National Student Design Competition 1994

PROBLEM

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS
345 East 47th Street, New York, New York 10017

If there are any questions about the design problem, Student Chapter Advisors and design course instructors are asked to contact:

Dr. Davis W. Hubbard
Michigan Technological University
Department of Chemical Engineering
Houghton, Michigan 49931

Telephone number 906-487-2140
Fax number 906-487-3213

Please read the rules on the following pages carefully before submitting a solution to AIChE.

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS
345 East 47 Street, New York, New York 10017

AIChE NATIONAL STUDENT DESIGN COMPETITION 1994

Waste Water Treatment for a Nitration Process

DEADLINE FOR MAILING

Solutions must be postmarked no later than **Midnight, June 10, 1994.**

RULES OF THE CONTEST

Solutions will be graded on (a) substantial correctness of results and soundness of conclusions, (b) ingenuity and logic employed, (c) accuracy of computations, and (d) form of presentation. Accuracy of computations is intended to mean primarily freedom from mistakes; extreme precision is not necessary.

It is to be assumed that the statement of the problem contains all the pertinent data except for those readily available in handbooks and similar reference works. The use of textbooks, handbooks, journal articles, and lecture notes is permitted, and use of the supporting data provided by AIChE for this case study is strongly encouraged.

Students may use any available commercial or library computer programs in preparing their solutions. Students are warned, however, that physical property data built into such programs may differ from data given in the problem statement. In such cases, as with data from other literature sources, values given in the problem statement are most applicable. Students using commercial or library computer programs or other solution aids should so state in their reports and include proper references and documentation. Students are further advised that the problem can be solved without the use of sophisticated computer programs. Judging is based on the overall suitability of the solution, not on skills in manipulating computer programs.

The Student Contest Problem is designed to be solved by individual chemical engineering students working entirely alone, and it is judged on that basis. There are, however, other academically sound approaches to using the problem. The following confidentiality rules therefore apply:

1. For students whose solutions may be considered for the contest:
The problem may not be discussed with anyone (students, faculty, or others, in or out of class) before or during the period allowed for solutions. Discussion with faculty and students at that college or university is permitted only after compete final reports have been submitted to the Chapter Advisor.

2. For students whose solutions are not intended for the contest:
Discussion with faculty and with other students at that college or university who are not participating in the contest is permitted.

3. For all students:
The problem may not be discussed with students or faculty from other colleges or universities, or with individuals in the same institution who are still working on the problem for the contest, until after June 10, 1994. This is particularly important in cases where neighboring institutions may be using different schedules.

Submission of a solution for the competition implies strict adherence to the following conditions:

(Failure to comply will result in solutions being returned to the appropriate Faculty Advisor for revision. Revised submissions must meet the original deadline.)

ELIGIBILITY

- ONLY AIChE NATIONAL STUDENT MEMBERS MAY SUBMIT A SOLUTION. Non-member entries will not be considered.
- Each Faculty Advisor should select the best solution or solutions, not to exceed two, from his or her chapter and send these by registered mail, as per the below instructions, to the Institute.

TIMELINE FOR COMPLETING THE SOLUTION

- A period of not more than thirty days is allowed for completion of the solution. This period may be selected at the discretion of the individual advisor, but in order to be eligible for an award a solution must be postmarked no later than midnight, June 10, 1994.
- THE FINISHED REPORT SHOULD BE SUBMITTED TO THE FACULTY ADVISOR WITHIN THE 30-DAY PERIOD.

REPORT FORMAT

- The body of the report must be suitable for reproduction, that is, typewritten or computer-generated. Tables may be written in ink. Supporting calculations and other appendix material may be in pencil.
- The solution itself must bear no reference to the student's name or institution by which it might be identified. In this connection, graph paper bearing the name of the institution should be avoided.

SENDING THE SOLUTION TO AICHE

- Two copies of each of the solution(s) must be sent to the below address; original manuscript(s) must remain in the possession of the Student Chapter Advisor, or Faculty Advisor, sponsoring the student(s).
- There should not be any variation in form of content between the solution submitted to the Faculty Advisor and that sent to the AIChE office.
- Each copy must be accompanied by the enclosed ENTRY FORM giving the contestant's name, AIChE membership number, college or university, Faculty Advisor name, address, home address, home telephone number, and student chapter, lightly attached to the report. This form will be retained for identification by the executive director of the Institute.
- DEADLINE: Entries must be postmarked no later than midnight, June 10, 1994.
- As soon as the winners have been notified, original manuscripts for first, second, third and honorable mention categories must be forwarded to the office of the executive director as soon as possible.

SEND TO:
Coordinator, Student Chapter Activities
American Institute of Chemical Engineers
345 East 47th Street
New York, New York 10017

DEADLINE: JUNE 10,1994

PROBLEM STATEMENT OUTLINE

AIChE Student Contest Problem

Waste Water Treatment for a Nitration Process

Introduction

Nitroglycerin ($C_3H_5N_3O_9$), a nitrate ester, is one of the most widely used explosives. It is a main component of dynamite and smokeless powder. In addition, it has therapeutic value as a vasodilator in the easing of cardiac pain arising from certain heart conditions.

Nitroglycerin (NG) is currently being manufactured in a continuous flow process using glycerol ($C_3H_8O_3$) and a mixture of nitric and sulfuric acids as basic raw materials. In addition, sodium carbonate and water are required materials for the process. Stringent standards for raw material purity and crude nitroglycerin treatment are required to insure a stable nitroglycerin product. The multi-step process generates several waste water streams containing residual nitroglycerin and inorganic salts, including sodium nitrate, sodium sulfate, sodium bicarbonate and sodium carbonate, which must be subsequently treated.

The current waste water treatment process is not adequate to meet new effluent standards. Recent studies have suggested that efficient and cost effective waste water treatment processes can be designed. On-site engineers have also suggested several possible changes in the current process configuration/operation which may help minimize the amount of waste water generated.

