SIMULATION IN THE DESIGN OF A CORN SYRUP REFINERY

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INTRODUCTION

In the past two years, corn sweeteners have strengthened their position in many traditional markets and made important strides into new ones. The Company's line of corn sweeteners include regular corn syrups, dextrose and high fructose syrup. Traditional major corn sweetener users include confectioners, bakers, fruit and vegetable canners and packers, jam and jelly makers, breweries and dairies - many of whom are using greater amounts of corn syrup as it becomes available. The major new market for corn sweetener is the soft drink industry, largest single domestic sweetener user, at a rate of 6 billion pounds annually.

Ground was broken in July, 1975, at Lafayette, Indiana, for a new $85 million corn wet milling plant which will enhance the Company's overall corn sweetener position. The plant, scheduled for completion at midyear 1977, will add more than 1 billion pounds of corn sweetener production capability. The facility is being engineered with a flexibility in end-product mix which will permit Staley to respond to future shifts in demand for various types of corn sweeteners.

Building a new facility is always something of an adventure. Some new and some old processes are combined in perhaps untried ways to produce some target group of products. Unknown interactions between known and unknown operations must be considered. A great deal of uncertainty surrounds the entire planning process. To reduce some of this uncertainty, a computer model was built of a portion of the new facility, the corn syrup processing section.

CORN WET MILLING

The corn wet milling process begins with steps rooted in tradition and ends in the most advanced enzyme technology. It is a process that extracts value from more than 350 million bushels of corn each year.

From the country elevators that dot the midwest, corn wet millers purchase the raw material -- usually No. 2 yellow dent corn -- for their processes. While its price fluctuates, corn is typically abundant and economical. About 6 percent of the nation's corn crop is used by the corn wet milling industry.

The corn wet milling process breaks the corn kernel into its principal components -- starch, gluten, hull and germ. The primary objective is to obtain the starch which makes up 67 percent of the kernel, so that it may be further refined or converted into corn sweeteners. In addition to starch, a corn kernel consists of 10 percent protein, 4.5 percent oil, 3.5 percent fiber, 2 percent mineral and 15 to 20 percent moisture.

Starch is the most versatile and valuable product produced by the corn wet milling process. It is perhaps the most economical pure carbohydrate source available. More than 60 percent of the 10.5 billion pounds of starch generated by the corn wet milling industry each year is further converted into corn sweeteners.

This conversion (hydrolysis) is achieved in large tanks where the starch slurry is treated with various enzymes. The enzyme is inactivated at various points depending upon the type of corn sweetener being produced. The higher the degree of conversion, the greater the modification of the syrup's physical properties. Degree of conversion of corn sweeteners is described in terms of dextrose equivalent or D.E. Later, the syrup goes through a multistage refining procedure to reach desired clarity and purity. A final step involves the evaporation of water to bring the syrup to an acceptable solids level.

THE MODEL

The system configuration for this model includes two evaporation steps, one carbon refining step, one ion exchange step, and required material flows including process wash water. (See Exhibit I.)

The model was built using the GASP IV simulation system and the FORTRAN programming language. GASP IV provides standard FORTRAN subroutines to step the model through time, and to capture and plot statistics of interest. The model consists of additional FORTRAN subroutines constructed to simulate elements of the process. Events are handled by the model as they occur. The model steps through time from event to event. An event is defined as an occurrence that may change the status of the model. Two types of events are considered, time events and state events. Time events are those that occur at some specifiable point in time, i.e., carbon filter columns are changed and backwashed every eight hours; a rail car is washed for loading every hour; a new product is started through the system with the next conversion tank after some specified point in time. State events occur when some value of interest reaches, or crosses, some specified level, i.e., a surge tank reaches full or empty; the total dry substance passing through the ion exchange column reaches a predetermined level; the dry substance in the output stream of the evaporator reaches a limit. These events occurring require that some action be taken to alter the status of the system in some predetermined manner. The model, on detecting one of these events, makes the appropriate change and then steps to the next event.

