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INDUCTION OF BIOLOGICAL ACTIVITY IN BAUXITE RESIDUE

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Bauxite residue lakes constitute the major environmental problem at alumina processing plants because their high alkalinity content is hostile to flora and fauna. Bench experiments have been conducted to determine if bauxite residue can be made non-hostile through biological activity.

The experiments were carried out jointly by the University of Georgia's Food Science Department and Alcoa Laboratories. Surprisingly, initial experiments demonstrated that low levels of metabolically injured bacteria were in bauxite residue from an abandoned lake as well as in lake water from an active lake. These bacteria can be induced to multiply by addition of standard laboratory biological nutrients, and the organic acids formed by the bacteria can neutralize the bauxite residue within a two-week period.

Subsequent experiments have shown that addition of ground hay as a nutrient will induce bacteria to grow and neutralize bauxite residue within two weeks resulting in a soil capable of supporting earthworms and plant growth.

INTRODUCTION

Bauxite residue (red mud) is a chemical waste formed as a result of treating bauxite by the Bayer process to recover alumina. The chemical and mineralogical composition of the residue as well as its particle size distribution is highly variable because of differences in bauxite grades and Bayer process operating conditions, but in general, this residue is a highly alkaline mixture of fine particle size metal oxides. The most common method of disposing of the residue is to contain it in dyked areas adjacent to the processing plant. The free moisture content of the residue is also highly variable, normally ranging from 20 to 60 weight percent water, and this water is a dilute caustic solution with pH above 12. The highly alkaline nature of the residue along with any water associated with it make it ecologically undesirable.

Many investigators have attempted to avoid the problem of impounding these wastes by recovering their mineral values. None of the methods are close to economical nor do they in most cases result in a more evironmentally sound waste. Numerous attempts have also been made to find uses for the residue in ceramics, cement or roadbuilding applications. These applications have resulted in small amounts of the residue being used in very isolated situations. The residue can conceivably be used in agricultural applications to help retain moisture in sandy soils, as a lime substitute in acid soils, or to enhance mineral deficient soils, but to date no significant amounts of residue have been used because of the cost of transportation and application. Thus, it is evident that in the foreseeable future bauxite residue will continue to accumulate around the majority of bauxite processing plants.

A limited amount of information is available in the published literature on attempts to rehabilitate land areas with and without neutralization once the residue has been deposited. Two Australian papers authored by Meecham and Bell,[4] and by Hinz and Doettling,[3] report on attempts to establish vegetation cover on abandoned disposal sites using indigenous plants known to survive harsh conditions. These papers conclude that growth can be established on coarse, sandy textured residues (or mixtures of coarse residue and flyash) but that for normal, fine textured residues top dressing with soil (3-7 cm thick) was found to be necessary.

Alcoa of Australia at its Kwinana Works near Perth, Australia has revegetated a 250-acre abandoned residue area. Three steps were made to increase the chances for success of this rehabilitation. First, approximately 500 well points were drilled into the 20 metre deposit. Second, the areas on the surface with low load bearing strength were stabilized by moving coarse residue from the edges. Third, approximately 1 cm of municipal and industrial organic waste was placed on the surface and mixed in (approx. 10 cm) by plowing. The well points continue to be pumped and result in three benefits; 1) the residue reaches a higher percent solids over a period of time, 2) the water table remains below the surface even in times of rainfall, and 3) leaching of alkalinity occurs over a long period of time. In 1976, cereal grasses and a few shrubs were seeded and planted on the area and in 1978 certain areas were fertilized and planted in vegetables. The area continues to have a healthy growth of vegetation, although all plant varieties have very shallow root systems.

Since 1978 Alcoa has been sponsoring a continuing investigation by Duke University.[5] Several species of alkaline-resistant grasses found in western United States were tested for their ability to grow in bauxite residue or treated residue. The study includes greenhouse as well as field tests. Field treatments on the surface of an abandoned residue lake included the use of sewage sludge (2 cm mixed into top 5 cm of residue), paper pulp waste (2 cm/5 cm of residue), Bermuda grass straw (placed on surface), and NPK fertilizer (6/12/6 156 kg per HA). None of the vegetation specimens were successful on untreated residue. The most success was gained on those areas treated with sewage sludge which contained predominantly coarse residue (>100 mesh), although limited success occurred in those areas which were predominantly fine residue. The pH of the sewage sludge treated residue varied from 8.8 for the predominantly coarse areas to 10.2 for the predominately fine areas. Grasses in used in the study are normally found growing on pH 10 soils.