Problem Statement

A design effort is to be undertaken to economically minimize the cost of treatment of waste waters from the nitroglycerin process. A proposed treatment system, described below, is to be selected as the base case for subsequent comparison to alternate treatment processes and/or alternate processing configurations/conditions. List the advantages/disadvantages of any alternatives considered. Prepare an evaluation for the most promising recommended design for wastewater treatment complete with pertinent flow diagrams, mass and energy balances, equipment list and specifications, cost estimates and discounted cash flow analysis assuming a 1995 plant start-up.

An eight year useful lifetime for the process (with zero salvage value) is to be assumed. The incremental addition to the selling price (\$/lb) of nitroglycerin is to be determined based upon a 15% discounted cash flow rate of return on the investment for the waste water treatment system and for any basic process changes recommended. An annual production rate of 1.5 million pounds of nitroglycerin is to be achieved.

Final Report Format

1. Executive Summary - Condensation of Report. Maximum of two (2) pages in length.

2. Introduction - Orient the reviewer to the task assigned.

3. Summary - Summarize the results of your analysis, conclusions, and recommendations. Very briefly tell what options were considered and the advantages/disadvantages of each.

4. Discussion - Present the details of your results including assumptions and their impact. Analyze your results. Tables and graphs need not be included in this section, but can be referenced.

5. Conclusions - Interpret your results. List your conclusions in decreasing order of significance.

6. Recommendations - Emphasize cost reduction and waste discharge minimization.

   Describe any process changes, implementation costs, and operating costs.

7. Attachments - Include as attachments all figures, tables and sample calculations, especially those specified in the Statement of the Problem. Include as a separate attachment a table or list of additional assumptions (beyond those provided in this problem statement) that were necessary for your problem solution.

Current Process Description

Figure 1 presents a schematic of the current process, exclusive of waste water treatment. The process consists of two major sections: the nitration section and the nitroglycerin stabilization section.

Glycerol and a mixed acid solution of nitric and sulfuric acids are fed to the nitration section where the exothermic reaction to form nitroglycerin takes place. Reaction of the glycerol is extremely rapid and, for all practical purposes, 100% complete. Other nitrated compounds, in addition to nitroglycerin, are known to be formed but their quantities may be considered negligible for the purpose of the current design effort.

An emulsion of acidic nitroglycerin and spent acid solution leaves the nitrator and is sent to the acid separator for phase separation. Nominal compositions, temperature and flow rates for the acid separator are given in Table 1. The spent acid is collected for return to the vendor for reprocessing to recover the residual nitric acid, as 98% nitric acid. The vendor is also capable of taking any generated acid water which contains at least 25% HNO_3 and recovering as 98% nitric acid. No cost is incurred for the disposal of spent acid/acidic water since we pay transportation and the vendor gives us a credit equivalent to the transportation cost. Any dissolved nitroglycerin in the acidic water will be recovered as equivalent nitric acid.

The nitration section is a highly specialized system and no changes are to be made in this section (within the dotted line) (Fig. 1) of the plant during the new design effort. A nominal production rate of 2200 lb/hr of acidic nitroglycerin, as indicated in Table 1, is to be maintained to prevent excursions from known, safe operating conditions.

The acidic nitroglycerin from the nitration section is sent to the stabilization section in which nitroglycerin is purified by a series of sodium carbonate-water solution and warm water washes to prevent decomposition (potentially explosive). All process equipment is fabricated from stainless steel, with a polished metal finish similar to that used in the food processing industry, in order to prevent the accumulation of pockets of nitroglycerin within the equipment. The section is designed so that gravity flow is adequate for the flow of the process streams. All wash vessels are fitted with a non-pressure closed lid and operations are conducted at essentially atmospheric pressure.

The acidic nitroglycerin overflows continuously from the top of the acid separator into the soda water washing system. In the first of three mechanically stirred soda wash vessels, the acidic nitroglycerin is emulsified with an equal volume of 12-13 wt.% sodium carbonate/soda water solution to neutralize the dissolved acids. Concentration of soda water may vary to maintain a 1:1 volume washing ratio. A resultant pH of

8 is maintained by slight variation of the sodium carbonate flow rate. Overflow into the second and third washers provides additional residence time. (See Table 2 for washer residence times.)

From the third soda water washer the emulsion enters the soda water separator where the neutralized nitroglycerin gravimetrically separates from the spent wash water. The mole fraction of the various carbonate-derived species, on a water free basis in the spent wash waters, can be estimated as a function of the pH of the soda wash water by assuming equilibrium of the relevant reactions. Figure 2 presents this equilibrium data as a function of pH. Table 3 presents the same information in tabular form. Table 4 lists the relevant reactions and their equilibrium constants at 25°C. The solubility of carbon dioxide can be estimated from Henry's Law constant for CO_2 in water as found in Perry's Chemical Engineering Handbook.

The solubility of nitroglycerin in the spent soda/fresh wash waters may be estimated using the solubility data for water given in Table 5. Water may be regarded as being essentially insoluble in nitroglycerin. Because of specific gravity differences, the nitroglycerin leaves from the bottom of the soda wash separator and flows into the warm water washing section. The spent soda wash water overflows to waste water treatment.

In the last washing steps, warm water (105°F) is added in the volume ratio of 1 to 1 to remove water soluble salts (sodium nitrate, sodium sulfate, sodium bicarbonate and sodium carbonate) from the nitroglycerin product. Two washers as shown are used in series to ensure adequate mixing and contact time before the final separation of the nitroglycerin from the wash water, the latter of which is sent to waste water treatment. The separated nitroglycerin product in the warm water separator is transported by an eductor in water to the nitroglycerin storage facility. The eductor water is maintained in a closed process loop unless the plant is to be shut down for more than a month. Prior to extended shut downs the eductor transfer water (approximately 1000 gallons) is sent to waste water treatment.

Adequate venting and air handling are in place in the plant to prevent workplace air contamination and automatic drowning systems are installed which will rapidly empty all process vessels and dilute the dumped reaction mixtures in the event of a temperature excursion in the process. The layout of the plant, shown in Figure 3, is designed to meet requisite safety standards for production and storage.

