed. The mean discharge of the stream at the lower gauging station is 5.92 MGD, which was equalled or exceeded 27 percent of the time. This clearly indicates a need for storage since for 73 percent of the time the streamflow is less than the mean flow. The safe yield of Waikoloa Stream with diversion at the Marine Dam without storage other than that which presently exists has been calculated to be 5.92 million gallons per day.

Character of the Watershed

The watershed of Waikoloa Stream at the Marine Dam is characteristic of the entire watershed area. The watershed is essentially underlain with volcanic rock of andesite nature weathered to a fine organic clay overburden usually less than 3 feet in thickness. The overburden has been described by many as saturated organic soil on the slopes and floor of the valley with alluvium in the narrow stream channel.

The terrain is often swampy because this area receives more than 100 inches of rain each year and the heavy organic soil is nearly always saturated. Dense tropical vegetation abounds in the lower levels of the watershed near the stream and in some cases might be termed a fern forest although stands of Ohia, pine, and eucalyptus also flourish at these elevations.

The Nature of the Problem

The water from the streams of the South Kohala district have long been noted for their extreme color and at times a distinct peaty taste. Early attempts at treatment by Soneda of the State Department of Health (1) led to the conclusion that the color bodies occurring in the water of streams in the area were refractive in nature and very difficult to remove.

The exact nature of the color bodies was undetermined, but it was suspected that the color was largely due to leaching of organic color and humic acids from the vegetation of the area.

The variation in color in the natural water was never determined but the persistence of color in the water throughout the year was objectionable from an esthetic as well as on an organoleptic standpoint.

SCOPE OF THIS STUDY

This study was conducted in four phases:

- (1) A survey of the water supply source to determine the cause of the color.
- (2) The determination of the parameters of the colored water.
- (3) An intensive study of the exact nature of the color body and
- (4) The establishment of methods of removal of the color body within the economics of normal water treatment plant operation.

This preliminary report will report only on the first two phases.

METHODS AND PROCEDURE

Characterization of the Water

Water from the Waikoloa Stream can best be characterized as a good quality surface water from a chemical standpoint. An analysis of the water follows:

TABLE 1. ANALYSIS OF WATER FROM WAIKOLOA STREAM (2)

pH	6.8-7.9
TURBIDITY	0-100+
COLOR IN mg/l	22-320
DISSOLVED OXYGEN	8.3
FREE CARBON DIOXIDE	0-5
SILICA	12
TOTAL HARDNESS	10-50
ALKALINITY	10-24
CALCIUM	2.1
MAGNESIUM	2.4
IRON	0.12
CHLORIDE	5
NITRATE	0.5
PHOSPHATE	-
TOTAL DISSOLVED SOLIDS	60-360

During much of the year this analysis holds true. However, the physical appearance of the stream varies with every period of rainfall. Particularly notable is the variation in color and associated with it a variance in pH. The extremes of the variance of these factors are noted in Table 2.

TABLE 2. VARIANCE IN SELECTED PHYSICAL PROPERTIES OF WAIKOLOA STREAM WATER.

PERIOD OF OBSERVATION: JUNE 30, 1966 TO JULY 15, 1967

	MAXIMUM	MINIMUM
COLOR	320.0	22.0
pH	7.9	5.8

During this period of observation based on weekly sampling, the color of the water remained in excess of 70 units for more than 70 per-

cent of the samplings. Whether this was caused by weather factors during the period of observation can not be determined. The water in Waikoloa Stream is reported (3) to run below 30 units for long periods of time, but, such low percentage was not observed.

The color bodies in the water were determined to be primarily organic. Their source is undoubtedly the decomposing fern and other flora of the watershed which have come to form the highly saturated organic soil of the watershed area.

The color bodies were found to have a negative zeta potential, that is they are negatively charged under all conditions of alkaline pH, *i.e.*, whenever the pH was above 7. The zeta potential at pH values below 7 were negative but with considerably less negative charge. The variance in zeta potential is shown in Table 3.

TABLE 3. VARIANCE IN ZETA POTENTIAL OF COLOR COLLOIDS FROM WAIKOLOA STREAM

	COLOR UNITS	ALKALINITY mg/l	ZETA POTENTIAL -mv
MAXIMUM	320	24	-36.0
MINIMUM	22	10	-20.6

There is no correlation between pH, acidity or alkalinity, color, and the zeta potential of the color colloid in the natural water.

Determination of Character of the Color Colloid

The early work of Soneda (1) in coagulation of water from Waikoloa Stream gave definite evidence that ordinary coagulation procedures were not effective in the removal of the natural color. Work done by others including the Board of Water Supply of the County of Hawaii gives ample evidence to bear out this fact (4).

The problem was approached through a study of the character of the color colloid. Chemical examination of the heavily colored water indicated that the color colloid was organic in nature. The heavy buffering capacity of the water also indicated that the colloid was an organic acid. The colloid micelle was visible in the ultramicroscope and it was determined to be of the order of .01 to 0.1 micron in diameter.

Selection of Equipment

Early works by Renes (5,6), Quincke (7), Hardy and Harvey (8), Smoluchowski (9), Helmholtz (9), Mattson (5,6,7,8,10), Northrop, Kunity, and Abramson (11), Briggs (12), Philipovich (13), Black (14,15,16), Riddick (17), and Sheerer (6), and Burbank (18), show the significance of purely physical properties of the colloid to the success or failure of the coagulation process. In view of these works, a physical chemical technique involving the measurement of the colloidal charge upon the color was selected for use.

The equipment selected for this measurement were the Brigg's cell as modified by Rock and Burbank (19) for the measurement of electrophoretic motility of the colloidal particle and the Riddick Zeta-Meter designed by Thomas Riddick (17) for the direct measurement of zeta potential, the charge upon the colloidal particle at the surface of the shear as it moves through the aqueous medium.

The Brigg's Cell. The Brigg's cell as modified by Rock and Burbank (19) is shown in Figure 1. The cell essentially consists of two flat pyrex glass slides spaced at 0.5 to 0.6-mm working distance sealed into a flat rectangular cell which is equipped with a filter neck, two platinum electrodes sealed in suitable glass receivers, a filter neck, and two stop-cock releases for venting. The cell is used with an ordinary monocular microscope with suitable electronic equipment to apply proper voltages across the cell in an appropriate direction.

The Riddick Cell. The Riddick cell is of cylindrical bore design with an approximately 4.4-mm internal diameter. The viewing unit is constructed of plastic with the exception of the electrodes. The supply wells serve as venting chambers. The entire unit shown in Figure 2 consists of the cell, a power supply, light source, indicating meters, and a specially adapted stereoscopic microscope. This unit can be purchased in a calibrated, ready-to-use condition, whereas the Brigg's cell must be manufactured and calibrated at the time of use.

