American
Institute of Chemical Engineers

STUDENT CONTEST PROBLEM

1983

345 East 47 Street • New York, New York 10017

CONTEST PROBLEM

1983

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS STUDENT CHAPTERS

Open Only to Undergraduates or Those
Without a Degree in Chemical Engineering

DEADLINE FOR MAILING

Solution must be postmarked not later than midnight, June 1, 1983

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. In cases where there is disagreement in the data reported in the literature, the values given in the statement of the problem have been chosen as being most nearly applicable.

The problem is not be discussed with any person whatever until June 1, 1983. This is particularly important in cases where neighboring institutions may not begin the problem until after its completion by another chapter. Submission of a solution for the competition implies adherence to the foregoing condition.

A period of not more than thirty consecutive days is allowed for completion of the solution. This period may be selected at the discretion of the individual counselor, but in order to be eligible for an award a solution must be postmarked not later than midnight, June 1, 1983.

The finished report should be submitted to the chapter counselor within the thirty-day period. There should not be any variation in form or content between the solution submitted to the chapter counselor and that sent to the AIChE office. The report should be neat and legible, but no part need be typewritten.

The solution should be accompanied by a letter of transmittal giving only the contestant's name, school address, home address, and student chapter, lightly attached to the report. This letter will be retained for identification by the Secretary of the Institute. 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.

Each counselor should select the best solution or solutions, not to exceed two, from his chapter and send these by registered mail to

J.C. Forman, Secretary
American Institute of Chemical Engineers
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New York, New York 10017

AIChE STUDENT CONTEST PROBLEM

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A Wood Pulp Mill Production Rate Increase Problem

INTRODUCTION

A pulp mill in the Southeastern U.S. produces fully bleached kraft pulp from pine wood. The mill has the capacity to bleach and dry more wood pulp than is presently being processed, so management would like to increase the production of unbleached pulp to take advantage of this capacity. The amount of increase possible is not known; you are asked to prepare a report on the subject.

The report you prepare must include the information asked for in the "Statement of the Problem." Following the "Statement of the Problem," you will find a general description of the kraft process, detailed descriptions of pertinent process units, and necessary technical and economic information. In preparing the report you should also take into consideration the following.

Increasing unbleached pulp production increases the loads in the brown stock washers, black liquor evaporators, cooking liquor manufacture and waste treatment.

Existing digesters are to be used; however, an earlier study has shown that digester production can be significantly increased by the following changes:

1. Increase digester fill rate by (a) using a higher pumping rate and (b) changing from manual valves to automatic valves.
2. Decrease digester heat-up time by heating the liquor as it is pumped from the solution mix tank to the digester.

As a consequence of the increased rate, the brown stock washer efficiency will decrease, but no equipment changes are to be made.

The amount of black liquor going to the evaporators will increase. Although the company will not consider adding evaporator bodies, rearrangement of flow is possible, and external heat exchangers may be added to increase the evaporation potential. For example, an earlier study recommended introducing all the feed into the fourth effect to increase capacity. Then the liquor from the fourth effect goes to the fifth effect and then on to the third effect.

At this time, management does not plan to increase the plant's waste treatment capacity, so the effluent Biological Oxygen Demand (BOD) limits will control the achievable production rate. However, the company management wants to know the maximum achievable production rate within the BOD limits and also the maximum possible production rate if BOD were not a limitation.

STATEMENT OF THE PROBLEM

Your assignment is to:

1. Prepare a flow sheet and material balance for the current maximum production rate of unbleached pulp (pulp flow and liquor flow).
2. Calculate the minimum theoretical digester cycle that can be achieved by increasing the cooking liquor fill rate and the liquor temperature.
3. Size the liquor heat exchanger, the liquor charging pump and liquor charging valve to achieve this capacity. Calculate pipe and valve changes needed at the solution mix tank to meet the cycle. Determine if the solution mix tank must be elevated to maintain the proper NPSH on the pump. Estimate the capital costs of these changes. (Ignore any cost of tank relocation.)
4. a. If there is no change in brown stock washer equipment, what will be the liquor losses with the washed pulp? Shower water rate can be increased but not to exceed a dilution factor of 6. What BOD of mill effluent will result? (It should be recognized that increased shower water will increase the need for evaporation capacity.)
   b. Determine the amount of evaporation capacity increase needed. If this can be provided by evaporator rearrangement and in-line heat exchangers, describe the new flow and estimate the cost of the exchangers.
5. Determine the increase in chemical make-up costs at the higher production rate. Chemical make-up in excess of tall oil spent acid is by salt cake and elemental sulfur addition to liquor before the recovery furnace until the sulfur stack loss exceeds 10 lbs. of sulfur/ton of bleached pulp. Any additional sulfur will be added as NaSH to the white liquor after the causticizing operation.
6. Using the results of (1)-(5) calculate the amount of capital costs this rate can support if a five-year payout of investment is required. How much of the justified capital is available to make other changes?
7. If the effluent BOD found in (4) exceeds the allowable discharge level, determine the maximum production rate that can be achieved with effluent BOD within the limits.
8. Present your findings in summary form with support calculations appended.

DESCRIPTION OF KRAFT PROCESS

Overview

Wood pulp is commonly made from southern pine by the kraft process. In this process the wood is reduced to chip form, and the chips are put in a pressure vessel for digestion by hot alkaline liquor. In this mill the digestion process is conducted in eight batch digesters. The alkaline liquor contains NaOH and Na_2S as active ingredients, and Na_2CO_3 is also present, contributing to the total titratable alkali.

Industry practice refers to alkali in terms of Na_2O required to provide an equal amount of sodium, and the following terms are used:

- Total Alkali—Na_2O equivalent to NaOH + Na_2S + Na_2CO_3
- Active Alkali — Na_2O equivalent to NaOH + Na_2S
- Effective Alkali — Na_2O equivalent to NaOH + ½ Na_2S

Another term used by industry is % sulfidity which is defined as:

$$\frac{Na_2O \text{ equivalent to } Na_2S}{\text{Total Alkali}} \times 100$$

Process specifications for the digestion process state the amount of active alkali and the % sulfidity that are to be used. These specifications also state the temperature at which the process is to be conducted and the length of time at the temperature. The digestion temperature is obtained by circulating the liquor through a heat exchanger external to the digester. (See Fig. 1.)