The use of inorganic acids to neutralize residue deposits does not seem to be attractive because it would require the availability of large quantities of waste acids in close proximity to the disposal site to reduce costs, and the salts formed would need to be removed from the residue and separately disposed of before vegetation would grow on the residue. In 1972-74 Alcoa sponsored an unpublished investigation by Auburn University[1] which demonstrated that small plots of fine red mud residue treated with 3 percent by weight gypsum would support Bermuda grass. The study, however, has not been followed up by a large scale demonstration.

The purpose of the present study is to improve our understanding of how bacterial activities can be encouraged to neutralize bauxite residue for the ultimate goal of turning at least some portion of a disposal areas back to healthy soil conditions. The experimental program was carried out jointly by the University of Georgia's Food Science Department and Alcoa Laboratories. The program at the University of Georgia was directed by Dr. M. K. Hamdy.

PRELIMINARY EXPERIMENTS

The initial experiments conducted by Dr. Hamdy at the University of Georgia were directed towards determining if bacteria were present in a bauxite residue and if they could be encouraged to grow and neutralize the residue pH. These test tube experiments were with small quantities of residue from the dry surface of an abandoned impoundment located in Mobile, Alabama. The experiments indicated that small numbers of metabolically injured bacteria were present in the bauxite residue and that the bacteria were mainly bacillus (a spore forming organism) or lactobacillus (a non-spore forming organism). With the aid of standard sterile microbiological nutrients these bacteria could repair their injury and be encouraged to grow in the bauxite residue. The organic acids which are by-products of the bacteria metabolism rapidly reduced the residue from an initial pH of 13 down to as low as 6.

Encouraged by these results, additional samples were obtained from Alcoa's Mobile Works. Four of the samples came from an abandoned bauxite residue impoundment. Two of these samples were from separate locations 0-5 cm below the dry surface of the impoundment and the other two samples were obtained 5-20 cm below the surface at those same locations. A fifth sample was of the bauxite residue slurry issuing from the plant into an active residue impoundment and a sixth sample was of the lake water in that active impoundment. The chemical analyses of these samples is shown in Table 1.

A series of one-litre flask experiments were performed to ascertain if bacteria were present in each of the plant samples and to determine what type of nutrients might be necessary to encourage the growth of those whose by-products would neutralize each sample. At the plant site the samples were collected with sterilized equipment and placed in sterile containers for shipment to the University of Georgia laboratory. In the laboratory precautions were taken to assure that experiments were carried out with sterile equipment and nutrients. The experiments were performed at both 37°C and room temperature. The length of the experiments varied but usually were conducted between 20 and 30 days. These experiments were carried out under aerobic or anaerobic conditions. In some cases small quantities of additional nutrients were added as boosters during the course of an experiment. The nutrient/residue mixtures were examined at intervals for pH level, number and type of bacteria and chemical analyses. The bacterial cell number for aerobic experiments was obtained by plate counts on Tryptic Soy Agar (TSA) incubated at 37°C for 48 hours and reported as colony forming units (CFU) per ml of sample. The same procedure was used for cell number determinations in anaerobic experiments except that sodium thioglycolate media replaced TSA.

A limited number of nutrients were used in these experiments and although the level of these nutrients was varied to gain some insight into their effectiveness, there was no concerted attempt to optimize the nutrient combinations. In the aerobic experiments, the nutrients included glucose (carbohydrate energy source), peptone (nitrogen for amino acids), yeast extract (vitamins and minerals), KH_2PO_4 (phosphate for ribonucleic acids) and $CaCO_3$ (buffer). In the anaerobic experiments these same nutrients were used and in addition sodium thioglycolate (reducing agent) and sodium ascorbate (vitamin C and A, redox controller). In all of these experiments the nutrients were added to deionized water and then mixed with the bauxite residue or lake water.