It might be added that the cost of the Brigg's cell is less than \$100 if a microscope is available. The Riddick Zeta-Meter costs \$2,500.

Procedures for the determination of motility and zeta potential for each unit are well defined (19). Measurements can be made with little training.

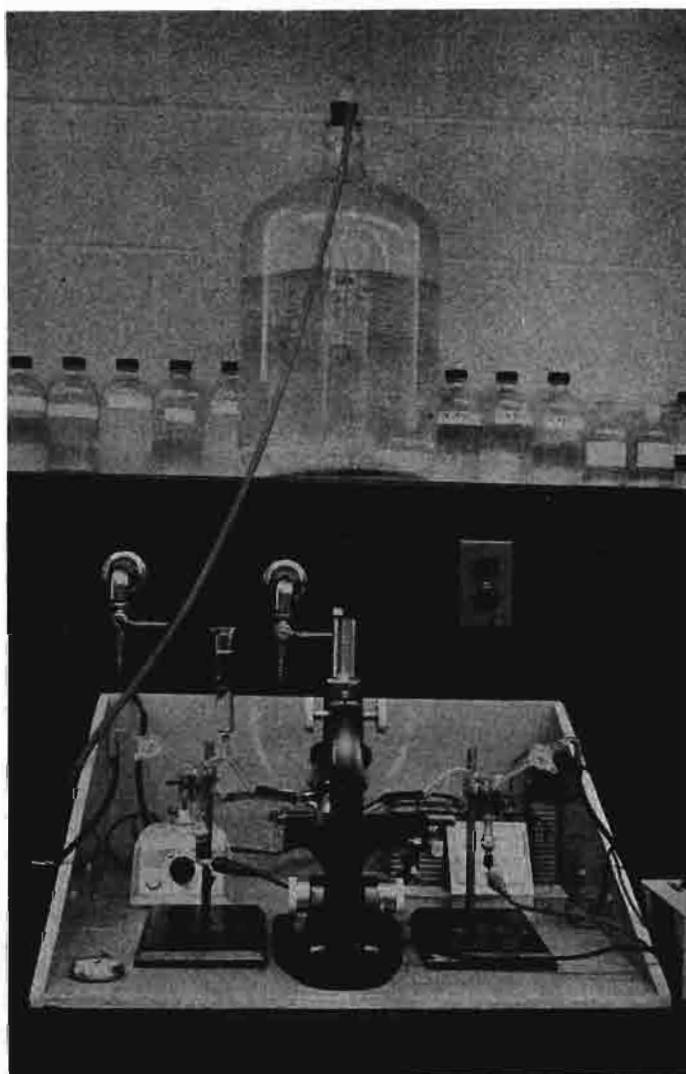


FIGURE 1: COMPLETE APPARATUS OF THE MODIFIED BRIGGS CELL.

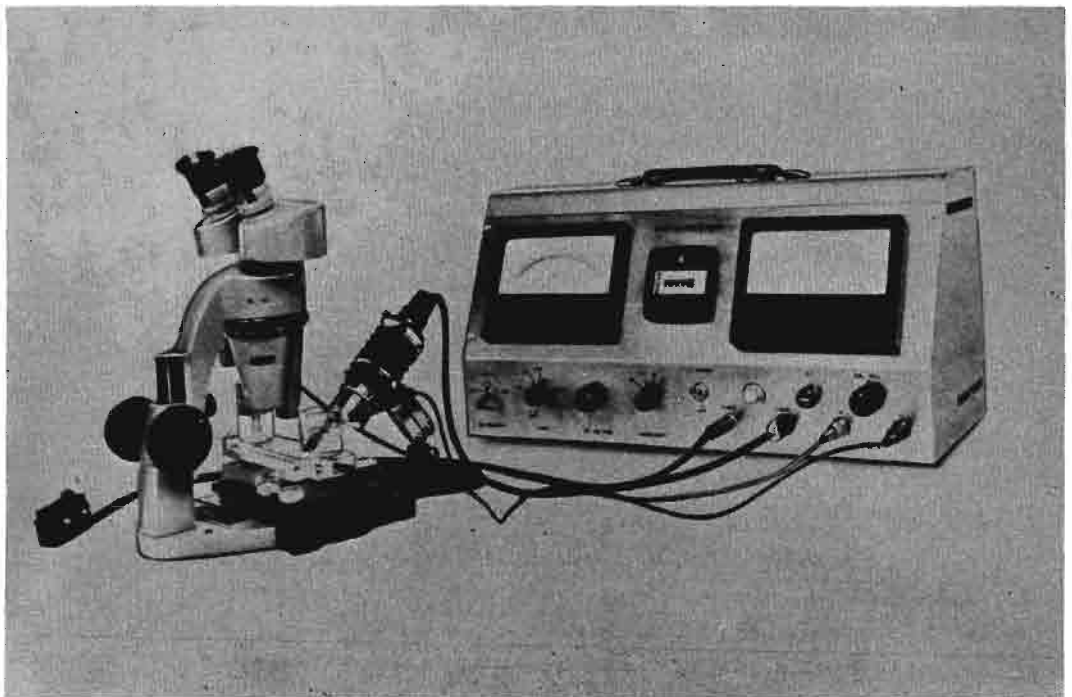
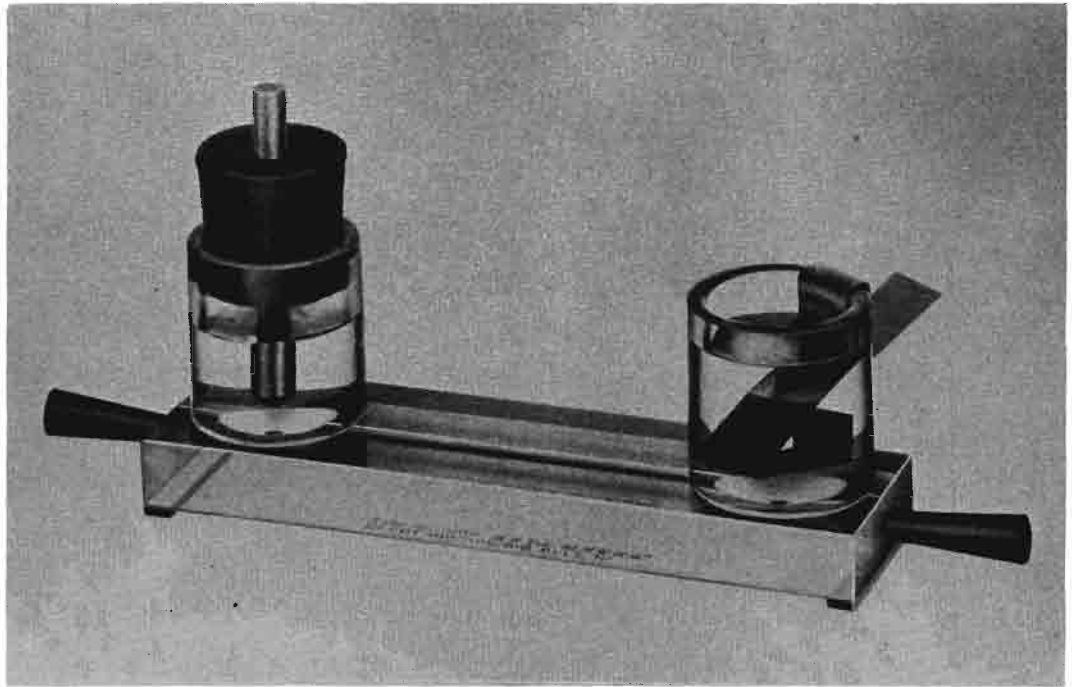