In the digestion process, the elevated temperature promotes the reaction of the alkaline chemicals with the lignin and carbohydrates of the wood. As the reaction proceeds, the reaction products dissolve in the cooking liquor. Since the lignin exists primarily as a binder between the fibers in the wood, the process aims to dissolve this material with a minimal loss in cellulose. The final product of this mill is a fully bleached pulp, so the digester process must deliver a product with good bleaching characteristics. This requirement results in a process that dissolves about 90% of the lignin, but in the process about 35% of the cellulose material is dissolved.

From the digester, the liquor and undissolved wood solids are blown from the cooking pressure to atmospheric pressure through a line into a blow tank. (See Fig. 1.)

Under this pressure reduction, the wood fibers are separated from each other, and a slurry of fibers and black liquor results. The fibers from southern pine have an average length of about 3 millimeters and an average diameter of about 40 microns, although they are not regular cylinders. The fiber-liquor slurry can be pumped by centrifugal pumps if the fiber concentration is less than 4 to 5% by weight.

When a slurry of fiber and liquor is placed on a septum, such as the wire surface of a vacuum filter, the liquor can pass through the wire leaving a wet mat of fibers on the septum. If a liquid is showered on the surface of this mat while vacuum is applied below the mat, the shower liquor can be drawn through the mat. In addition, the mat can be compacted by the application of a pressure so that additional liquor is expressed from the mat. In a pulp mill, these steps are used to wash the black liquor from the pulp in a countercurrent washing operation. The washed pulp is sent to the bleach plant for further processing. The black liquor is evaporated so that it can be used as a fuel in a furnace. (See Fig. 2.)

In addition to cellulose and lignin, the wood chips contain complex esters of fatty and resin acids. The alkaline conditions of digestion saponify these esters to form a soap material from the acids. This material is not soluble in the liquor, and at an intermediate point in the evaporation process it is possible to separate this soap from the black liquor in a skim tank. This soap is then treated with sulfuric acid and separated into two streams. One stream is crude tall oil which is sold. The other stream contains the Na_2SO_4 of the reaction and the entrained black liquor from the skimming operation. This stream is returned to the 50% black liquor tank.

Combustion of the black liquor makes the kraft process economical because the heating value of the dissolved wood is utilized and the inorganic chemicals are recovered. (See Fig. 3.) As a result of the combustion, the ash from the recovery furnace consists of Na_2CO_3 and Na_2S. When this ash is dissolved in water, green liquor is produced. The causticizing operation follows in which the green liquor is treated with slaked lime. The important reactions in the causticizing operation are:

Lime Slaking: $CaO + H_2O \rightarrow Ca(OH)_2$

Causticizing: $Ca(OH)_2 + Na_2CO_3 \rightarrow 2\,NaOH + CaCO_3 \downarrow$

$$Na_2S + H_2O \rightarrow NaHS + NaOH$$

Lime Burning: $CaCO_3 \xrightarrow[\text{heat}]{} CaO + CO_2$

After causticizing, the solution is called white liquor, and this is used to make cooking liquor needed in digesting. The Na_2CO_3 conversion is not complete so the total titratable alkali typically contains 10-15% as Na_2CO_3.

During the digestion, washing, and evaporation processes, there are losses of Na and S which must be made up if the liquor system is to remain in balance. Typically the make-up is before the recovery furnace, with salt cake (Na_2SO_4) and molten sulfur being added. Sulfur has to be added independently because volatile sulfur compounds lead to losses that are greater than the equivalent Na losses.

In this plant chlorine dioxide is produced for the bleaching process. A sulfuric acid stream is available from this plant. This "spent acid" is used in the crude tall oil separation, so some Na_2SO_4 is made up by this stream.

All liquid waste streams of the pulp mill are collected and directed to aeration and settling basins for treatment. The liquid flows through these basins, and a reduction of BOD of the waste stream results. After sufficient treatment, the effluent is released to a nearby stream. The BOD of the effluent is monitored to assure conformance with governmental regulations.

Operation of Digester (Figure 1)

After a cook has completely blown from the digester into the blow tank, the blow valve is closed, and the top is removed from the digester. A visual inspection is made of the digester to determine that the contents have been completely blown from the vessel. When this fact is confirmed, the chip conveyor is actuated, and the digester is filled with wood chips from the chip silos. When the digester is filled with chips, the digester top is replaced and secured. A signal is sent to the digester operator that the digester is ready for a cook. The average time between the completion of a digester blow and the "ready for cook" signal is 35 minutes. Of this time, 15 minutes is used to feed chips into the digester.

On receiving this signal, the digester operator walks from the operating station to the digester to open the liquor-charging valve manually. This valve is partially opened, the vent valve is opened, and the liquor-charging pump is started. During charging, air is vented, and the maximum liquor addition rate must be such that no liquor is carried into the vent line.

After the required liquor has been pumped into the digester, the pump is automatically stopped, and a signal is given to the operator. The operator then goes to the digester and closes the liquor-charging valve and starts the circulating pump. The average time required for each of these steps is:

1.	Time between digester "ready" signal and start to open valve	1.20 min.
2.	Time to open valve	0.45 min.
3.	Time to pump liquor	6.75 min.
4.	Time to return to digester	1.10 min.
5.	Time to close valve and start circulating pump	0.50 min.
	Total	10.00 min.

When the circulating pump has been started, the digestion process can be started. In this process, the liquor is circulated from the digester through an external shell and tube heat exchanger where steam is used to heat the liquor to the required temperature of 346°F. The time required for the temperature to rise to this set point is dependent upon the flow rate of 150 psig steam. The maximum flow rate of this steam is 45,000 lb/hr.

During this period of rising temperature, the vent valve is open so that the non-condensables and turpentine can be removed from the digester. This flow goes to a surface condenser for collection of the turpentine. When the desired maximum liquor temperature has been reached, this vent valve is closed.