There were no distinct differences in how the four bauxite residue samples from the inactive impoundment responded to treatment with nutrients. Figure 1 shows typical data for one of these residues with a nutrient combination which gave good results under aerobic and anaerobic conditions. The nutrient media used in this case contained:

	g/L
Glucose	30
Peptone	2.5
Yeast Extract	2.0
KH_2PO_4	0.02
$CaCO_3$	0.01

Under both aerobic and anaerobic conditions the pH of the test slurries dropped rapidly to pH 6.5 with the anaerobic experiments staying at that level while the aerobic pH rose back to about pH 7. The bacterial count of both experiments rapidly increased from a level of 10^4 CFU/ml up to the

TABLE I.

CHEMICAL ANALYSES OF BAUXITE RESIDUE AND LAKE WATER SAMPLES

	Samples from Abandoned Impoundment					
	Sample Near Dyke		Sample 20 m From Dyke		Fresh	Lake
	0-5cm	5-20cm	0-5cm	5-20cm	Slurry	Water
	wt %	wt %	wt %	wt %	wt %	g/L
Al_2O_3	18	15	19	16	29	Al_2O_3 8.5
Fe_2O_3	33	31	23	28	17	T.C. 15.7
SiO_2	7	7	10	8	19	Na_2CO_3 8.9
Na_2O	2	4	6	5	10	
TiO_2	8	12	12	12	3	
% Solids	71	56	67	31	7	

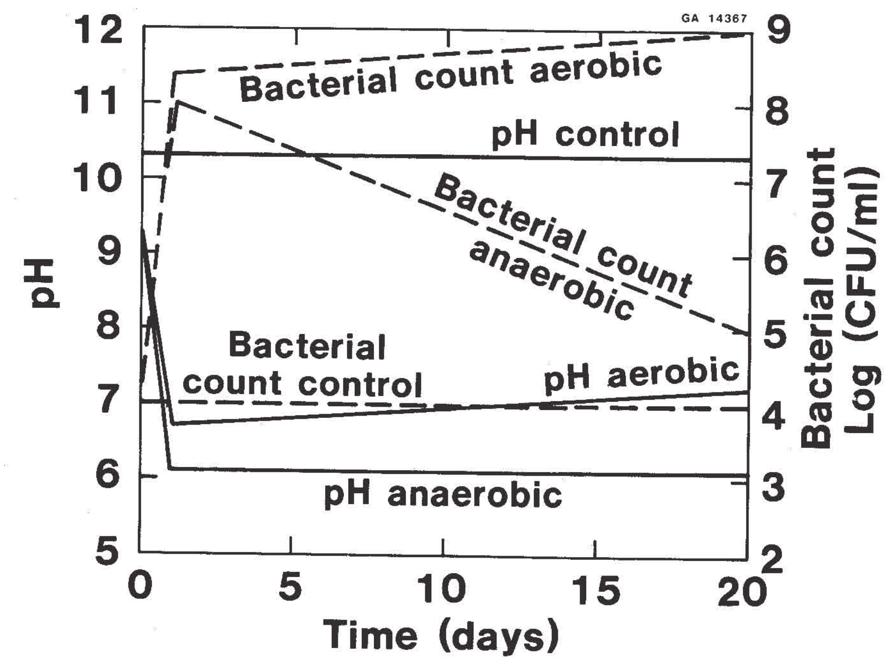

FIGURE 1. EXPERIMENTS WITH BAUXITE RESIDUE FROM ABANDONED IMPOUNDMENT 2:1 NUTRIENT MEDIA: RESIDUE

range of 10^8 CFU/ml with the anaerobic experiment showing a decrease as the experiment progressed. The control data shown are for the same residue slurried up to the same solids concentration with deionized water with no added nutrients. Figure 2 shows data for the fresh plant slurry and lake water. The fresh plant slurry sample had an order of magnitude fewer bacterial count initially and took approximately 10 days for the pH level to drop and the bacterial count to increase to their final levels. In the lake water sample the initial bacterial count was approximately the same as in the abandoned residue samples, but the growth slower (approx. 8 days). The pH response was similar to the abandoned residue samples.