FIGURE 2: ZETA METER, (TOP) ZETA-METER CELL
(BOTTOM) COMPLETE ZETA-METER APPARATUS.

Coagulation Theory. The zeta potential concept of coagulation was promulgated very early in the century. The first logical explanation in terms of zeta potential was by Kaufman (20) followed by Black (14,15,16,21).

The concept of a color colloid as presented by Kaufman is shown in Figure 3. It indicates clearly the surface of shear and the zeta potential which may be measured at that point. Similarly Figures 3, 4, and 5 show the effect upon the colloidal micelle of the addition of a coagulant in reducing the zeta potential.

The work of Black (16) with natural color has revealed that maximum coagulation of colloids occurs near the isoelectric point, or point of minimum zeta potential, but if there is more than one isoelectric point, coagulation is often more effective for one dosage value of coagulant than for the other.

Riddick (17) has worked extensively with colored waters of the New England area and has reported success in the removal of both turbidity and the smaller organic colloids by control of the zeta potential.

More recently Stumm (22) investigated the possibility that it is not necessarily the isoelectric point and electrokinetic phenomena that play the most important role in coagulation but the effect of chemical interaction in the formation of a coagulating settling polymer.

For many years it has been known that three forces caused colloids to remain in suspension and remain refractory to coagulation. The most significant force was "Brownian Movement," the motion imparted to a colloid by the bombardment or collision with molecules of the surrounding medium. This phenomenon is always evident in any colloidal suspension.

The second and also important force involved in the suspension of colloids was the force of repulsion accompanying the zeta potential. The surface of shear of each colloid is electrically charged due to the sorption of ions and gives the colloid its characteristic charge. The electrostatic charge on the colloid, in comparison with the charge on other colloids in the suspension, results in mutual attraction of oppositely charged colloidal micelles or the repulsion of similarly charged micelles. In most water suspensions, all colloids bear the same charge and are mutually repelled into the so-called "sol" state, a stable suspension in which the colloids remain in an active dispersed state indefinitely.

The third and least evident forces are Van der Waal's forces of attraction which are a function of the attraction of one mass for another.