Proposed Waste Water Treatment Process

The proposed waste water treatment process involves the collection of the soda water wash waste and the warm water wash waste in the settling tank (1000 gallons capacity) as shown in Figure 1 which, in turn, is to feed the treatment process. The waste water is first sent through a series of four activated carbon beds to remove residual nitroglycerin down to a level of 1 ppm or less and then to an evaporator system which produces dry inorganic salts for subsequent sale/disposal. Discharge water must have less than 100 ppm as nitrates.

Figure 4 presents a schematic of the proposed activated carbon system. The feasibility of such a system has been demonstrated. Fifty-five gallon canisters filled with activated carbon and equipped with a liquid distributor to promote plug flow through the carbon were used in the completed studies. The effluent from the first canister was monitored and when the 1 ppm threshold for nitroglycerin was reached, the first canister in the train was removed and a new fresh canister was added to the end of the train. Available pilot plant data are presented in Table 6.

The spent carbon, still water wet, is mixed with coal for use as a fuel in the coal fired generation plant on the plant site. This disposal method is regarded as being safe provided the nitroglycerin to carbon ratio is less than 1 to 1 on a weight basis. No cost is incurred with spent carbon disposal in this manner. Steel from spent drums can be considered scrap metal.

Figure 5 presents a schematic of the proposed evaporator system. Table 7 presents stream data for the evaporator system based upon a preliminary design recently completed.

Waste Water Handling Alternatives

A number of alternatives for waste water handling have been suggested. In one recent study, ultraviolet light (UV) was shown to degrade nitroglycerin. The available data is given in Figure 6. As shown, UV had relatively little effect on the spent wash water streams but did reduce nitroglycerin in the eductor transfer water since the inorganic nitrate concentration was less than 1000 ppm. For UV to be effective in destroying nitroglycerin, the inorganic nitrate concentra-tion should be less than 1000 ppm. Estimated capital and installed cost of an UV system capable of supplying 120 UV units/hr is $235,000. Operating cost to provide 1 UV unit/1000 gl is $0.0857/ UV unit.

Reverse osmosis and electrodialysis have been suggested as a means of concentrating the inorganic salt solutions but no test data is available. In addition, selected processing to recover/regenerate nitric acid for recycling has been suggested as a possibility.

Modifications of the equipment configuration and/or operation of the stabilization section have been recommended in order to minimize the impact of the waste water streams on the treatment system. These recommendations have included:

1.) Countercurrent flow of wash waters,
2.) An extractive water pre-wash step before the soda water wash,
3.) The use of ammonium hydroxide rather than sodium carbonate for neutralization (sodium hydroxide is not suitable since NG is hydrolyzed by a strong base),
4.) An active air sweeping of the void space of the soda washer to prevent the buildup of a carbon dioxide atmosphere. This is expected to reduce sodium carbonate requirements but may result in excess foaming to the point of overflow of the nitroglycerin containing emulsion in the soda water washers.

Alternatives which tend to minimize the quantity of waste water and/or enhance the value of recovered waste salts appear on the surface to be the most attractive for investigation. Alternatives other than those noted above undoubtedly also exist and should be investigated as deemed feasible and desirable.

Preliminary cost estimates may be based upon the equipment costs found in Peters and Timmerhaus, or Ulrich using Lang's factors for a fluid processing plant. Please cite references, page number and table/figure used for cost estimates. Table 8 summarizes utility and manpower costs to be used. Table 9 provides information on the recovered salt resale/disposal costs.

Other Operational Factors

Since the nitration section of the plant (which is not to be modified) offers excess production capacity, options exist for the scheduling of plant operation in order to meet the requisite yearly production rate for nitroglycerin. Continuous runs of up to 1 month in length may be considered prior to scheduled shut down for maintenance. The plant may also be operated for a period as short as four hours before shut down.

Prior to a run, the acid separator is charged with stored spent acid and the washing train is currently charged with fresh water. For short runs in particular, start-up transients in the composition of the waste waters need to be considered in the design and performance evaluation of any proposed waste water treatment process and used to advantage if possible.

References

M. S. Peters and K. D. Timmerhaus,
Plant Design and Economics for Chemical Engineers,
Fourth Edition, McGraw-Hill, Inc. (1991)

R. H. Perry and D. Green
Perry's Chemical Engineer's Handbook,
Sixth Edition, McGraw-Hill, Inc. (1984)

G. D. Ulrich,
A Guide to Chemical Engineering Process Design and Economics,
John Wiley & Sons, Inc. (1984)

"Chemical Marketing Reporter", published by Schnell Publishing Company, Inc. Weekly publication

Table 1

Operation of the Acid Separator

Temperature: 62°F

Acidic Nitroglycerin
Nominal Flow Rate: 2200 lb/hr
Nominal Composition (wt. frac.)

Nitroglycerin	0.933
Nitric Acid	0.065
Sulfuric Acid	0.002

Spent Acid
Nominal Flow Rate: 2950 lb/hr
Nominal Composition (wt. frac.)

Nitroglycerin	0.025
Nitric Acid	0.106
Sulfuric Acid	0.712
Water	0.157

Table 2

Washer Residence Times

Washers: 2.5 minutes in each washer vessel
Each washer equipped with a 1.5 HP mixer.
Soda water washer operates at 90°F
Warm water washer operates at 105°F
Ratio of washwater to Nitroglycerin must be maintained at 1:1 vol/vol for safety reasons

Separators: 25 minutes for the water phase.
6 minutes for the nitroglycerin phase.