The conversion process reduces the long chain starch molecule into shorter saccharide molecules. The characteristics of a given product are determined by the quantities of the different length saccharides making up the syrup. The most important saccharides are the shortest three molecules, dextrose, maltose and malto-triose. The model considers the percentage of these three components with a fourth component which includes all higher saccharides. The dry substance content of the syrup is also considered. At each step, the component saccharide distribution and the dry substance (DS) are recalculated.

The model considers four products with differing saccharide distributions. For each product a nominal, maximum and minimum is specified for each of the saccharides; i.e.,

	Nominal	Maximum	Minimum
Dextrose	40%	41.5%	36.3%
Maltose	29%	31.6%	28.3%
Malto-Triose	6%	13.8%	4.0%
Highers (Ups)	25%	27.0%	20.2%

would represent a common syrup. Each of the four products in the model roughly represents a group of similar products.

The model begins with a single conversion batch tank. Syrup flows from this tank at some rate up to a specified maximum with a determined dry substance content. When the tank empties, it is immediately reset to full, thus simulating multiple conversion tanks. The saccharide composition of a batch of syrup is determined by randomly sampling a normal distribution with mean equal to the nominal and standard deviation equal to a fraction of the range for the product currently being produced. The saccharide distribution drawn from the normal curve must sum to 1.0 or a different sample is taken. The model can be told that the next conversion tank is a product different from the one currently in process and the change will automatically be effected. If the change is to or from a product radically different than the other, each process tank will empty and both carbon and ion exchange wash cycles initiated as the new product flows through the system.

The next step in the model is to blend sweetwater into the main syrup stream. Sweetwater is generated from four sources -- carbon filter backwashing, ion exchange recharging, rail car washing and miscellaneous flows. Before a syrup rail car can be refilled, the prior syrup must be entirely purged. The washwater used to clean the car contains sufficient quantities of syrup to be worth recovering. This water, therefore, is reprocessed as sweetwater. The miscellaneous flows include tank overflows and pump seal water.

The capability to blend is constrained by product saccharide composition and dry substance (DS) percentage. In actual practice, a saccharide distribution analysis can be made in just under an hour. In the model, the sweetwater and current conversion tank analysis are determined hourly. One hour later, this analysis is used to determine a ratio of sweetwater to source rates that will use a maximum amount of sweetwater without violating the saccharide limits for the product being made. Additionally, the combined sweetwater-source stream is maintained above a minimum DS level. To avoid sudden changes in DS level fed to the first evaporator, this minimum is determined by how much material remains in the sweetwater tank. In this manner, the amount of sweetwater mixed into the main stream is forced to transition smoothly from level to level, the sweetwater supply is never exhausted, yet, as much sweetwater as possible is used when the tank is relatively full. A linear programming model is used to affect this mixing.

A word on the determination of composition is in order. At any point in time (in the model), each rate of flow, tank level and composition is exactly known. The model does not flow but steps from point-in-time to point-in-time. It is, therefore, assumed that all rates remain constant through a step. At the end of each step, all tank levels and compositions are recalculated, using the known levels and compositions at the beginning of the step and the known rates of flow. These calculations then provide exact knowledge of the system at the end of the step and the beginning of the next step. Well agitated tanks are assumed, providing homogeneous mixture.

The combined sweetwater-source stream flows into a surge tank that feeds the first evaporator. As this tank fills, the rates of flow into the tank are slowed to avoid overflow. As the tank empties, the rates are increased gradually to maximum. Flow from the tank is controlled by the needs of the evaporation process. If the DS is above a predetermined level, excessive water has been removed and the unit is operating at minimum. To correct the situation, the rate of flow to the machine must be increased. In a similar manner, if the level drops below specification, the unit is operating at maximum and the rate must be reduced. Also, if the dry substance is in specification but the machine is operating below capacity, the rate is increased gradually toward capacity.

The carbon filtering and ion exchange processes are not modeled in detail but are essentially treated as pipes. Surge tanks precede each of these processes with rates of flow controlled by tank levels. Flow from the ion exchange process is into a surge tank prior to the final evaporator. This evaporator is controlled with the same method as the first evaporator, the output DS level and capacity being the only difference.