The digester is maintained at this maximum temperature for the length of time required by a computer program that calculates the area under the temperature-time curve. There are 1° or 2°F variations from the desired 346°F so the program results in slight variances in the time of digesting. There are also differences among the eight digesters. The average heat-up time is 68.75 minutes, and the average hold time is 58.5 minutes.

When the computer indicates that the digesting is complete, the operator is signalled and the blow valve is opened. The entire contents of the digester are blown into the blow tank where steam flashes from the superheated mixture and flows to an accumulator for condensation. The reduction in pressure between the digester and the blow tank causes the digested chips to disintegrate into essentially discrete pulp fibers. The average length of time for the blow is 13.5 minutes. All of the digesters blow into a single blow tank.

Brown Stock Washing (Figures 1 and 4)

The pulp and black liquor mixture in the blow tank is diluted with a stream of strong black liquor so that the mixture can be pumped to the train of three brown stock washers. This slurry passes through knotter screens where the large pieces of non-pulped wood are removed. From the knotter screens, the flow is introduced to the first of three brown stock washers. The brown stock washers are horizontal, rotating cylinder, vacuum filters on which the pulp fibers form a mat. The vat liquor drains through the mat, and additional liquor of lower solids concentration is showered on the mat for washing. At the discharge from the cylinder, the mat is compacted by a pressure roller before being lifted from the cylinder. This compacted mat is then fed to the second washer and the operation repeated. Washing is accomplished by using hot water as shower liquid on the third washer. The washed pulp is stored for bleaching. Strong black liquor is removed from the filtrate of the first washer and pumped to the evaporators for concentration.

Brown stock washer calculations are described in the Appendix.

Black Liquor Evaporators (Figure 2)

The black liquor from brown stock washing is fed to both the fourth and fifth evaporator effects. The liquid from these two effects is mixed and fed to the third effect. Liquor from the third effect flows to a soap skim tank in which a soapy material that is to be treated for recovery of crude tall oil is removed from the surface. The underflow from the skim tank is returned to the second effect of the evaporators. Liquor from the second effect is fed to the first effect, and then liquor flows from the first effect to a 50% solids storage tank. Liquor from this tank is fed to a concentrator effect where the solids content is increased to 63% solids. (This concentrator is also a long tube, vertical evaporator.) The resulting heavy black liquor is then fed to the recovery furnace for burning of the organic material and recovery of the inorganic material. To make up for sodium and sulfur losses during the process, salt cake may be added to the liquor before combustion.

The vapor side of the evaporators flow countercurrent to the liquor flow. In this evaporator system, steam is admitted to both the concentrator and first effect. Vapor from the concentrator and the three flash tanks shown in Figure 2 mixes with the vapor flow from the second effect and is used in the third effect. Vapor from the first effect is used in the second effect. The third effect vapor is used in the fourth effect and fourth effect vapor is used in the fifth effect. Vapor from the fifth effect is condensed under vacuum. This condensate is mixed with the condensate from the second, third, and fourth effects and used in brown stock washing.

Digester Liquor Making (Figures 3 and 5)

White liquor is produced in the inorganic chemical recovery cycle by reacting lime with the green liquor from the recovery furnace. The resultant mixture is clarified to remove the $CaCO_3$ and other insoluble material. This clarified white liquor is pumped to digesting where the concentration is adjusted by dilution with water in a solution mix tank.

Enough liquor for one digester charge is produced in the mix tank. This tank is actually the upper compartment of a two-compartment vessel. When the proper concentration and volume of liquor have been produced, a valve is opened and the entire contents of this mix tank flow into the lower compartment through an interconnecting pipe. This compartment is the digester use tank.

The digester liquor remains in this tank until the operator of the digester pumps it into the digester.

Mix Tank fill time =	9.7 minutes
Use Tank fill time =	11.3 minutes
	21.0 minutes turn-around

OPERATING INFORMATION

The average turn-around time for a digester is 185.375 minutes. For the eight digesters this results in 62.14 digester charges as the maximum number in a 24-hour period. Experience has shown that over an extended period of time, such as a month, the average number of digester charges that can be obtained is 90% of the maximum number.

For any equipment design the maximum instantaneous rate should be used. This rate is also to be used when calculating chemical losses from the brown stock washers.

The mill operates 24 hours per day throughout the year, but shutdowns for scheduled repairs and holidays result in 350 operating days per year.

EQUIPMENT SPECIFICATIONS AND DATA

Digester Specifications

Volume available for wood	4,150 ft³
Vessel Weight	100,000 lb
Specific heat (vessel)	0.12 BTU/lb - °F
Diameter	12'-4"
Elevation at liquor addition line	103'-0"
Diameter of vent nozzle	3"
Diameter of vent line	6"
Digester Spacing	20 ft
Length of longest vent line	400 ft
Digester wall temperature after chips loaded	190°F

Digester Heat Exchanger Specifications

Liquor Circulation rate	3,000 gpm
Steam Flow, maximum	45,000 lb/hr
Steam pressure	150 psig - 450°F
Surface Area	1,600 ft²
Initial Liquor Temperature	180°F

Existing Pump Data (Figure 1)

Weak Black Liquor	10,000 gpm
Intermediate Black Liquor	10,000 gpm
Strong Black Liquor	10,000 gpm
Cooking Liquor	3,100 gpm, 150 HP motor, 12-¼" diameter impeller (See Fig. 6.)

Piping from Solution Mix Tank to Digester

Equivalent Pipe Lengths to Most Distant Digester

Pipe Dia.	Length
12"	932 ft
10"	100 ft
6"	90 ft

The liquor addition valve is a 10"-diameter gate valve located in the 12" piping. This valve is normally opened about 40% of its travel.