Table 2 lists the chemical analyses of the treated residue and water samples (after filtering and a one displacement wash of the treated residue). The data in Table 2 are not entirely consistent probably because the bauxite residue was not carefully split for experimental samples, however, in general, the indication is that major constituent in the residue affected by bacterial neutralization was soda and that 40-60% of the original soda in the residue was extracted.

From those experiments where nutrient levels were varied it was concluded that phosphate addition alone was not effective and that glucose was essential.

DEMONSTRATION EXPERIMENTS

Two sets of small scale experiments were made to gain some insight into the transport of bacteria through the residue. These experiments were carried out in glass columns 5 cm I.D.x 60 cm long with 13 external sample ports along the length of each column. Column A was charged with bauxite residue (550 grams of residue from the abandoned Mobile impoundment) and 275 ml of media was placed on top of the residue without mixing. The media contained the following per litre of D.I. water: 30 gm glucose, 2.5 gm peptone, 1.5 gm yeast extract, .02 gm K_2HPO_4, and .01 gm $CaCO_3$. Column B had the same amount of residue and media, however, the two were mixed before being added to the column. The experiments were carried out at room temperature. Samples were withdrawn from selected ports at intervals of time and both pH and bacterial analysis were made. In samples from port 1 (5cm below settled residue surface) the pH rapidly decreased to the range of 6-7 and the bacterial count increased to the 10^8 CFU/ml as shown in Figure 3. The data for port 11 (30 cm below the settled residue surface), is shown in Figure 4. In this case the pH and bacterial count response of column A lagged considerably behind Column B. The data from the ports between 1 and 11 followed a consistent pattern with the data shown in Figures 3 and 4. In these small columns the volume removed as samples was promoting to some extent downward movement and mixing. Thus the experiments can not be used to quantify the downward movement of nutreients and bacterial growth but indicate that it will occur. Gaseous by-products were evident in these column experiments and bubble rise could be an important mechanism to promote movement and mixing.

A series of experiments were made to determine if some cheaper readily available nutrient could be used to effect microbial activity in the bauxite residue. In these experiments a paper pulp residue from the Mobile area as well as sewage sludge were used with minimum positive

TABLE 2

CHEMICAL ANALYSES OF TREATED SAMPLES

	Sample from Abandoned Impoundment				Fresh Slurry		Lake Water	
	Before	Control	Aerobic	Anaerobic	Before**	Aerobic	Before **	Aerobic
Residue wt %								
Al_2O_3	16	15	15	15	29	28		
Fe_2O_3	28	31	30	30	17	19		
SiO_2	8	9	8	8	19	17		
Na_2O	5	5	3	2	10	9		
CaO	13	11	12	12	3	2		
TiO_2	12	13	13	13	7	8		
% Na_2O Ext.*	--	6	41	58	---	16		
Liquid mg/L								
Organic carbon		1400	3000	7400	1000	3700	1000	6200
Nitrogen		1	147	262	---	356	---	327
Na_2O		1200	5500	7100	14400	7900	14400	4300
CaO		5	600	3700	---	92		73
Fe_2O_3		1	7	64	---	34		2
Al_2O_3		13	13	37	8500	3300	8500	1300
P_2O_5		3	3	1	---	67		49

*Based on normalizing Fe_2O_3 + TiO_2 when comparing samples.
**Undiluted by media.