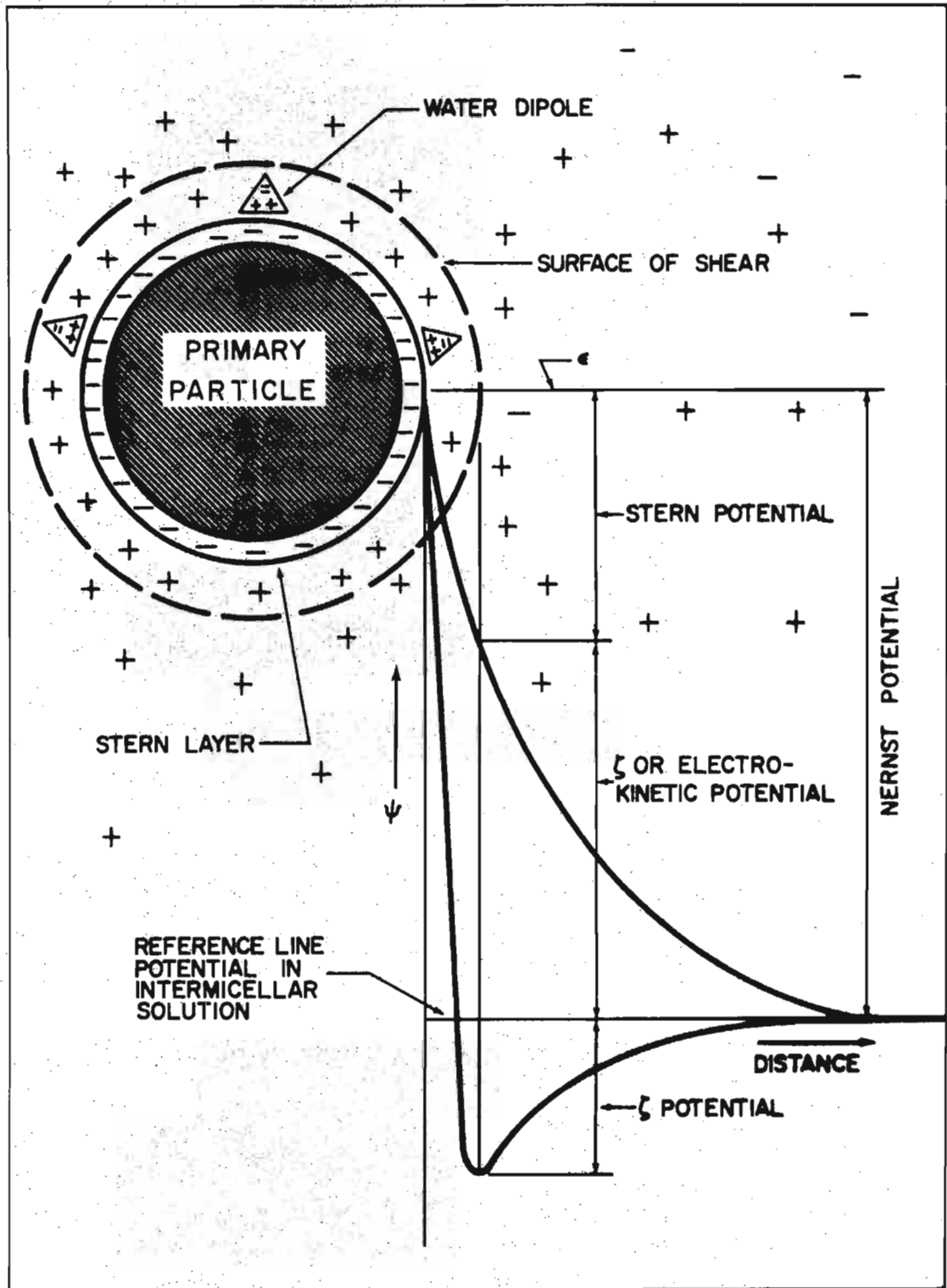
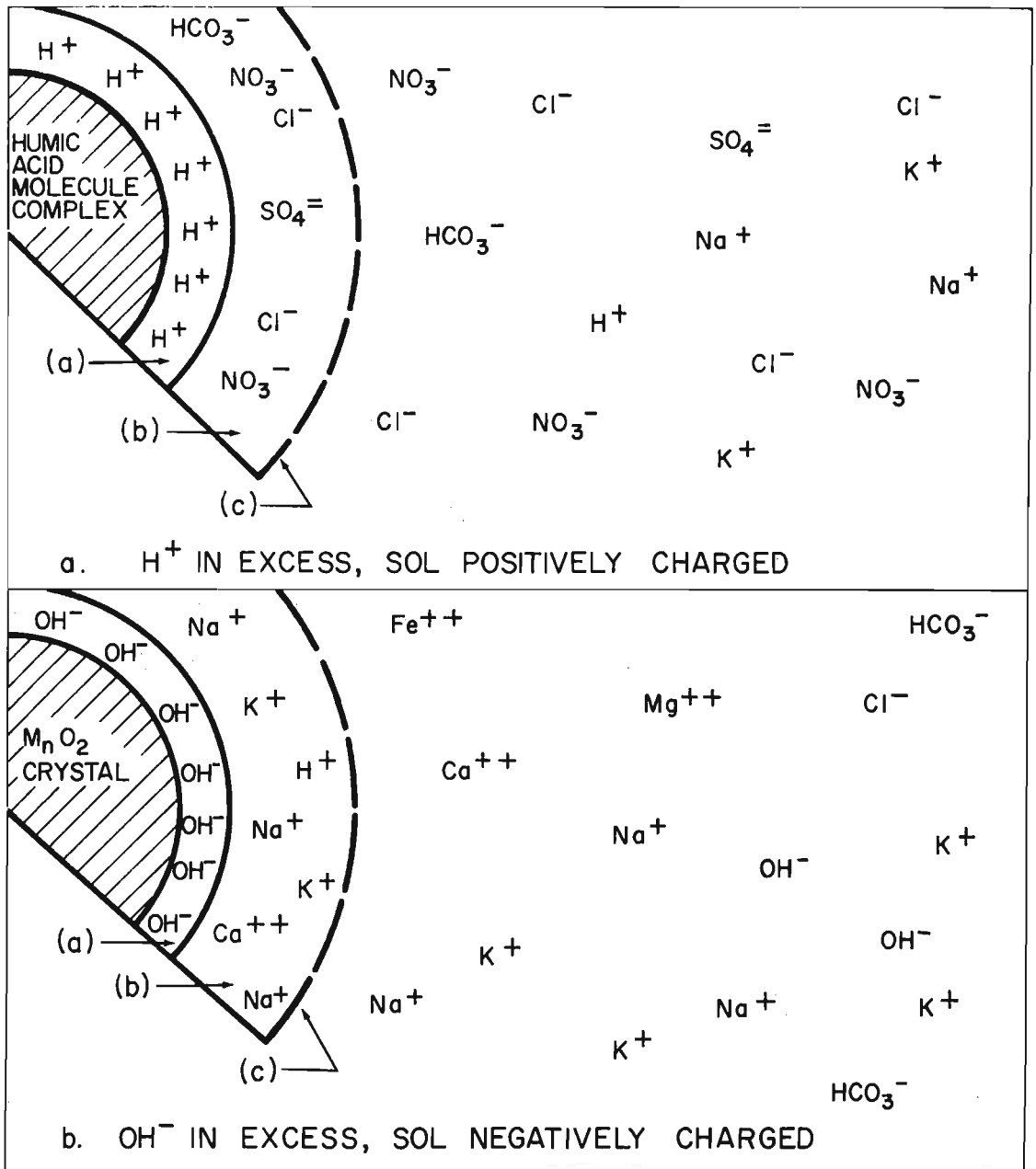


FIGURE 3: THE ELECTRICAL DOUBLE LAYER AND THE VARIOUS POTENTIALS.



- (a) INNER LAYER OF POTENTIAL DETERMINING IONS
- (b) STERN OR ATTACHED PORTION OF OUTER LAYER
- (c) SURFACE OF SHEAR
- (d) DIFFUSE OUTER LAYER

FIGURE 4: THE COLLOIDAL MICELLE AND GOUY FREUNDLICH DOUBLE DIFFUSE LAYER.