The perturbation in the system is the changing flow of sweetwater. Both the DS and the quantity of sweetwater change, depending on the cycles of the sources. The system, primarily the blending and first evaporation processes, must cope with the surges without upsetting the system. This is accomplished primarily by allowing the surge tanks to absorb shifts until specified tank level crossing points are reached. Rate adjustments are then made to avoid over or underflowing these tanks.

INPUTS AND OUTPUTS

The model is run in a time-sharing environment on a Honeywell 6000 series computer. Because of the ease in modifying the program, the majority of the parameters are changed in the subroutine containing the initial conditions and run parameters. The model subroutines are recompiled each time the model is run; run time being a more plentiful resource than disk storage space. The only input required is the standard GASP IV parameters to establish data collection and plotting requirements.

Outputs of interest are illustrated in Exhibits II through V. Exhibit II shows the statistics for a typical run. For the run illustrated, two sweetwater tanks were used, four products were produced with 9.6 million pounds of total good production and 346 thousand pounds of out-of-specification material produced as a result of changing from one product to another. Tank capacities are listed for the run. Sweetwater Tank 3 is indicated with a capacity of two pounds, effectively eliminating that tank from the run. The evaporator capacities for the run were 90,000 and 45,000 pounds of water evaporated per hour. Target dry substance output from the evaporators were 55% and 80%. This run does not represent the final recommendations.

Output statistics of interest are tabulated. The most significant is the mean rate from the source tank shown at 150,100 pounds per hour, this run thus meeting target. The mean dry substance from the first evaporator is shown as 54.95%, checking nicely with the target 55%. Final dry substance is shown as 80.02% also checking with the target 80%.

Exhibit III lists the cars loaded during the run. The time from the start of the run and the time from the start of the day are both tabulated. Total pounds loaded is listed. The dry substance percentage and composition of the syrup by saccharide is shown. The dextrose equivalent is listed. The product in the car is shown, with the "OS" indicating that the product in the car matches none of the product specifications. The Baume' at 100° F. (a measure of density) is also shown.

Exhibits IV and V, this example about 15 hours of a 150-hour run, allow one to follow the run as it moved through time. The tank plot (Exhibit IV) illustrates tank levels showing where corrective action must be taken. The sudden increase in the level in Sweetwater Tank 1 is a result of backwashing the ion exchange column. This is closely followed by an increase in the first evaporator feed tank as the material moves through the system. The saccharide distribution plot (Exhibit V) illustrates a change from product one to product two, the dextrose level falling and the higher saccharides increasing. During the change-over period the product was out-of-specification as indicated by the line of "S's". The final dry substance was held fairly constant over this period. The "W's" at the bottom of the graph indicate rail car washing, with the material flowing into the sweetwater system. The height of the "W's" from the base of the graph indicate the syrup type being washed out.

VARYING THE PARAMETERS

Any of the elements of the model can, of course, be changed and the effect observed. For the study to-date, the factors most often changed have been tank sizes, evaporator sizes and system control parameters. A stable system was achieved for specified tank and evaporator sizes. The greatest challenge had been to develop a set of control parameters that would allow the model to absorb factor changes without going bananas (a technical term describing severe instability). Basically, all control changes result from state variables (tank levels, etc.) crossing predefined checkpoints and appropriate changes made to flow rates. This approach roughly simulates the manner in which the plant would be run manually.

CONCLUSIONS

An early hypothesis was that a sweetwater holding tank for each product group would reduce the total sweetwater storage capacity required. This proved not to be the case. Multiple tanks, in fact, resulted in a greater total requirement be approximately a factor of three. One sweetwater tank is concluded to be sufficient.

The system was modeled with 100,000 lbs. capacity (approximately 10,000 gallons) storage tanks to provide surge between processes. It was found that sweetwater surges caused a bottleneck in the tank prior to the first evaporator. To prevent overflowing this tank, a reduction in the flow of syrup from conversion was required, reducing average flow below design requirements. The first evaporator feed tank was increased to 200,000 lbs., substantially improving flow. The smaller size tanks appeared adequate for the other processes.