Full flow C_v = 6,350
40% travel C_v = 1,270

Elevation of charging pump = 57'-2"
Note: "C_v" is defined in the *Chemical Engineer's Handbook*, pp. 5-35, 5-36. (See reference 1)

Evaporator Data

	Temperature, °F Liquid	Temperature, °F Vapor	% Solids	U BTU/hr ft² °F
Evaporator Flash	210	192	50.0	—
Evaporator 1	269	285	48.0	318
Evaporator 2	234	252	33.2	284
Evaporator 3	200	224	26.2	242
Evaporator 4	170	192	19.3	269
Evaporator 5	143	166	20.5	281
Concentrator	251	285	61.8	148
Concentrator Flash	219	192	63.0	—
Condenser	—	139	—	152

Feed Rate during test — 636,000 lb/hr @ 13.5% solids

Brown Stock Washer Data (See Appendix for calculations)

- Maximum filtrate velocity in downleg — 10 fps
- Down leg — 20" schedule 40 pipe
- Pulp consistency leaving each washer — 18%
- Vat consistency — 1% except as limited by maximum filtrate flow and not to exceed 1.8%
- Dilution Factor — 4 pounds of water/pound of dry pulp

The dilution factor (D) is the amount of wash water used which is in addition to the amount of water equivalent to the mat liquor accompanying the pulp leaving Washer 3. Thus, $W_{w3} = W_{P3} + D$

Temperatures: Blow tank — 210°F; Wash water — 140°F; Black liquor leaving washer No. 1 — 190°F

Test runs of the brown stock washers were conducted to determine the effects of production rate and dilution factor on the Displacement Ratio. Results of these tests are given in the table below.

Brown Stock Washer Data

Unbleached Pulp Production Rate (Bone Dry tons/day)	Displacement Ratio @ Dilution Factor 0	2	4	6
650	.40	.45	.50	.50
725	.35	.40	.45	.47
775	.30	.35	.40	.42
825	.25	.30	.35	.38

Solution Mix Tank

Inside Diameter = 15'-6"

Pipe and fittings between compartments in order of liquor flow:

Pipe or Fitting	Length	
10"	9"	
10" ell	standard	
10"	8 ft-6"	
10"-8" reducer		This portion of piping can be changed to allow higher liquor flow rates. (start)
8"	6 ft	
8" ell	standard	
8"	15 ft	
8" ell	standard	
8"	2 ft	
8" butterfly valve		
8"	3 ft	
10"-8" reducer		(end)
10"	7 ft	
10"-45° ell	standard	
10"	9"	

Heat Exchanger Design Criteria

- Minimum Liquor Velocity — 6 fps
- Maximum Liquor Velocity — 12 fps
- Maximum Tube Length — 24 ft
- Tube Material — 316 stainless steel

Digester Liquor Valve Data

	C_v
10" reduced bore plug valve	2275
10" full bore plug valve	5950

Solution Mix Tank Valve Data

	C_v
8" butterfly valve	2000
10" butterfly valve	3120
12" butterfly valve	4800

TECHNICAL DATA

Yield and Material Balance Information

- Unless otherwise specified, yields are based on moisture-free wood.
- Unbleached pulp yield — 45% of the dry wood charged to the digester.
- Bleached pulp yield — 90% of unbleached pulp yield.
- Tall Oil — 20 lb/ton of wood.
- Turpentine — 2.3 lb/ton of wood.
- Total sulfur losses — 30 lb/ton unbleached pulp.
- Lime make-up — 10% of lime usage.
- Waste from knotters is insignificant.

Environmental Information

- BOD from brown stock washer operation = 0.2 lb/lb black liquor solids leaving Washer 3 with pulp.
- BOD from rest of plant — 82 lb per bleached ton per day
- Maximum allowable sulfur emission from recovery furnace stack — 10 lb S/ton of bleached pulp
- Aerator removes 86% of BOD
- Effluent from aerator, allowable discharge values (averaged monthly):

Daily Average Bleached Pulp Production	Daily Average BOD Effluent
(tons/day)	(lb/day)
550	8,250
600	9,000
650	9,250
700	9,500
750	9,750

Digester Liquor Specifications

- Liquid/wood ratio — 3.5 (lbs of total liquid/lb of dry wood, including the water in the wood chips)
- Liquor temperature in solution mix tank — 180°F
- Steam pressure available for preheating liquor — 50 psig (saturated)
- Solution mix tank concentration — 10.25% Na_2O (Total alkali), weight basis
- Chemical composition expressed as Na_2O
  - $NaOH$ — 60%
  - Na_2S — 28%
  - Na_2CO_3 — 12%
- Strong white liquor concentration — 8.48 lb Na_2O/ft^3 (Total alkali)
- Strong white liquor density — 68.6 lb/ft^3

Wood Chip Characteristics

Average Moist Content — 52%
Bone dry weight per cubic foot — 12.5 pounds
Dimensions (average): length - ¾"; width - 1"; thickness - ⅜"
Surface area/chip = 12 in^2
Specific heat @ 52% H_2O) - 0.68 BTU/lb - °F
Average temperature = 80°F
Density of wood @ 52% H_2O and 80°F = 40.6 lb/ft^3
Shape factor of chips — 0.50 (See reference 2)

Chlorine Dioxide Manufacture

- ClO_2/ton bleached pulp = 16 lb

Spent Acid Contents	lb/lb ClO_2
Na_2SO_4	2.26
H_2SO_4	3.20

- Spent acid rate per minute = 11.5 lb/tpd ClO_2
- Spent acid concentration = 50% H_2SO_4 by weight
  Note: tpd = tons per day.

Tall Oil Processing

- Minimum H_2SO_4 required = 0.25 lb/lb tall oil
- Skimmings composition (weight %): Tall oil — 40%; Black liquor — 60%

Properties of Cooking Liquor

Temp. °F	Viscosity - Centipoise	Density (lb/ft^3)
120	0.95	66.7
140	0.79	66.3
160	0.65	65.9
180	0.55	65.4
200	0.47	65.1

Note: For pressure drop of cooking liquor flowing through wood chips use method in *Chemical Engineers Handbook*, pp 5-52 ff. (See reference 2)

Properties of White Liquor

For physical properties of white liquor, not specified, the values for NaOH solutions of equivalent strength may be used.