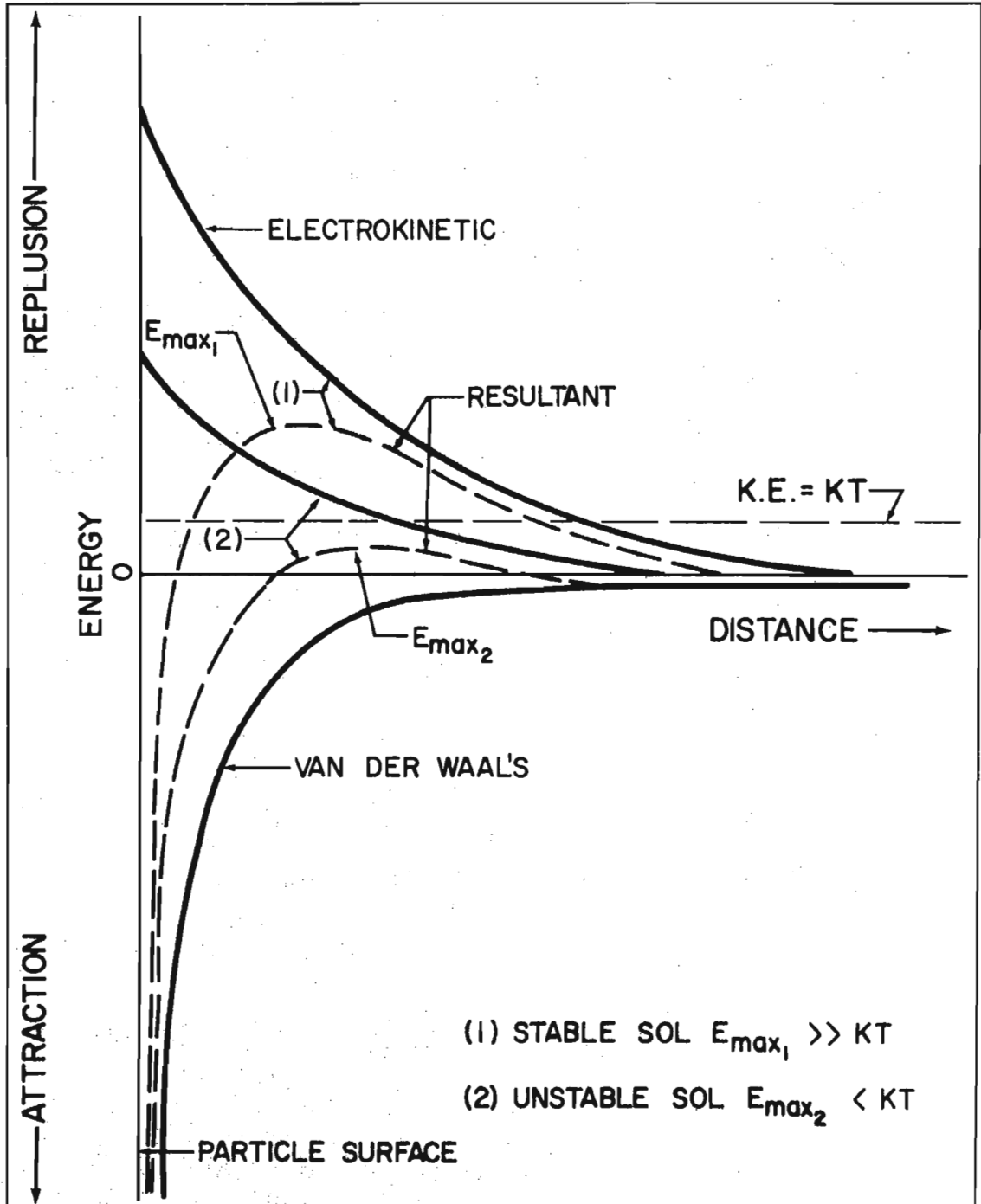


FIGURE 5: RELATION OF ELECTROKINETIC AND VAN DER WAAL'S FORCES TO STABILITY OF A COLLOIDAL SOLUTION.

These forces are of very minor magnitude and come into play only when the electrostatic forces have been neutralized to near the isoelectric point or near-zero zeta potential. Near zero zeta potential, Van der Waal's forces exert an influence on the masses involved to attract one another and the floc is formed. The colloid sol is destroyed and the colloidal particles coalesce to form larger particles, which influenced by gravitational forces, settle or precipitate out of suspension.

Thus, the primary object of coagulation of a color colloid is to neutralize and decrease the zeta potential to a level at which Van der Waal's forces cause floc formation for settlement and removal.

The Process of Coagulation. The chemical engineering process of the coagulation of water is effected simply by the addition of chemicals to a raw water to obtain polyvalent cations (or anions) which are effective in the neutralization of the zeta potential of the colloidal micelle. Neutralization of the zeta potential is followed by the aggregation and settlement of the finely divided particles under the influence of Van der Waal's forces.

The chemicals most efficient in effecting this process are aluminum sulfate, ferric sulfate, ferrous sulfate, ferric chloride, and sodium aluminate. The choice of chemical coagulant and the conditions of its application are dependent upon the charge on the colloid, the degree of dispersion, the desired strength of floc, and the results to be obtained.

Many waters are effectively coagulated only with excessive quantities (non-economic amounts) of coagulants or a prolonged period of flocculation and settling. Frequently the strength of the floc may be inadequate to withstand the movement necessary in processing, in which case the floc is peptized, *i.e.*, dispersed, making it extremely difficult to reform for settlement. The settling velocity of the floc resulting from coagulation may be so low that it can not be removed effectively in the usual equipment. These problems have led to the use of polyelectrolytes or coagulant aids to increase floc strength and mass for more rapid settlement. On the other hand, an overdose of coagulant can sometimes reverse the zeta potential from one sign to the other, *i.e.*, negative to positive or vice versa. This results in dispersion of the colloid and the floc micelle formed at zero zeta potential. Similarly the peptization of the floc by violent agitation can cause a similar reversal of sign of the zeta potential as well as an increase in magnitude of electrostatic charge.

The general action of a coagulant and the change in color with zeta potential is shown in Figure 6.

The position of the isoelectric point depends upon the characteristics of the colloid in the raw water and the character and dosage of the coagulant. R. W. Ockershausen, *et al.*, (23) has suggested that a range of -6 to -10-mv zeta potential is best for alum and its associated aids. Rock and Burbank (19) have agreed with Riddick (17) that a range of 0 ± 5 mv zeta potential yields the best range of results in the coagulation and flocculation process in current full scale practice.

Procedure Followed in this Study

Over a period of one year, frequent samples from the Waikoloa Stream supply have been collected at two sites, one at a point of usage at the Kawaihae storage reservoir and the other at the Kamuela reservoir site. Regular sampling on a weekly basis was initiated in August 1967 from the Kamuela reservoir source.

Analysis of the Water

The characteristics of the water that have a direct bearing upon the coagulation process are determined in accordance with *Standard Methods for the Examination of Water and Waste Water* (24).

Jar Testing

Jar testing under conditions simulating those found in the field has been the accepted standard of measurement in coagulation studies. The usual practice is to perform trial-and-error jar testing at varying pH values to determine the optimum pH for floc formation. Once the optimum pH of coagulation and floc formation is found, a second series of tests, on a trial-and-error basis, is made to determine the minimum dosage of coagulant necessary at that pH value. Although this procedure was followed, it was modified by the determination of the zeta potential as coagulation and flocculation progressed.

The efficiency of the process was judged on several points, (i) the ease and rapidity of floc formation, (ii) the reduction in color, (iii) the determination of the isoelectric point as set by zero zeta potential.