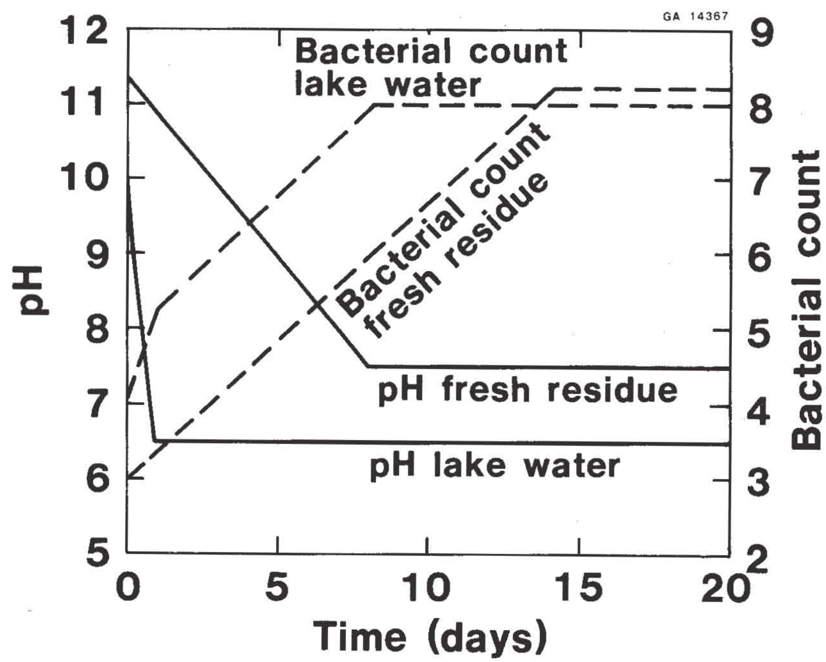

FIGURE 2. EXPERIMENTS WITH FRESH BAUXITE RESIDUE ENTERING ACTIVE LAKE AND WITH LAKE WATER
2:1 NUTRIENT MEDIA: SAMPLE

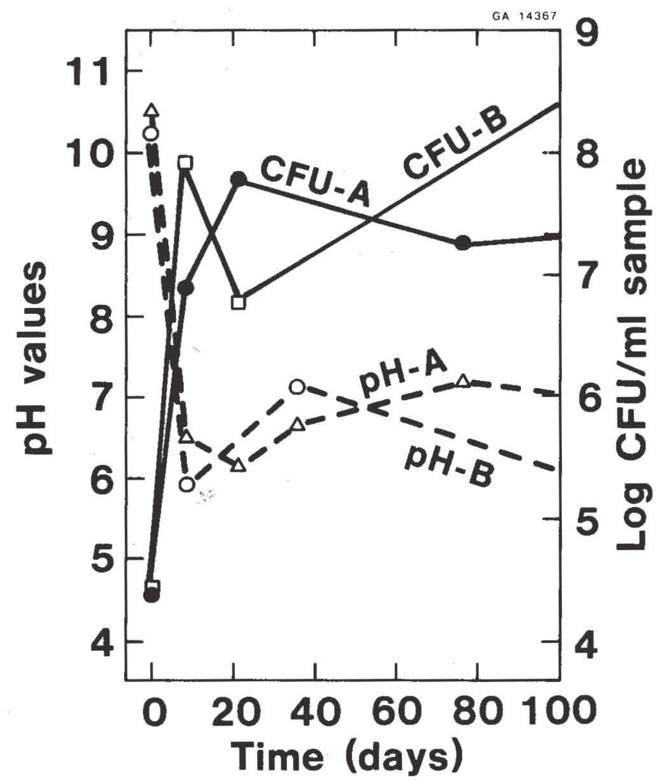

FIGURE 3. COLUMN EXPERIMENT, PORT 1 (A AND B)

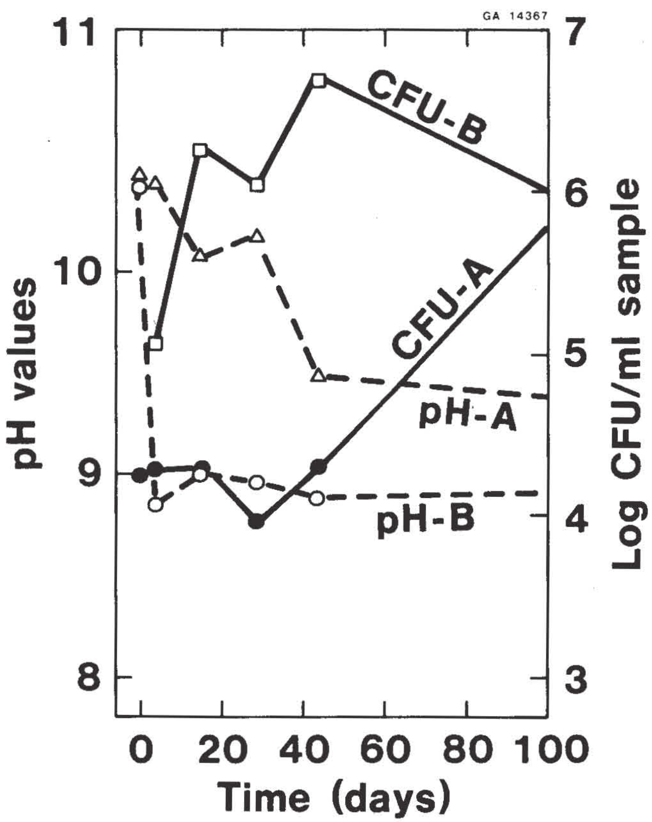

FIGURE 4. COLUMN EXPERIMENT, PORT II (A AND B)