Properties of Black Liquor

% Solids	Boiling Point Rise, °F
12	3
25	6
32	8
42	12
50	16
62	26

Specific heat of black liquor solids — 0.28 BTU/lb - °F

ECONOMIC DATA

General

The profit before taxes that can be realized from an increase in production of 1 ton (bone dry) of bleached pulp is $275. Increased chemical usage per ton and additional capital investment reduce this value.

- Increases in power must be supplied by purchase @ $0.05 per kwh.
- Any steam used in new heat exchangers costs $5.00 per million BTU.
- Investment Tax Credit — 10% of capital, deductible in first going year.
- Company Income Tax Rate — 46%
- Property Taxes and Insurance — 2% of capital
- Depreciation — 5% per year
- Payout Requirement — 5 years
- $\text{Payout Time} = \dfrac{\text{Fixed Capital Investment}}{\text{Annual Net Profit + Depreciation}}$

It may be assumed that the inflation effect on pulp price and cost items will offset each other, so that the extra ton spread will remain constant.

1983 Equipment Costs

Heat Exchangers Costs:

Heating Area - ft^2	$/$ft^2$
1,000	$67
1,500	57
2,000	54
5,000	50
10,000	49

Electric Motor Costs:

HP	$
150	$4,400
200	6,000
250	7,600
350	8,800

New Pump Impeller Cost — $1,500

316 SS Pipe Costs:

10"	$60/ft
12"	$90/ft

Digester Liquor Valve Costs:

	Cost/Valve
10" reduced bore plug valve	$ 7,300
10" full bore plug valve	17,000

Solution Mix Tank Valve Costs:

	Cost
8" butterfly valve	existing
10" butterfly valve	$6,800
12" butterfly valve	8,800

Chemical Costs

Salt cake — $0.042/lb
Sulfur — $0.075/lb
ClO_2 spent acid is available at no cost
50% of added elemental sulfur lost in stack gases
95% recovery of salt cake in recovery furnace
NaSH — $0.16/lb
Purchased lime — $0.038/lb
Reburned lime — $0.015/lb

Installed Costs of Equipment

Equipment	Installation Factor
Heat exchangers	3.0
Pumps and motors	4.0
Valves and piping	2.5

Installed cost = equipment cost × installation factor
Management, Engineering and Construction Overhead costs = 0.5 × installed cost

APPENDIX

Brown Stock Washer Calculations

Washing in a countercurrent system of vacuum washers is accomplished by two mechanisms: (1) by dilution in the vat with liquor of lower concentration than that liquor which accompanies the pulp, draining this liquor from the pulp mat as the washer drum rotates and (2) by partial displacement of this contained liquor by the shower liquor.

Perkins, et al, have developed a calculation method that has been found to be applicable to the washers in this pulp mill. (See reference 3).

Operating data have been obtained to determine the effects of dilution factor and pulp flow rate on displacement ratio. Selection of a pulp flow rate and dilution factor and application of the following equations allow the calculation of the solids leaving with the pulp from the third brown stock washer. Figure 4 and the table of definitions below describe the various streams.

- S_1 = % solute in liquor accompanying pulp leaving Washer 1
- S_2 = % solute in liquor accompanying pulp leaving Washer 2
- S_3 = % solute in liquor accompanying pulp leaving Washer 3
- S_b = % solute in undiluted blow tank liquor
- R = Solids reduction ratio
- $R_1 = S_1/S_b$
- $R_2 = S_2/S_1$
- $R_3 = S_3/S_2$
- S_{s_m} = % solute in shower liquor (For Washer m, m = 1,2,3)
- S_{v_m} = % solute in vat liquor (For Washer m)
- S_e = % solute in liquor to evaporators
- W_{P_m} = Weight of liquor accompanying pulp leaving the washer at solids S_m (pounds per pound dry pulp)
- W_{ts_m} = Weight of total shower liquor at solids S_{s_m} (pounds per pound dry pulp)
- $W_{ts_3} = W_{P3} + D$
- D = Dilution factor (pounds of water per pound dry pulp)
- W_{v_m} = Weight of vat liquor at solids S_{v_m} (pounds per pound dry pulp)
- W_b = Weight of liquor accompanying pulp in blow tank
- W_e = Weight of liquor going to evaporators (pounds per pound dry pulp)
- $D.R._m$ = Displacement ratio =

$$\frac{S_{v_m} - S_m}{S_{v_m} - S_{s_m}} \quad \text{(For Washer m)}$$

- $$R_{g_m} = \frac{\text{shower liquor in sheet from Washer m}}{\text{total shower liquor}}$$
  $(= R_{s_m}\,(D.R.)_m)$
- $R_{s_m} = W_{P_m}/W_{ts_m}$ (For Washer m)
- $R_{v_m} = W_{P_m}/W_{v_m}$ (For Washer m)
- $R_b = W_b/W_{P3}$
- $R_e = W_{P3}/W_e$
- $$\% \text{ Consistency} = \frac{\text{pounds dry pulp}}{\text{pounds liquor + pounds dry pulp}} \times 100$$
- $$R_3 = \frac{(1 - D.R._3)\,[R_{v_3} + (1 - R_{v_3})\,R_{s_3}]}{1 + R_{s_3}\,(1 - D.R._3)\,(1 - R_{v_3})}$$
- $$R_2 = \frac{(1 - D.R._2)\,[R_{v_2} + (1 - R_{v_2})\,R_{s_2})}{1 + R_{s_2}\,(1 - D.R._2)(1 - R_{v_2})\,R_3 - R_{s_2}\,(D.R._2)(1 - R_3)}$$
- $$R_1 = \frac{(1 - D.R._1)\,[R_bR_{v_1} + (1 - R_bR_{v_1})\,R_{s_1}]}{1 + R_e(1 - D.R._1)(1 - R_bR_{v_1})R_2R_3 - R_{s_1}(D.R._1)(1 - R_2R_3)}$$
- $S_3 = R_1R_2R_3S_b$
- $$S_e = \frac{W_bS_b - W_{P3}S_3}{W_b + D}$$