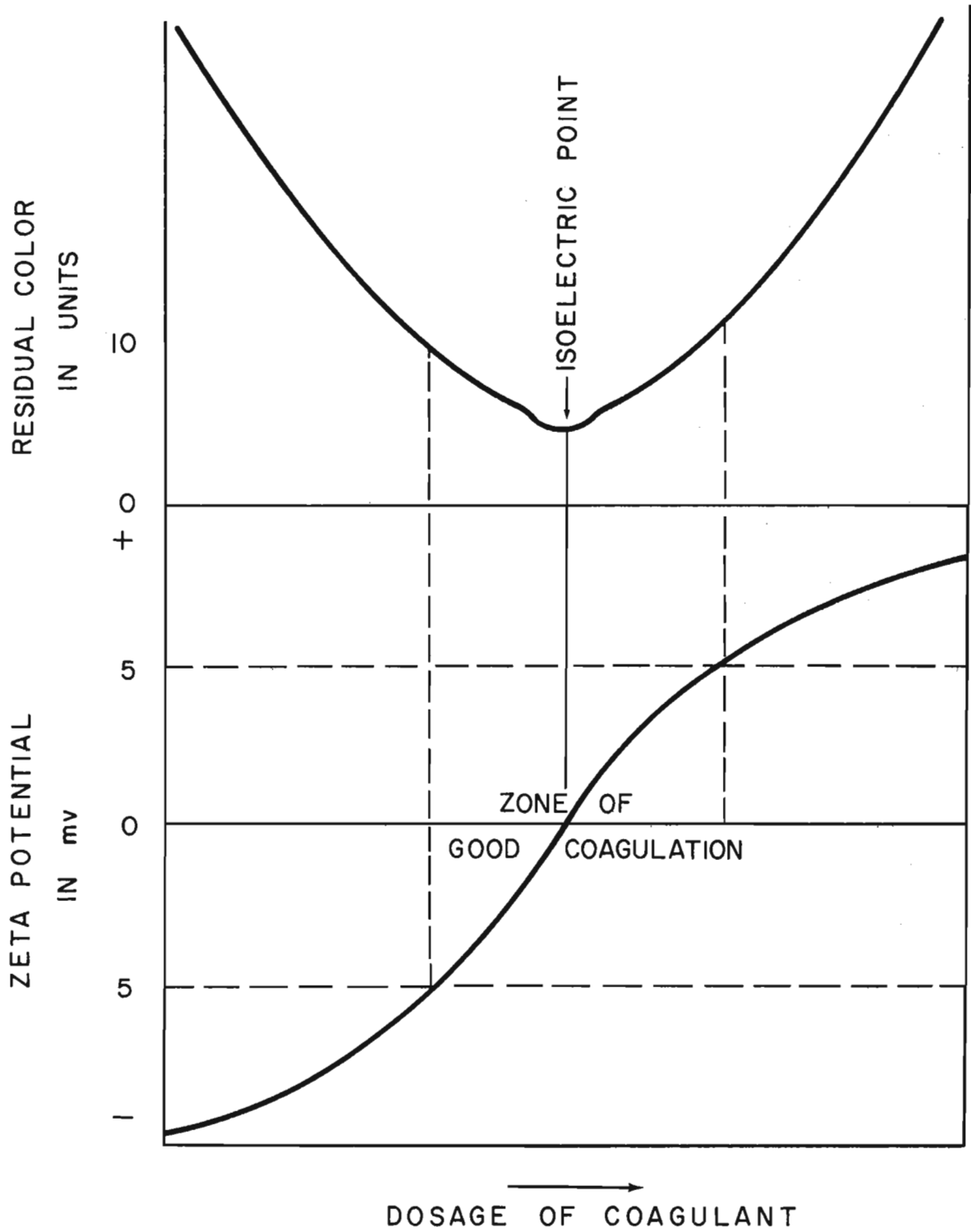


FIGURE 6: THE RELATIONSHIP BETWEEN ZETA POTENTIAL AND RESIDUAL COLOR.

The exact experimental conditions and procedure are given below:

1. For the jar tests, a six-paddle Phipps - Bird stirrer was used.
2. For the determination of zeta potential, a zeta meter was used.
3. For treatment; alum $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$ and Ferric sulfate $\text{Fe}_2(\text{SO}_4)_3 \times \text{H}_2\text{O}$ were used.
4. Sample volume; 500 ml in 800 ml beakers.
5. Samples were stirred for 30 seconds to 1 minute at a paddle speed of 80 to 100 rpm while the chemical coagulant was being added. At the end of the rapid-mix period, paddle speed was reduced to 20 to 30 rpm for 20 to 25 minutes of flocculation.
6. For pH adjustment, solutions of about 0.2N NaOH and 0.1N H_2SO_4 were used.
7. Color was determined by comparison with a series of standards which ranged from 0 to 60 units, per *Standard Methods*.
8. Samples were filtered through Whatman No. 1 filter paper before color determination.

RESULTS

Characteristics of the Raw Water

The characteristics of the water from Waikoloa Stream represented in the samples collected is shown in Table 4.

TABLE 4. SALIENT CHARACTERISTICS OF THE WAIKOLOA STREAM

	HIGHEST	LOWEST	AVERAGE
COLOR	320.0	22.0	80.0
pH	7.9	5.8	6.7
ZETA POTENTIAL	-18.5	-36.0	-23.0
HARDNESS AS CaCO_3	28.0	12.0	18.0
ALKALINITY AS CaCO_3	24.0	10.0	16.0
ACIDITY AS CaCO_3	15.0	6.0	10.0

Effect of Coagulation

Over a period of one year's testing, it has been found:

(1) When Alum $\text{Al}(\text{SO}_4)_3$ is used alone at an average dosage of 25 mg/l (± 5 mg/l), the color of the surface water in Hawaii could be reduced from as high as 140 to as low as 10 units ± 5 .

(2) When ferric sulfate, $\text{Fe}_2(\text{SO}_4)_3 \times \text{H}_2\text{O}$, is used alone, an optimum dosage of about 20 to 25 mg/l is obtained in reducing the color from about 100 to 120 down to as low as 5 units.

(3) Zeta potential of the particles in the colored water can be

brought down from $-25 \text{ mv} \pm 5$ to 0 ± 5 by increasing the dosage of coagulant. The optimum alum dosage to change the zeta potential is about 25 to 30 mg/l and the optimum ferric sulfate dosage for the same purpose is 20 mg/l to 25 mg/l of ferric sulfate.

(4) Color reduction corresponds to the increase of zeta potential from negative to about zero millivolts. When the coagulant dose exceeded is excessive, there is no color reduction and sometimes even an increase of color by the coagulant-color colloid mixture.

(5) The optimum pH for color removal, with alum alone is about 7. When ferric sulfate is used alone the optimum pH ranges from 6 to 8.5. The best color and zeta potential reductions are obtained in these ranges of pH values.

Figures 7 and 8 show the effect of coagulation upon color. The results were obtained in a series of selected studies. In Figure 7, the effect of pH at a constant dosage of alum is demonstrated. Alum has a narrow range of pH. Optimum results may be obtained for good color removal near pH 7. Figure 8 shows the effect of pH at a constant dosage of ferric sulfate. Ferric sulfate has a wider range of pH (from pH 6 to pH 8) for acceptable color removal.