The model was initially constructed on the hypothesis that two evaporators of equal size would be used. The first evaporator would produce a syrup stream at 50% nominal DS; the second unit would complete the evaporation to product specification. Any capacity imbalance between evaporators would be corrected by varying the DS output of the first evaporator within the limits of 45% to 55%. It was later decided to run the first evaporator at 55% and determine capacity requirements to balance the system. The greater efficiency of the unit intended for primary evaporation suggested the efficacy of this alternate approach.

Various sizes of evaporators were tried at both primary and secondary evaporation. To achieve design throughput, it was concluded that the first unit should have a capacity of evaporating 75,000 lbs. of water per hour. The final unit should have an evaporation capacity of 35,000 lbs. of water per hour.

With the above elements of the system specified, the sweetwater tank required to serve the process should have a capacity of 260,000 lbs. This requirement occurs while running all four products. These results are from runs simulating 150 hours of operation, just short of one week.

This model has provided the information required for process design and is considered a successful project. The model is now being revised to incorporate the actual equipment chosen. Additional runs will be made to examine run conditions and the resulting effect on product specifications. Also, the assumed manual control algorithm is being modified to simulate computer control. There has been some discussion on expanding the model to include other sections of the wet milling process. At Staley's, computer modeling is considered a useful management tool.

REFERENCES

A. Alan B. Pritsker, The GASP IV Simulation Language, John Wiley & Sons, New York, 1974.

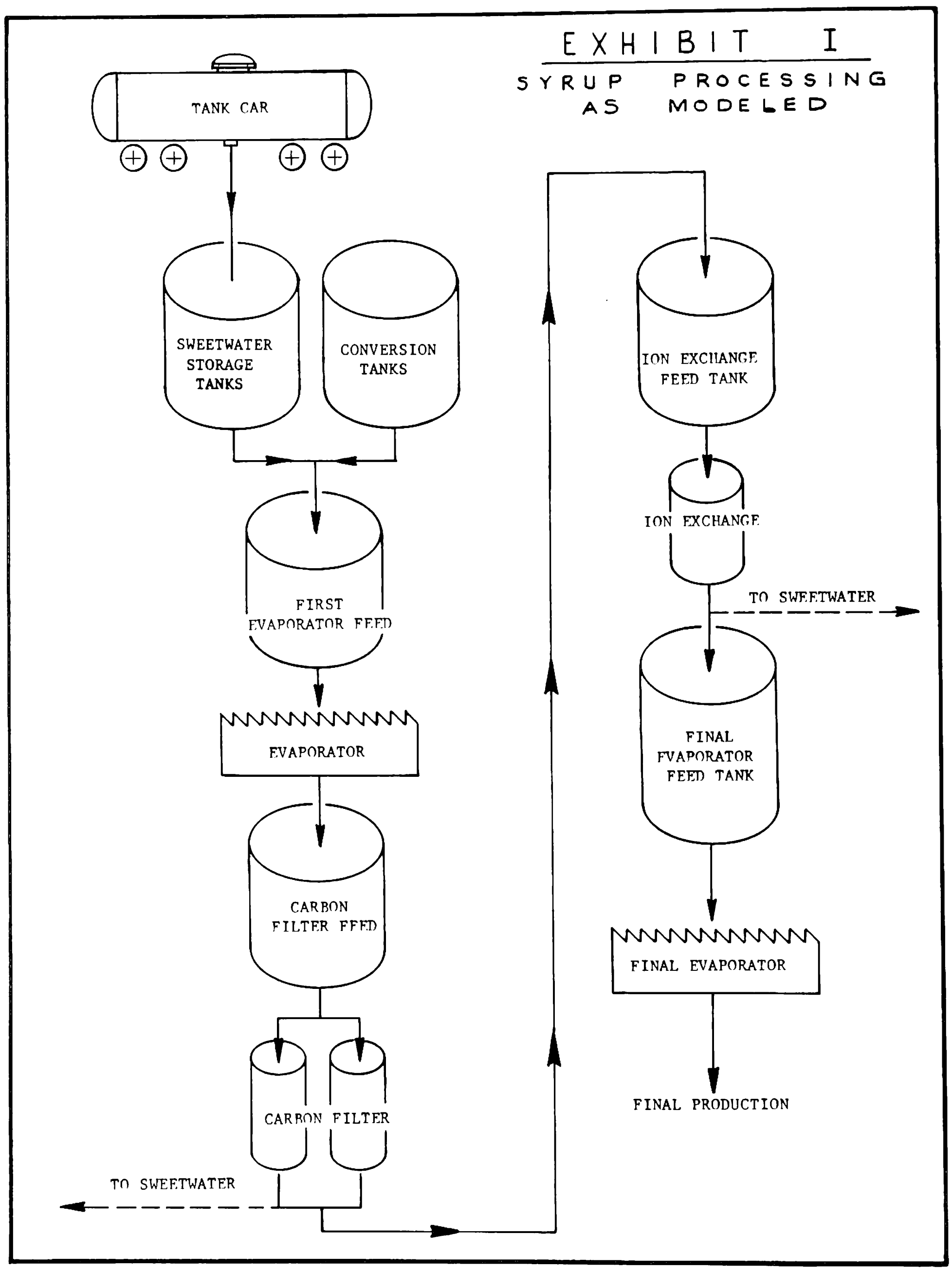
EXHIBIT I
SYRUP PROCESSING AS MODELED
TANK CAR
SWEETWATER STORAGE TANKS
CONVERSION TANKS
FIRST EVAPORATOR FEED
EVAPORATOR
CARBON FILTER FEED
CARBON FILTER
TO SWEETWATER
ION EXCHANGE FEED TANK
ION EXCHANGE
TO SWEETWATER
FINAL EVAPORATOR FEED TANK
FINAL EVAPORATOR
FINAL PRODUCTION