Mole Fraction of Various Carbonate Derived Species versus pH

pH	HCO_3^-	$CO_3^=$	H_2CO_3	CO_2 (dissolved)
1.0000	0.2606E-05	0.1222E-14	0.1498E-02	0.9985E+00
2.0000	0.2606E-04	0.1222E-12	0.1498E-02	0.9985E+00
3.0000	0.2605E-03	0.1222E-10	0.1497E-02	0.9982E+00
4.0000	0.2599E-02	0.1219E-08	0.1494E-02	0.9959E+00
5.0000	0.2540E-01	0.1191E-06	0.1460E-02	0.9731E+00
6.0000	0.2067E+00	0.9696E-05	0.1188E-02	0.7921E+00
7.0000	0.7224E+00	0.3388E-03	0.4152E-03	0.2768E+00
8.0000	0.9587E+00	0.4496E-02	0.5510E-04	0.3673E-01
9.0000	0.9517E+00	0.4464E-01	0.5470E-05	0.3646E-02
10.0000	0.6806E+00	0.3192E+00	0.3911E-06	0.2607E-03
11.0000	0.1757E+00	0.8242E+00	0.1010E-07	0.6734E-05
12.0000	0.2088E-01	0.9791E+00	0.1200E-09	0.7999E-07
13.0000	0.2128E-02	0.9979E+00	0.1223E-11	0.8152E-09

Table 3

Chemical Reactions and Equilibrium Constants at 25°C - Carbonate Derived Species

1. $CO_2(g) \rightleftharpoons CO_2\ (dissolved)$

   Use Henry's Law - Data given in Perry's Chemical Engineers' Handbook.

2. $CO_2(d) + H_2O \rightleftharpoons H_2CO_3$

   $$K_1 = \frac{[H_2CO_3]}{[CO_2]} = 1.5 \times 10^{-3}$$

3. $H_2CO_3 \rightleftharpoons HCO_3^- + H^+$

   $$K_2 = \frac{[H^+]\,[HCO_3^-]}{[H_2CO_3]} = 1.74 \times 10^{-4}$$

4. $HCO_3^- \rightleftharpoons CO_3^= + H^+$

   $$K_3 = \frac{[H^+]\,CO_3^=}{HCO_3^-} = 4.69 \times 10^{-11}$$

5. $H_2O \rightleftharpoons OH^- + H^+$

   $$[OH^-]\,[H^+] = 1 \times 10^{-14}$$

Note: Total Dissolved Carbon

$$= [HCO_3^-] + [CO_3^=] + [H_2CO_3] + [CO_2]$$

$$= [HCO_3^-] \quad 1 + \frac{K_3}{[H^+]} + \frac{[H^+]}{K_2} + \frac{[H^+]}{K_1\,K_2}$$

From which the fraction of each carbonate-derived specie making up the total dissolved carbon can be calculated as a function of pH.

Table 4

Table 5

Selected Properties of Nitroglycerin

Specific gravity 1.6 @15°C

Viscosity 35.5 centipoise @20°C

Nitroglycerin Solubility in Water/Soda Water

0.16 wt% @15°C
0.18 wt% @20°C
0.25 wt% @50°C

Nitroglycerin Solubility in Acidic Water

0.35% in 10% HNO_3 at 20°C
0.60% in 20% HNO_3 at 20°C
1.0% in 30% HNO_3 at 20°C
2.2% in 40% HNO_3 at 20°C

Partition Coefficient for Nitric Acid in Acidic Water/Acidic NG

$$= 30 \; \frac{\text{wt \% } HNO_3 \text{ in acidic water}}{\text{wt \% } HNO_3 \text{ in acidic NG}}$$

Assume equilibrium is reached within the stated retention times of washers and separators.

Assume partition coefficient constant up to 40% HNO_3 in acidic water. Recycle of acidic water may be necessary to ensure a 1:1 volume ratio of wash water to NG.

Assume all H_2SO_4 is extracted into the water phase.

Table 6

Pilot Plant Data

Activated Carbon Treatment
of Nitroglycerin Wastewater

Nitroglycerin loading in wastewater:
1020 PPM

Wastewater flow rate into 55 gallon canister:
10 GPM

Cross sectional area of canister:
3.14 ft^2

Bulk Density of dry activated carbon:
32 lb/ft^3

Breakthrough correlation:

$$Y = 3.90 X - 2.05$$

Where
X is the bed depth of activated carbon (ft.)
Y is the time (hrs) at breakthrough at the 1 PPM threshold

Maximum bed depth in 55 gallon canister:

2 ft.

Cost per drum $700
Includes drum weighing 60 lbs,
containing a nominal 200 lbs of activated
carbon and an internal distributor.

Stream No.	Temp. °F	Press PSIA	State	Flow, lbs/hr	
				Water	Salts
1	55.	---	Liquid	34,300	700
2	194.	---	Liquid	34,300	700
3	210.	---	Liquid	34,300	700
4	208.	---	Liquid	9,363	700
5	212.5	---	Liquid	2,100	700
6	218.2	---	Slurry	1,050	700
7	210.	12.77	Vapor	32,250	0
8	264.	17.19	Vapor	33,300	0
9	250.	30.	Steam	0	0
10	212.	---	Liquid	2,000	0
11	220.	17.19	V-L Mix	36,437	0
12	220.	---	Condensate	34,729	0
13	220.	17.19	Vapor	1,708	0
14	218.2	12.77	Vapor	1,050	0
15	220.	17.19	Vapor	608	0
16	220.	---	Condensate	555	0
17	220.	17.19	Vapor	53	0
18	220.	---	Condensate	1,100	0
19	212.	---	Liquid	33,840	0
20	70.	---	Liquid	33,480	0
21	250.	---	Powder	0	700
22	340.	118.	Steam	1,137	0
23	340.	---	Condensate	1,137	0
24	212.	14.7	Vapor	1,050	0
25	212.	14.7	Vapor	1,544	0
26	212.	14.7	Vapor	50	0

(Refer to Figure 5)

Heat Inputs:

Source	BTU/Hour
Compressor	793,665
Thin-Film Rotor	68,000
Crystallizer Circ. Pump	100,000
Other Pumps	Small

Heat Losses (Estimated):

Equipment	BTU/Hour
Evaporator	200,000
Crystallizer	100,000
Distillate Tank	40,000
Thin-Film Dryer	50,000

Table 7 - Evaporator System Stream Data

Table 8
Utility and Manpower Data

Electricity 3 phase 60 cycle 13.2KV

Steam 4" pipe at 120 PSIG saturated

Air 4" pipe at 95 PSIG

Cooling water 12" main at 152 PSIG static

1800 gpm flowing at 108 PSIG Residual Pressure
Winter temperature 45°F
Summer temperature 80°F