Further studies have been initiated utilizing lower dosages of coagulants in company with selected coagulant aids. The results are excellent. The study is being continued to determine the most economical combination, which will produce good color removal at low dosages of both coagulant and coagulant aid, consistent with the formation of a tough rapid-settling floc.

CONCLUSION

At the end of one year of research into the problem of the removal of refractory color bodies from Hawaii's surface water as typified by the water from Waikoloa Stream, we may conclude:

1. The color bodies in Waikoloa Stream water are predominantly organic colors, characteristic of humic and tannic acids of vegetable origin.

2. The color of the water has varied from a maximum value of 320 units to a minimum value of 22 units. The average value, based on the present data, is 80 units for the one year period of observation. The

zeta potential of this color colloid complex has varied from -36 mv to -18.5 mv.

3. Satisfactory coagulation and color removal can best be achieved with the use of alum or ferric sulfate. Dosages are within the limits expected for coagulation of raw water with such high level color colloids. With alum an average dosage of 25 mg/l \pm 5 can reduce the color level from 140 to as low as 10 units \pm 5 to meet the U.S. Public Health Service Standards for Interstate carriers. With ferric sulfate as a coagulant, an average dosage of 20 mg/l \pm 5 can reduce the color level of the water to as low as 5 color units over a wide range of pH values (6 to 8.5).

4. The use of coagulant aids holds great promise for successful color removals at lower coagulant dosages and minimal coagulant aid addition.