EXHIBIT II

RUN STATISTICS

MAXIMUM TOTAL POUNDS VOLUME IN SWEETWATER TANKS

TANK 1	185304.
TANK 2	160403.
TANK 3	0.
ALL TANKS	345707.

PRODUCTION TOTALS (POUNDS)

PRODUCT 1	4096063.
PRODUCT 2	2037715.
PRODUCT 3	1901081.
PRODUCT 4	1639580.
TOTAL GOOD PRODUCT	9674440.
OUT OF SPEC - PRODUCT CHANGE	346636.
OUT OF SPEC	0.
TOTAL PRODUCTION	10021075.

	SWT WTR 1	SWT WTR 2	SWT WTR 3	1ST EVAR	CARBON	IONEX	2ND EVAR
TANK CAPACITIES	1000000.	1000000.	2.	200000.	100000.	100000.	100000.
MAXIMUM EVAPORATOR RATE				90000.			45000.
NOMINAL DRY SYBSTANCE FROM EVAPORATOR				0.550			0.800

	MEAN	STD DEV	MINIMUM	MAXIMUM
% SWEETWATER TO FIRST EVAPORATOR	0.1294E 00	0.6721E-01	0.	0.4196E 00
RATE TO FIRST EVAPORATOR	0.1778E 06	0.1648E 05	0.1056E 06	0.2183E 06
DRY SUBSTANCE FROM FIRST EVAPORATOR	0.5495E 00	0.2990E-02	0.5000E 00	0.5511E 00
WATER EVAPORATED FIRST EVAPORATOR	0.7587E 05	0.1309E 05	0.	0.9000E 05
RATE TO CARBON COLUMNS	0.5013E 05	0.9105E 04	0.2939E 05	0.7000E 05
RATE TO ION EXCHANGE	0.9849E 05	0.1580E 05	0.6483E 05	0.1350E 06
RATE TO FINAL EVAPORATOR	0.9811E 05	0.2323E 05	0.6855E 05	0.1422E 06
DRY SUBSTANCE FROM FINAL EVAPORATOR	0.8002E 00	0.8449E-03	0.8000E 00	0.8092E 00
RATE FROM SOURCE TANK	0.1501E 06	0.1832E 05	0.	0.1570E 06
WATER EVAPORATED FINAL EVAPORATOR	0.3030E 05	0.7943E 04	0.	0.4442E 05
RATE TO SWEETWATER TANK	0.2275E 05	0.3343E 05	0.	0.1722E 06
DRY SUBSTANCE TO FIRST EVAPORATOR	0.3069E 00	0.2109E-01	0.2320E 00	0.3427E 00