Well Water (Potable) 4" main at 100 PSIG

Cost

$6/1000 lb	Steam
$1/1000 ft^3	Air
$60/Meg Watt Hour	Electricity
$1/1000 gal	Well Water
$.60/1000 gal	River Water
$2.50/1000 gal	Sewage

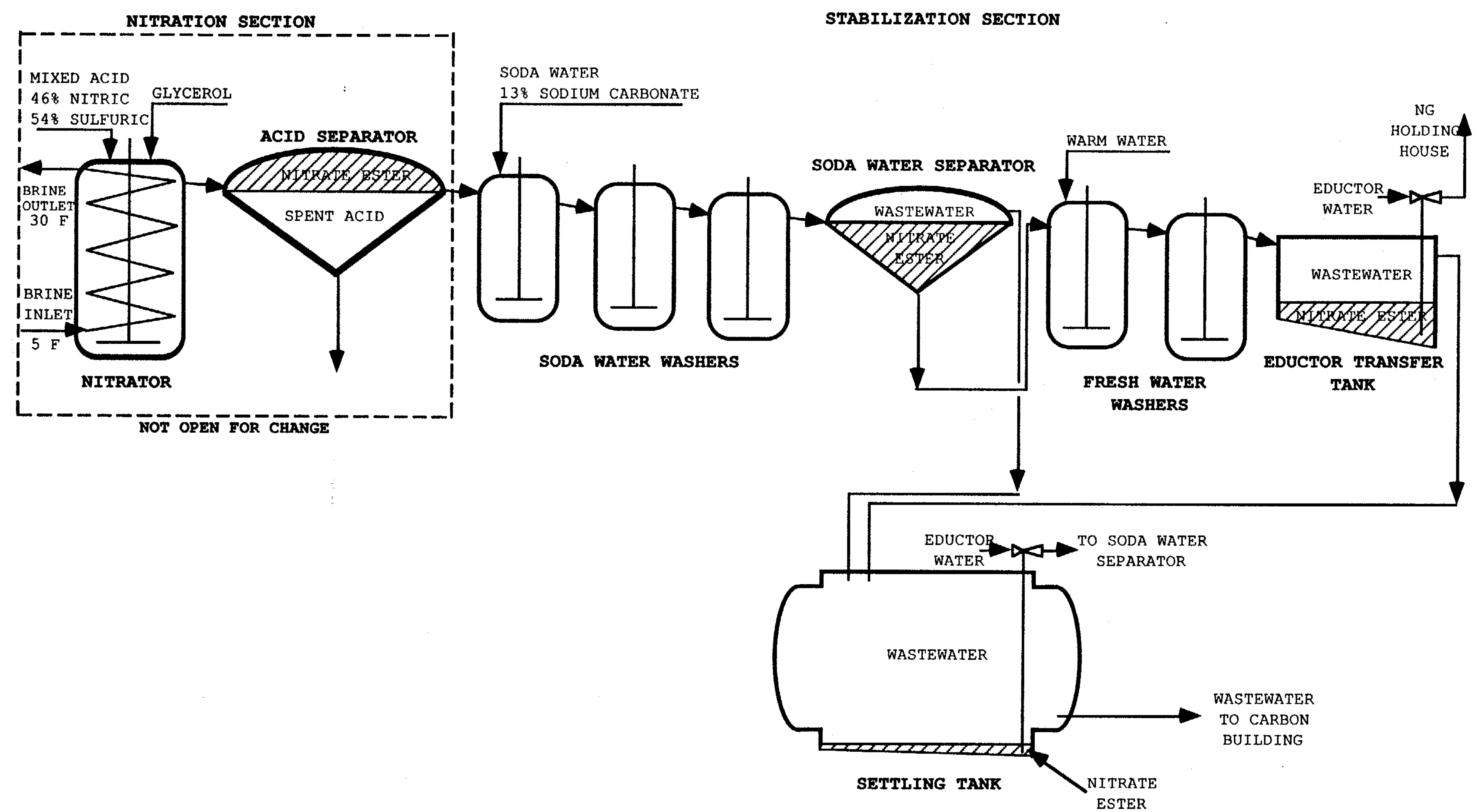
Manhour Labor $62 Labor and Overhead

Table 9
Recovered Salts Re-sale Value/Disposal Costs

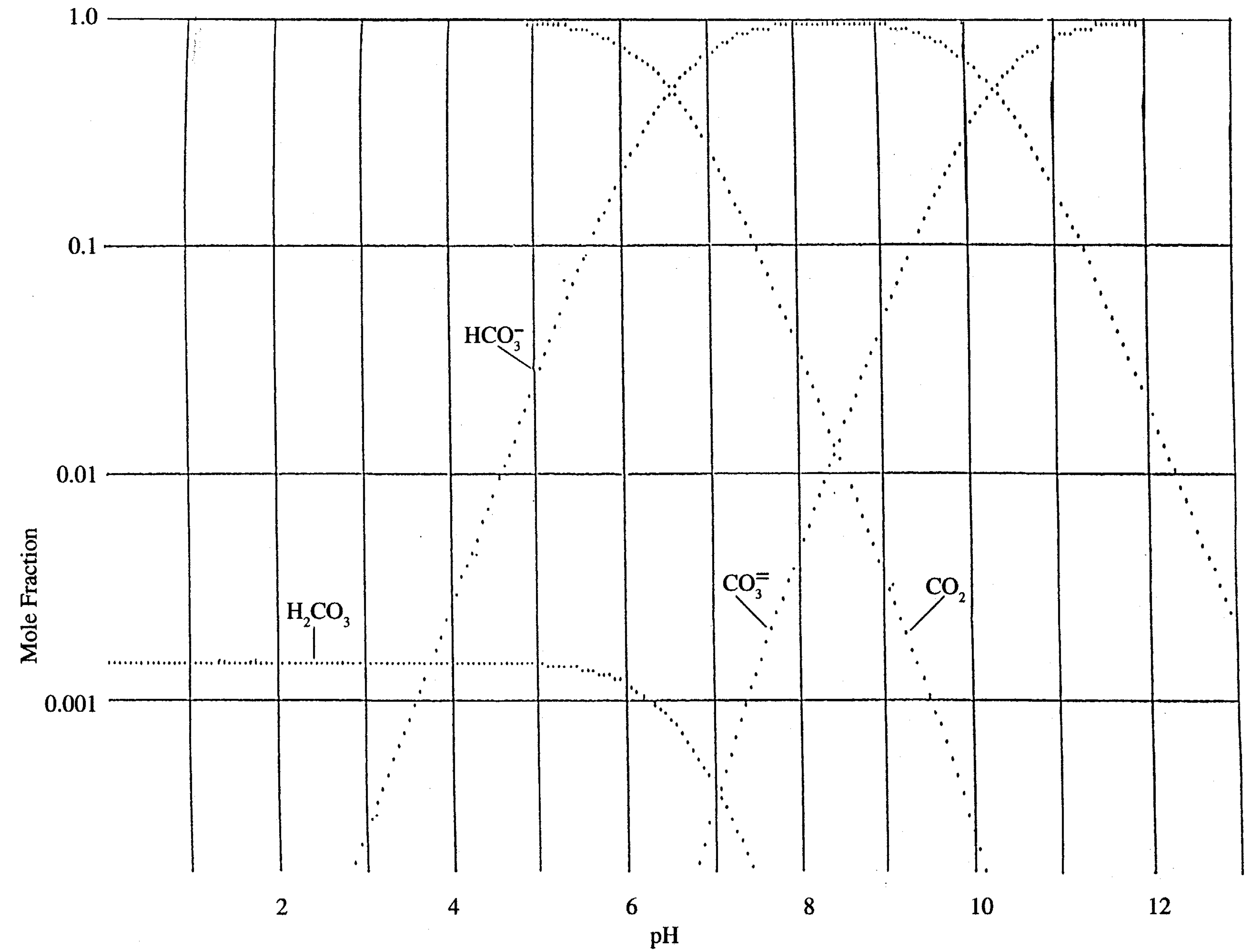
Sodium nitrate salt mixtures disposed of as