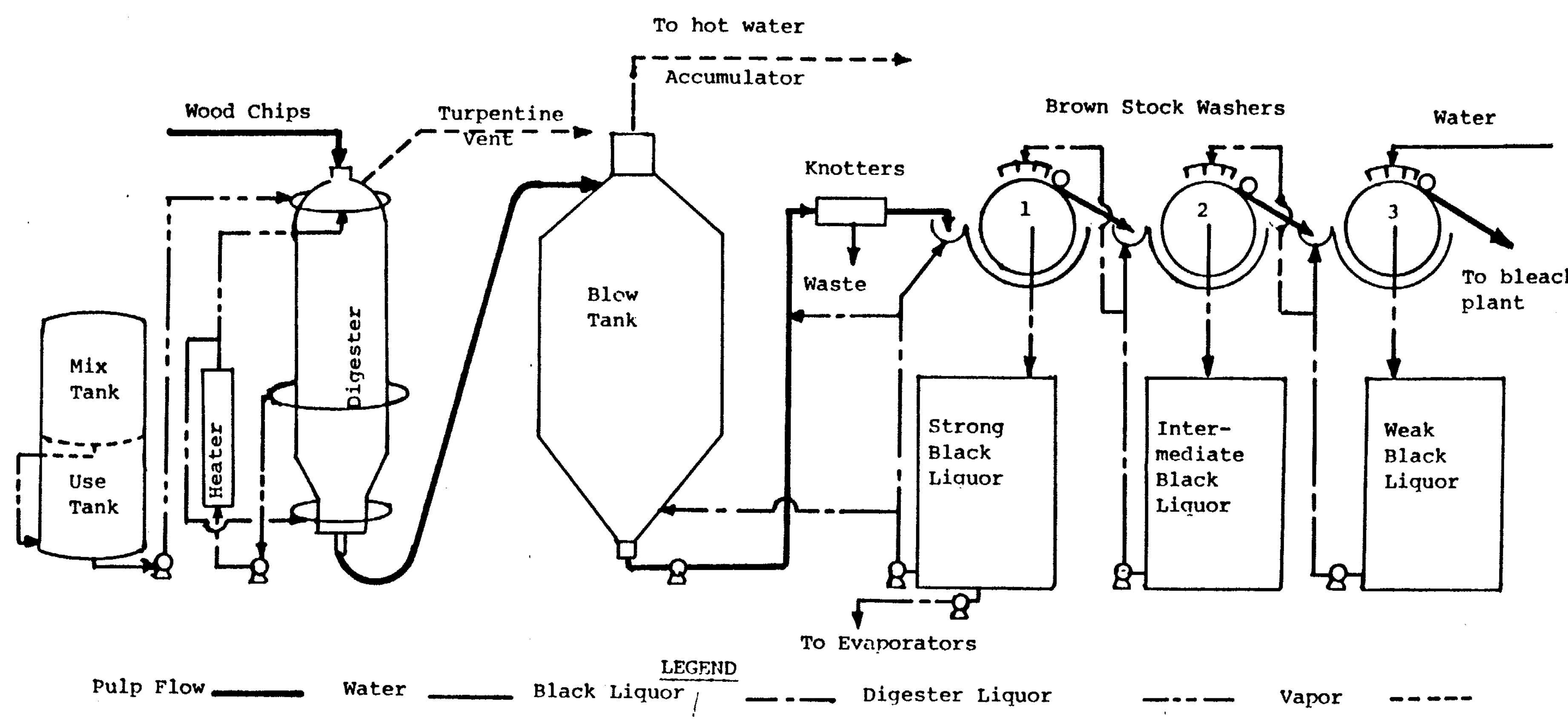
References

(1) Perry, R.H. and Chilton, C.H., eds. *Chemical Engineers Handbook*. 5th edition, New York: McGraw-Hill, 1973, p. 5-35, 5-36.

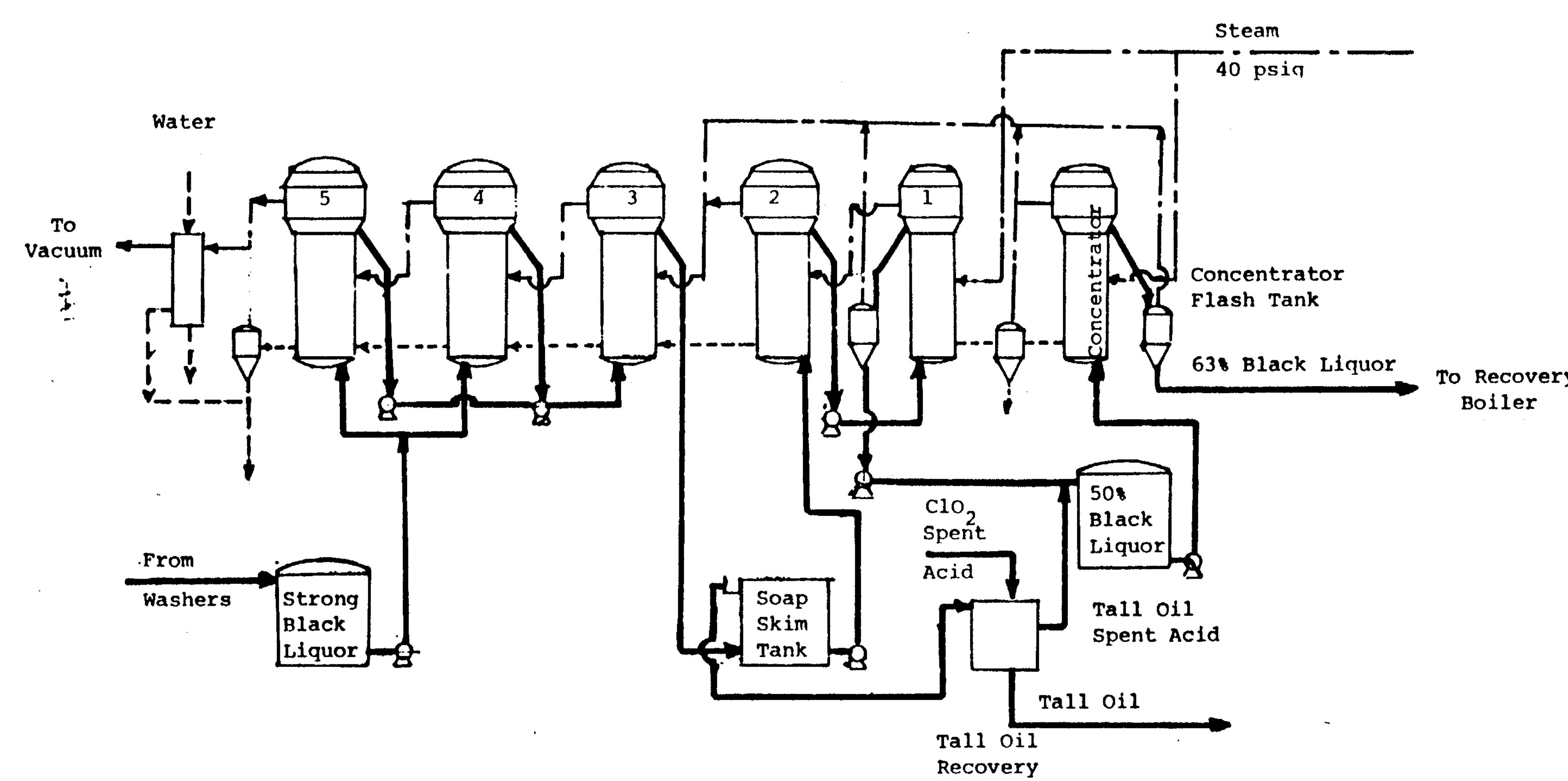
(2) Ibid, p. 5-52.