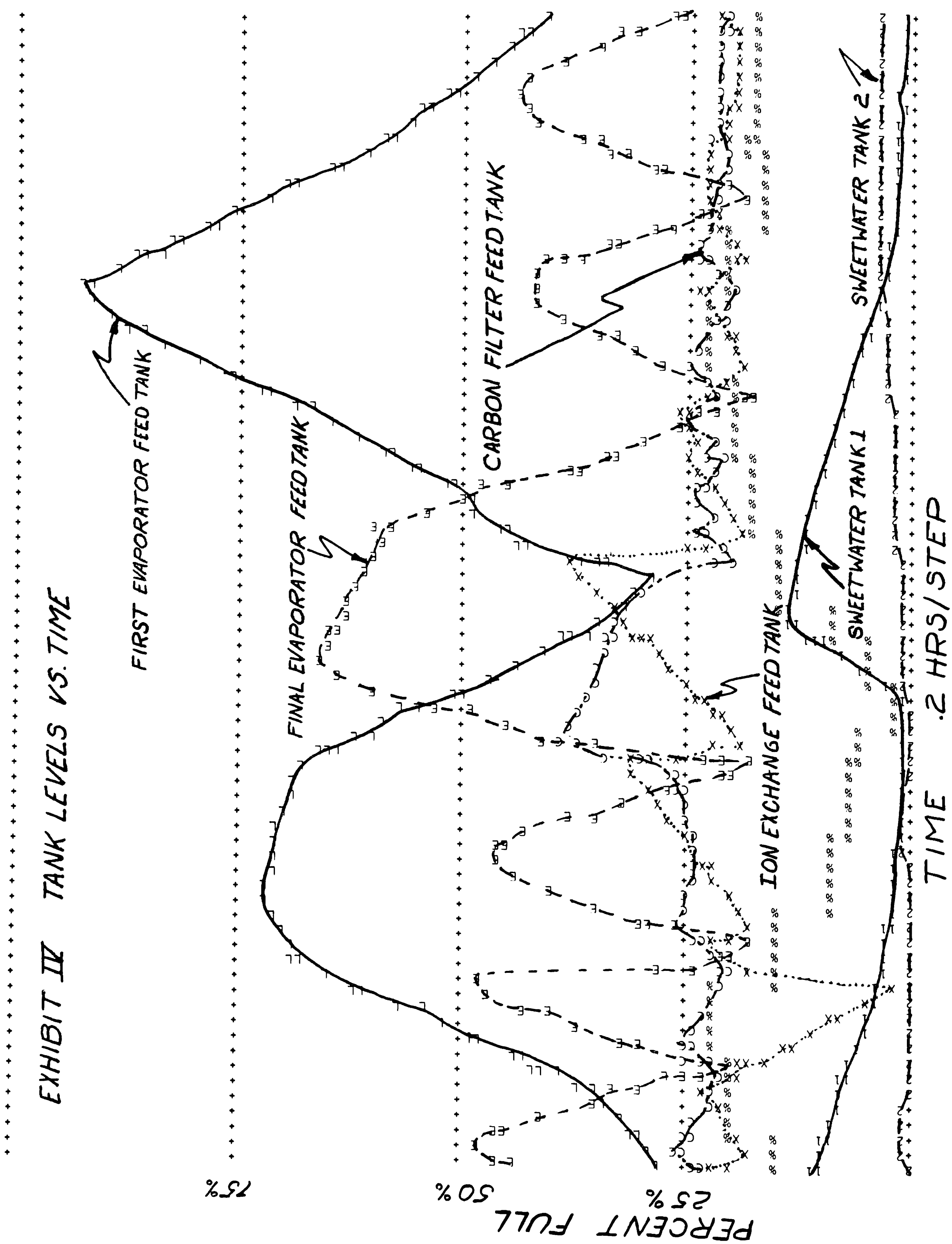
EXHIBIT IV TANK LEVELS VS. TIME
FIRST EVAPORATOR FEED TANK
FINAL EVAPORATOR FEED TANK
CARBON FILTER FEED TANK
ION EXCHANGE FEED TANK
SWEETWATER TANK 1
SWEETWATER TANK 2
TIME .2 HRS/STEP
PERCENT FULL
25%
50%
75%