hazardous waste $300/ton

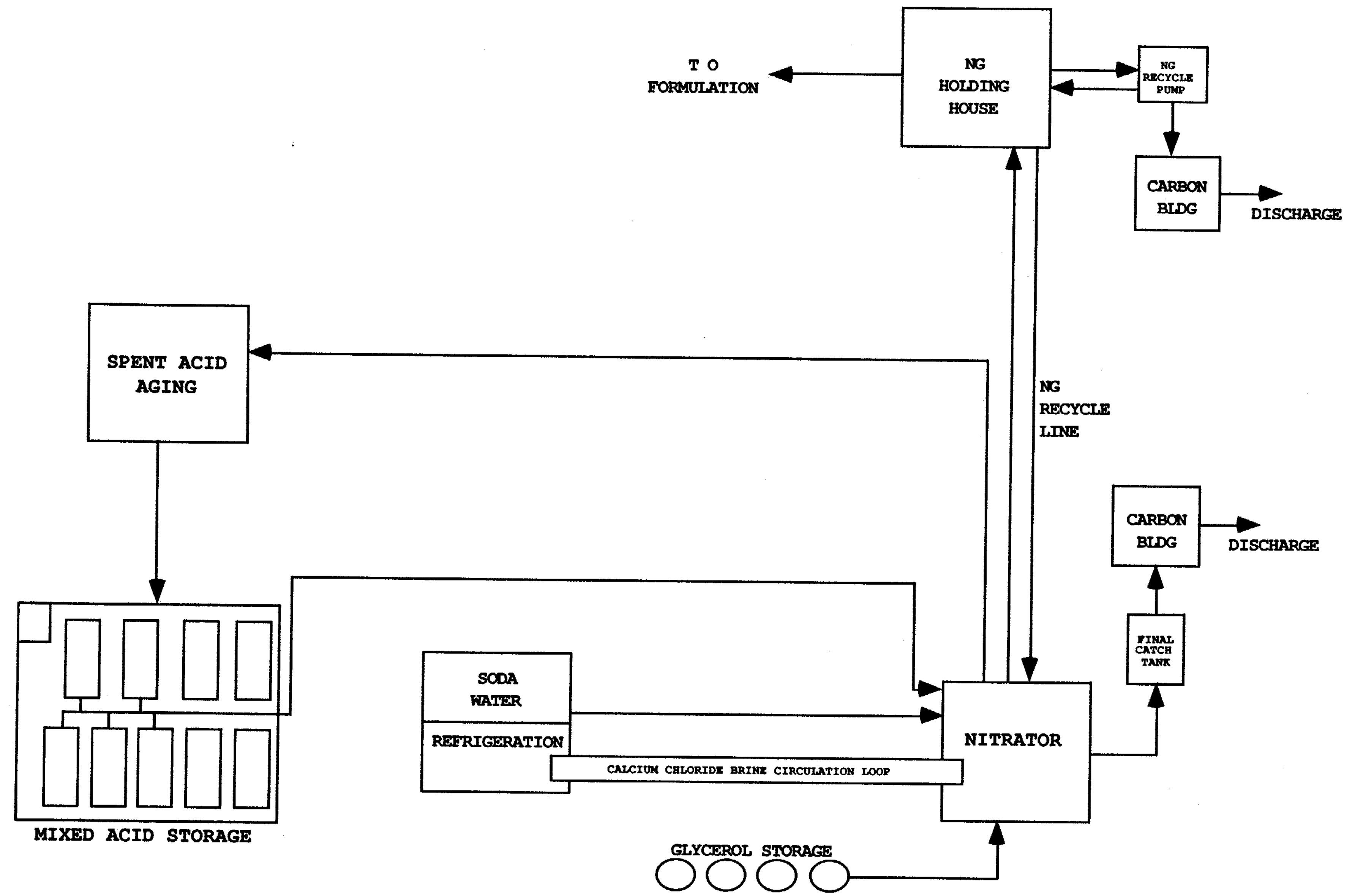
Any chemicals consumed or salvaged should be priced as in "Chemical Marketing Reporter" and assumed cost should be stated.