(3) Perkins, J.K., *et al*, "Brown Stock Washing Efficiency. Displacement Ratio Method of Determination," *Tappi*, Vol. 37, No. 3, March, 1954, p. 83-89.

FIGURE NO. 1



To hot water
Accumulator
Wood Chips
Turpentine
Vent
Brown Stock Washers
Water
Knotters
Waste
1
2
3
To bleach
plant
Mix
Tank
Use
Tank
Heater
Digester
Blow
Tank
Strong
Black
Liquor
Inter-
mediate
Black
Liquor
Weak
Black
Liquor
To Evaporators
LEGEND
Pulp Flow
Water
Black Liquor
Digester Liquor
Vapor



LEGEND

Black Liquor ——— Steam —·— Condensate - - - -

FIGURE NO. 2

BLACK LIQUOR EVAPORATORS

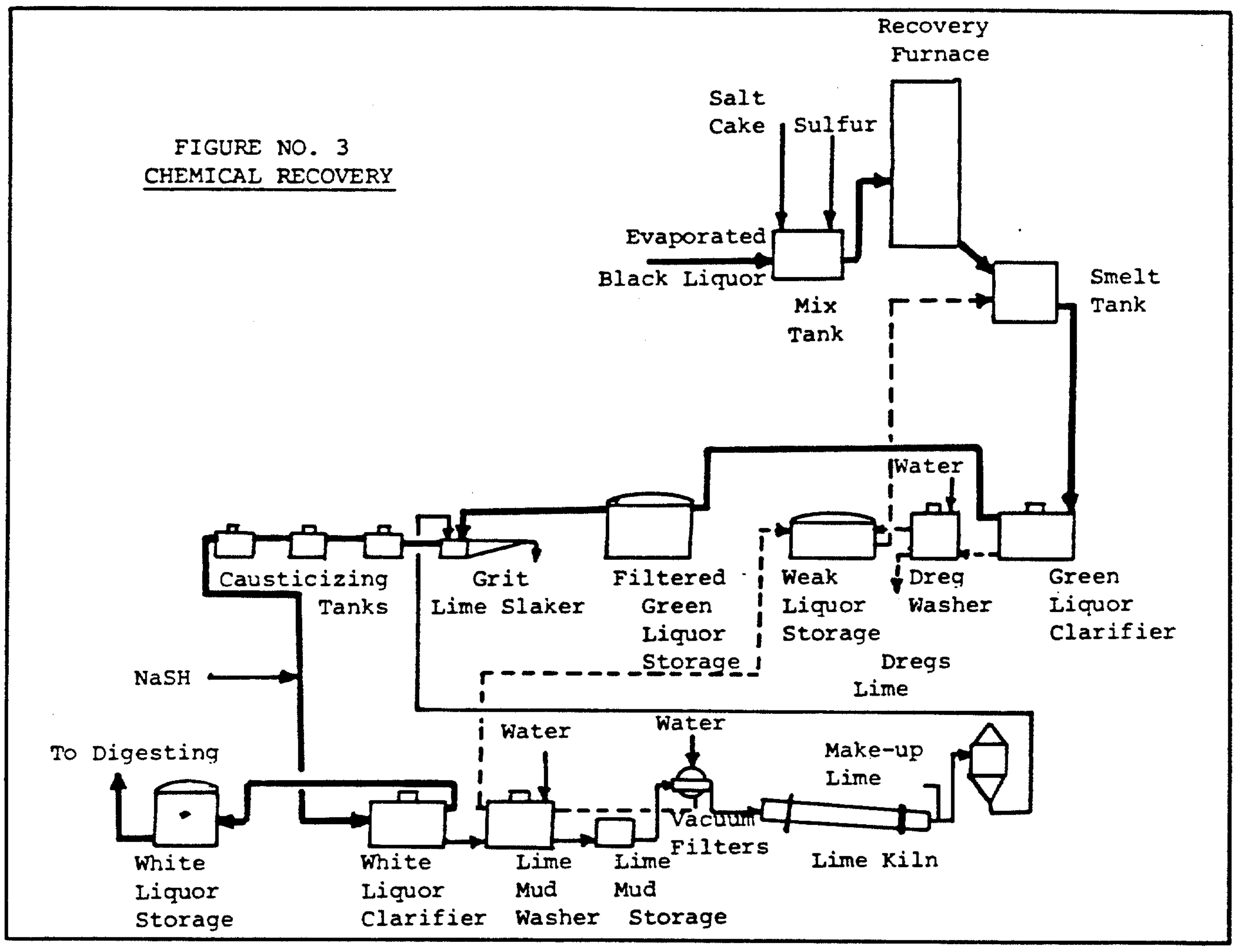


FIGURE NO. 3
CHEMICAL RECOVERY

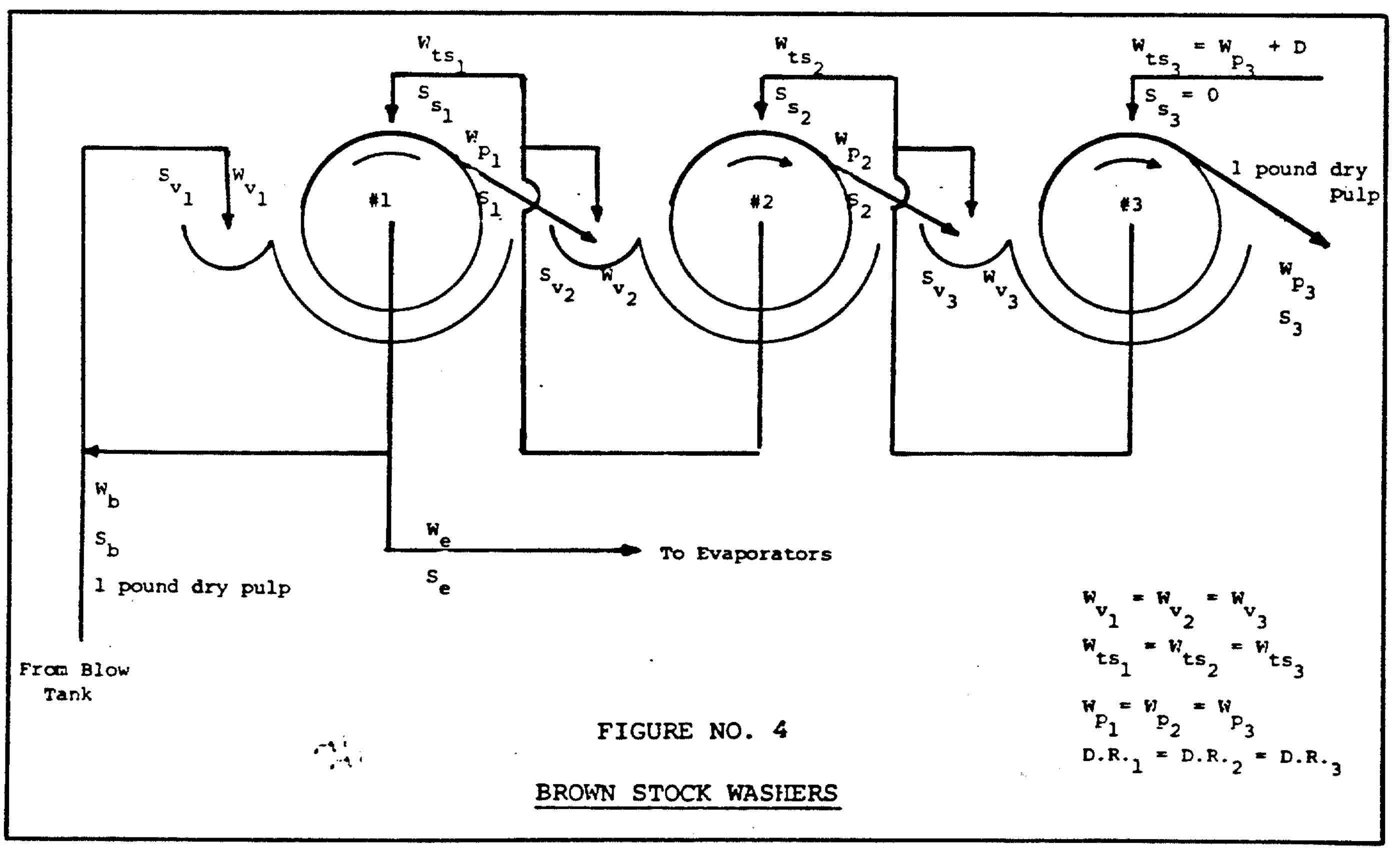


FIGURE NO. 4

BROWN STOCK WASHERS

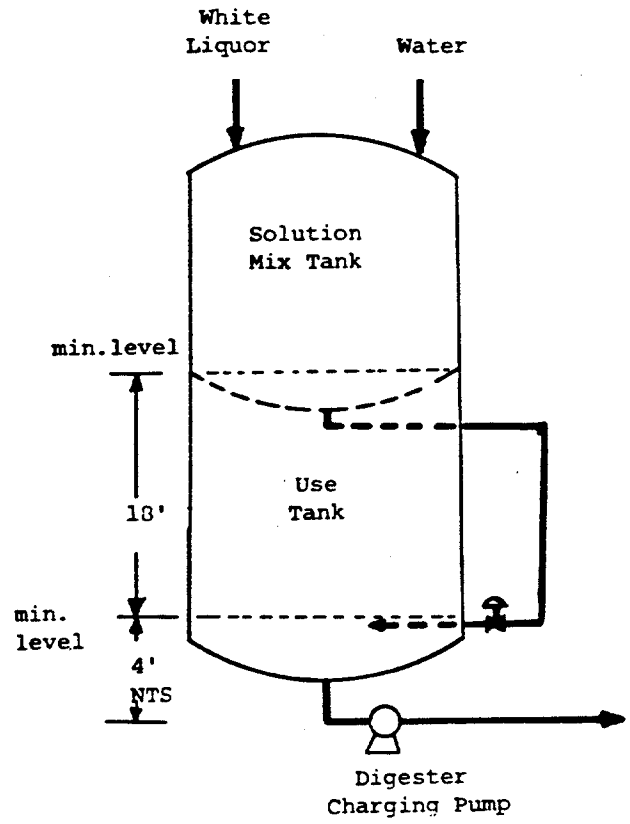


FIGURE NO. 5

SOLUTION MIX TANK

FIGURE 6

COOKING LIQUOR CHARGING PUMP CHARACTERISTICS