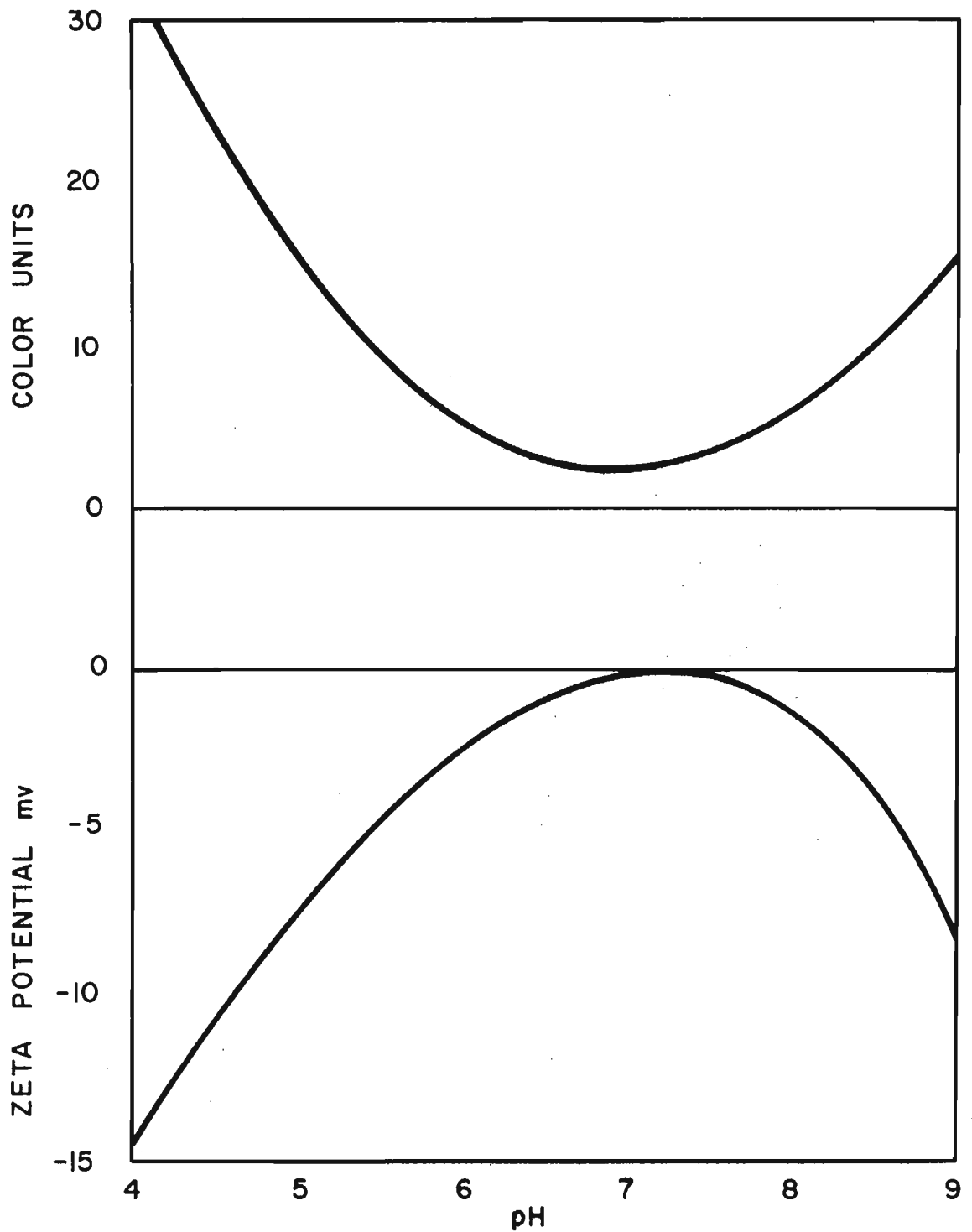


FIGURE 7: EFFECT OF pH ON COAGULATION RESULTS
COAGULANT ALUM 20 mg/l
RAW WATER COLOR 64 UNITS
ZETA POTENTIAL -19.6 mv

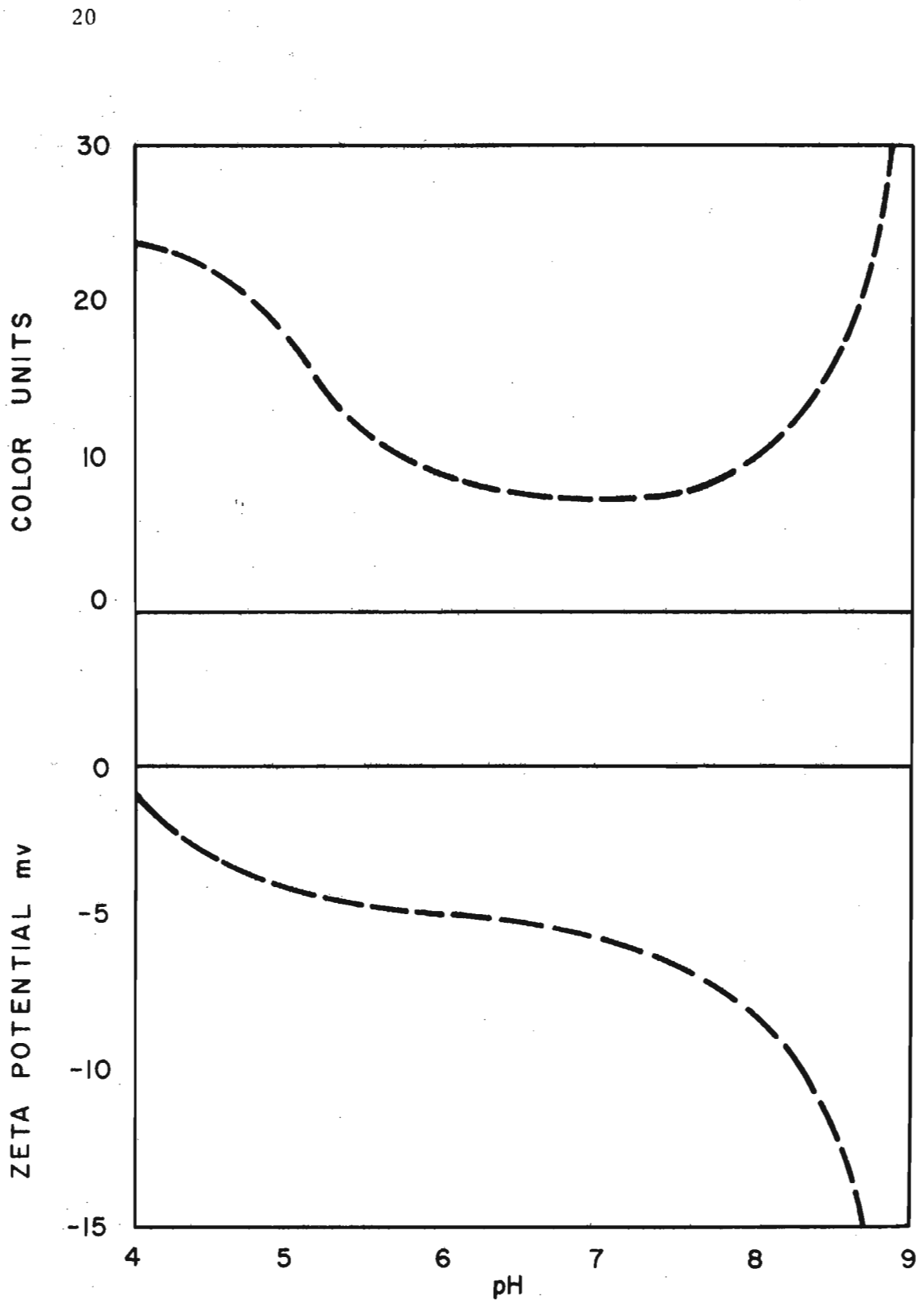


FIGURE 8: EFFECT OF pH ON COAGULATION RESULTS
COAGULANT: FERRIC SULFATE 35 mg/l
RAW WATER: COLOR 64 UNITS
ZETA POTENTIAL -19.6 mv

BIBLIOGRAPHY

1. Soneda, Shinji, Report of the Director of Environmental Sanitation (1951), Department of Health, State of Hawaii.
2. Official Record - Analysis of Water of Waikoloa Stream, Division of Laboratories, State Department of Health, State of Hawaii.
3. Watson, E. J., Belt Collins Associates, Consulting Engineer, Personal Communication, 1965.
4. Thompson, W. Y., Manager, Board of Water Supply, County of Hawaii, Personal Communication, 1965.
5. Abramson, H. A., *Journal of General Physiology*, 12, (469) (711), 1929.
6. Abramson, H. A., *Colloid Chemistry Symposium*, Monograph VI, New York, 1928.
7. Abramson, H. A., Moyar, L. S. and Gorin, M. H., *Electrophoresis of Proteins and Chemistry of Soil Services*, Reinhold, New York, 1942.
8. Lerche, C., *Acta Pathologica, Microbial, Scandinavia Supplement 98* (1), 1953.
9. Mark, H., and Verwey, E. J. W., "Advances in Colloid Science," *Inter-science Publication*, 1950.
10. *Zeta Meter Operating Manual*, 1961, Zeta Meter, Inc., 369-E-149th St., New York 55, New York.
11. Black, A. P., Smith, A. L., "Determinations of Mobility of Colloidal Particles by Microelectrophoresis," *Journal of the American Water Works Association*, 54, (926), August 1962.
12. Briggs, D. R., "A Pyrex All-Glass Microelectrophoretic Cell," *Industrial Engineering Chemistry, Analytical Edition*, 12, (703), 1940.
13. Pilipovich, J. B., *et al.*, "Electrophoretic Studies of Water Coagulation," *Journal American Water Works Association*, 50, (1467), November 1958.
14. Black, A. P., "Basic Mechanisms of Coagulation," *Journal American Water Works Association*, 52, (492), 1960.
15. Black, A. P. and Hannah, S. A., "Electrophoretic Studies of Coagulation for the Removal of Turbidity," *Journal American Water Works Association*, 53, (438), 1961.
16. Black, A. P. and Willems, D. G., "Electrophoretic Studies of Coagulation for the Removal of Organic Color," *Journal American Water Works Association*, 53, (589), 1961.
17. Riddick, T. M., "Zeta Potential and Its Application to Difficult Waters," *Journal American Water Works Association*, August 1961.

18. Burbank, N. C., Jr., Lauderdale, R. A., and Eliassen, R., "Removal of Radioactive Particulate Matter from Water by Coagulation," U.S. Atomic Energy Commission Publication, NYO-444D, 1956.
19. Rock, R. M. and Burbank, N. C., Jr., "Improved Brigg's Microelectrophoresis Cell and Comparisons with the Riddick Cell," *Journal American Water Works Association*, 58, (6) (676), June 1966.
20. Kaufman, W. J., Nesbitt, J. B., Goldman, M. I. and Eliassen, R., "The Removal of Radioactive Anions by Water Treatment," U.S. Atomic Energy Commission Publication AEC NYO-1571, 1952.
21. Black, A. P. and Smith, A. L., "Determination of Mobility of Colloidal Particles by Microelectrophoresis," *Journal American Water Works Association*, 54, (926), August 1962.
22. Stumm, W. and Morgan J. J., "Chemical Aspects of Coagulation," *Journal American Water Works Association*, 54, (971), August 1962.
23. Ockershansen, R. W. and Peterman, C. J., *Discussion Journal American Water Works Association*, 56, (224), 1964.
24. *Standard Methods for the Examination of Water and Waste Water*, APHA, AWWA, WPCF, 12th Edition, 1965.