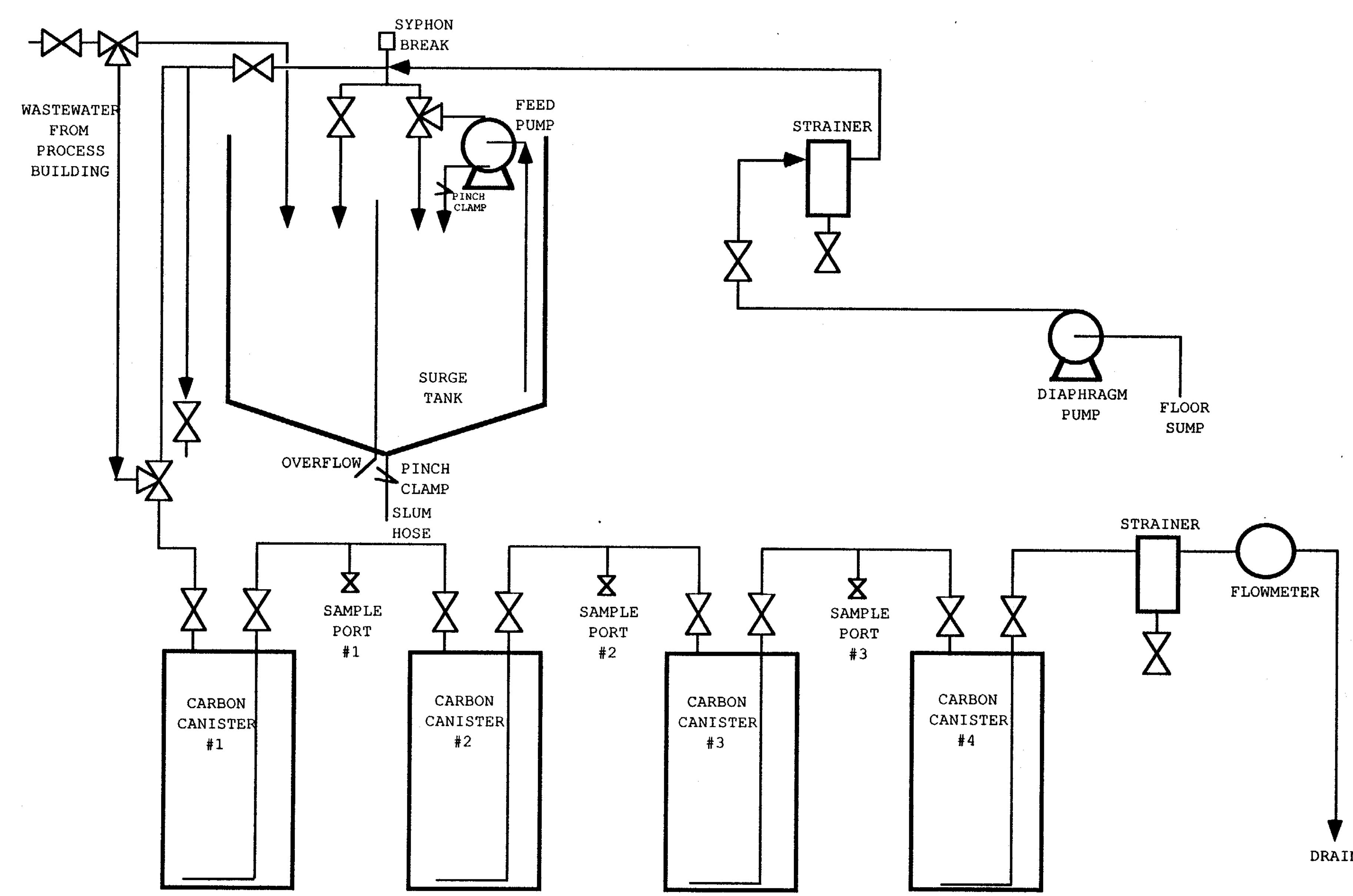
NITRATION PROCESS
FIGURE 1



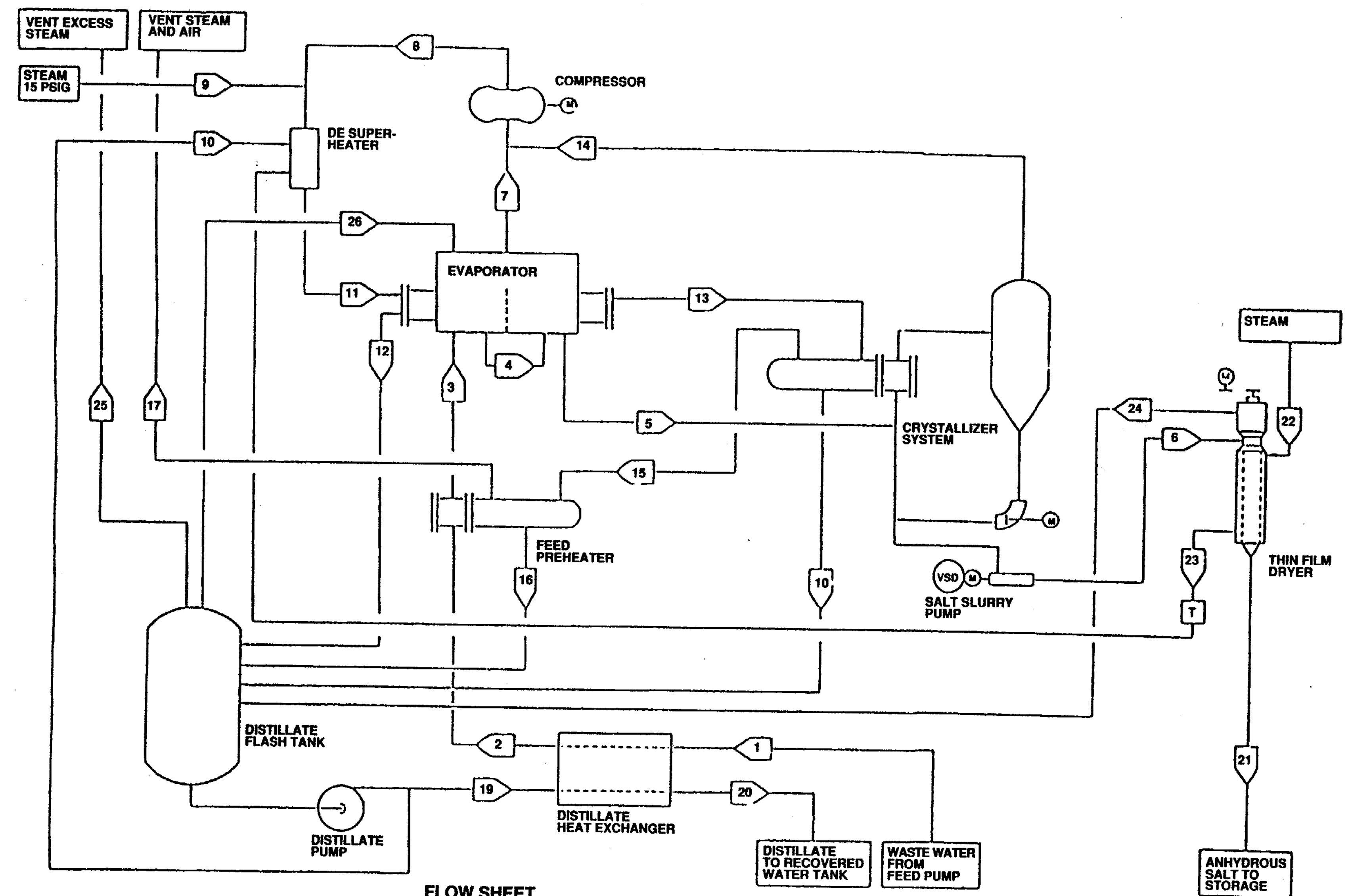
CARBONATE DERIVED SPECIES AS A FUNCTION OF pH
FIGURE 2



NITRATION FACILITY
FIGURE 3



FLOW DIAGRAM FOR CARBON BUILDINGS