results. Experiments were carried out successfully, however, with two types of finely chopped hay. One was a Johnson and Bermuda grass hay mixture containing 7.9% moisture, 5.0% protein, 2.6% sugar and a cell count of 6 x 10^5 CFU/gm. The second was an alfalfa hay containing 10.8% moisture, 12.6% protein, 8.7% sugar and a cell count of 5 x 10^4 CFU/gm. The latter hay with its higher sugar content gave better results. Experiments in this series included tests: (1) with and without additional nutrients (2) with and without additional water added to the system and (3) with and without the hay being sterilized. The result of these experiments was to demonstrate that hay alone was an adequate nutrient and that it was effective when mixed into the moist residue without additional water. Experiments also showed that hay was effective as a nutrient either sterile or non-sterile.

Data are shown in Figure 5 for an experiment where 24 kg of residue from the abandoned Mobile impoundment was treated with sterilized alfalfa hay in the ratio of 40 gm hay:1000 gm of residue. The hay was mixed into the residue with no water addition. Within 11 days the pH of the mixture dropped to 7.5 and the bacterial count rose to 10^9 CFU/gm of sample.

Portions of the treated residue were then used in some simple experiments to determine if the residue would support plant and animal life. In pot experiments an ornamental grass, Liriopi mujari and common earthworms, Allolobophora caliginosa continue to survive after periods up to 6 months (1981 October). In these experiments water is added as needed but the pots are kept in saucers so that none of the leacheable salts are allowed to leave the pot system.

In the above experiments sterile hay was preferred because unpleasant odors were not noticeable during the experiments. Odors present in all other experiments were not discussed because no generalizations seemed appropriate. It was noticed, however, that many of the experiments had unpleasant odors in the air space above the residue. Some, however, did not and this suggests that it may be possible to prevent unpleasant odors from occuring during this type of residue treatment by introducing quantities of appropriate bacteria with a chosen nutrient so that these bacteria have an opportunity to be dominant during the neutralization process.

ISOLATION OF BACTERIA

In all experiments one of the key measurements has been to culture samples and obtain bacterial counts (CFU/ml or gm). From many of these cultures the predominant microflora were further isolated and cultured so that they could be classified. More than 150 predominant microflora were initially isolated but these reduced down to fifty separate isolates once duplicates were sorted out by grouping the bacteria according to colony morphology and response to selected biochemical tests. A number of specific bacteria identified are listed in Table 3 by groupings. The system being used for classification is that listed in Bergey's Manual of Determinative Bacterology.[2] Not unexpectedly, the biochemical test responses of about one-third of the bacteria do not completely fit any of the identified bacteria in this manual. Classification tests for the remaining isolates are continuing.