FIGURE 4

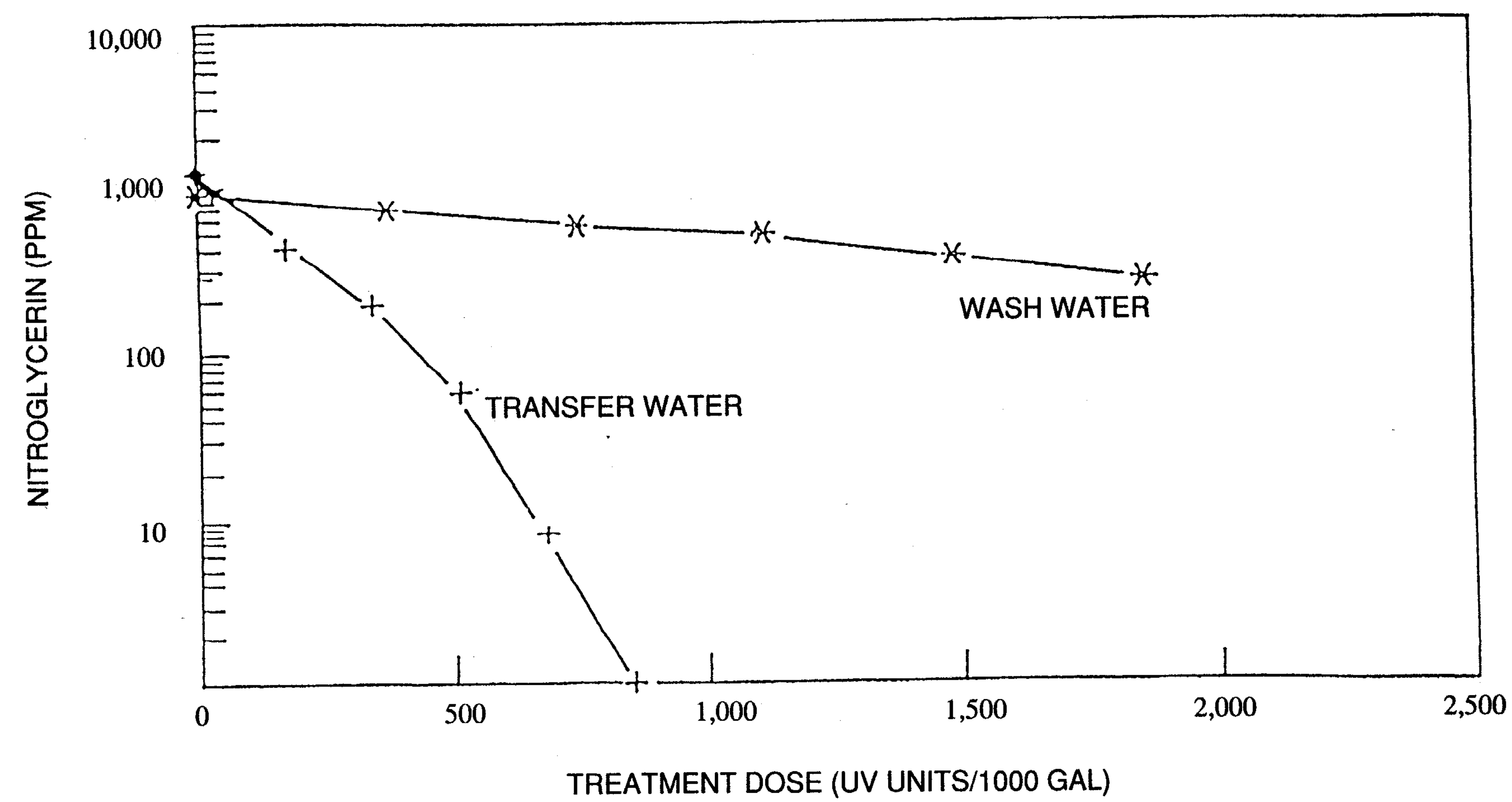


FLOW SHEET
NO SCALE

SCHEMATIC OF THE EVAPORATOR SYSTEM

FIGURE 5

(Refer to Table 7 for Steam Flow Rates)



ULTRAVIOLET-BASED TREATMENT OF NG NITRATION WASTEWATER
FIGURE 6