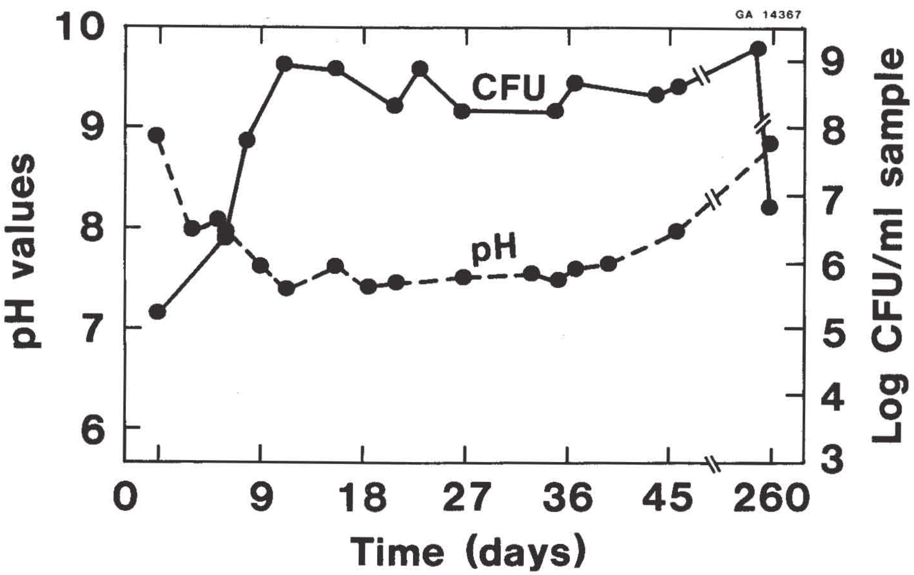

FIGURE 5. RESPONSE OF BAUXITE RESIDUE TO 4% ALFALFA HAY ADDITION

TABLE 3. SUMMARY OF ORGANISM IDENTIFICATION

FAMILY	GENUS	SPECIES
BACILLACEAE rods, G(+), motile, spored, aerobic or facultative	BACILLUS	B. megaterium, B. cereus and others (9 identified and 6 not identified)
LACTOBACILLACEAE rods, non-motile, G(+), facultative, complex nutritional requirements	LACTOBACILLUS	L. casei, L. leichmanii and others (11 identified)
STREPTOCOCCACEAE spherical cells, G(+) non-motile, no spores, facultative	LEUCONOSTOC	L. mesenteroides, L. cremoris
MICROCOCCACEAE spherical, G(+), non-motile aerobic or facultative	MICROCOCCUS	M. varians, M. luteus
	STAPHYLOCOCCUS	S. aureus
PSEUDOMONADACEAE rods, G(-), motile, aerobes	PSEUDOMONAS	P. aeruginosa, P. putrefaciens
ENTEROBACTERIACEAE rods, G(-), motile, no spores aerobic or facultative	FLAVOBACTERIUM ENTEROBACTER PROTEUS	F. rigense E. agglomerans P. vulgaris

The characterization of bacteria found in the bauxite residue experiments is important because it gives insights into the balance of nutrients eventually needed and the types of chemical reaction products that can be expected. It also opens the possibility of introducing bacteria with positive attributes into the treatment process and thus maintaining control of a process that otherwise might be unpredictable. Some of the desireable attributes which were present in certain of the bacteria are:

1. Ability to produce organic acids by-products from carbon sources.
2. Motility
3. Anaerobic or facultative.
4. Ability to produce pleasant smelling by-products.
5. Capable of surviving in alkaline environment.
6. Not pathogenic.

IMPLEMENTATION IN PROCESSING PLANT SYSTEMS

The neutralization of bauxite residue by nutrient addition while appearing promising on small experiments needs to be tried on a much larger scale to demonstrate its feasibility and long term effect. The present experiments indicate that hay can be used as a nutrient and the cost would be approximately $1.80/metric ton dry residue treated with hay valued at $1.00/bale. Conceivably this cost would double with time because the chemically combined soda present in the residue would gradually be released and need to be neutralized by continuing treatments. The cost of the equipment, bacterial cultures, or hay sterilization as needed are not included in the estimate. Depending upon the particular plant site, however, other types of properly balanced nutrient sources may be available at even lower cost.

These experiments suggest ways in which residue treatment could be incorporated into a plant system. Those plants which utilize the "Giulini dry stacking method" could adapt a nutrient and bacteria addition step at some point prior to the residue issuing into the disposal area. Although the small column test showed that bacteria and nutrients can move downward in a residue column with time, it is too large an extrapolation to believe that an abandoned residue impoundment could be treated throughout by merely continuing to add nutrients to the top surface. It would seem more feasible, however, if impoundment had been equipped initially with drains in the bottom to promote the downward movement of nutrients and bacteria. That treatment, however, would at best take an extremely long time (100 years/20 m residue depth). Plowing of nutrients into the top surface of an abandoned residue lake could result in that portion being neutralized and presumably suitable for vegetation growth. Any treatment of residue going to a lake system where the clarified lake water is returned to the Bayer plant seems unlikely because the soluble organics salts formed by the bacterial action would accumulate in the Bayer system and be harmful to plant yields and product purity.

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