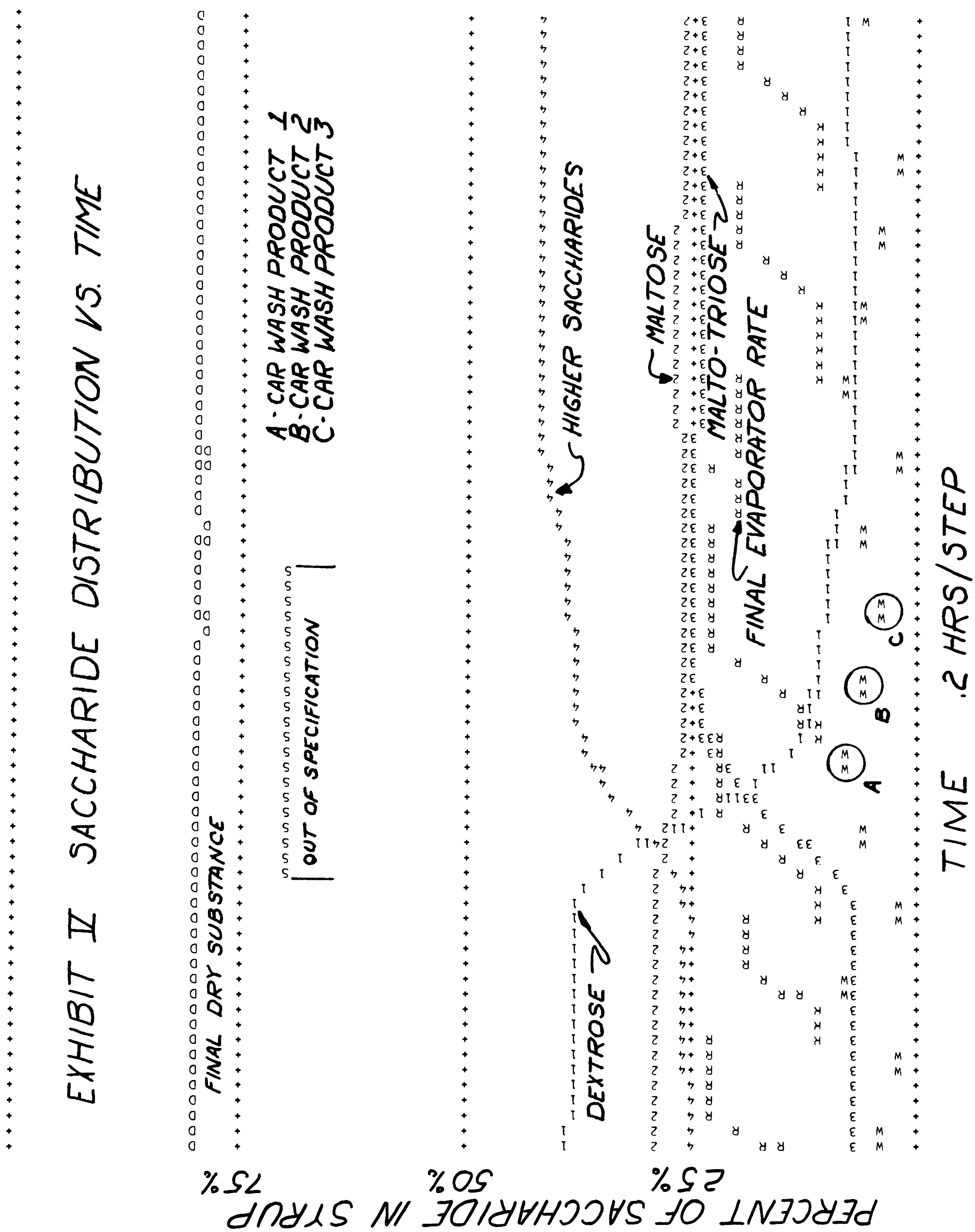
EXHIBIT II SACCHARIDE DISTRIBUTION VS. TIME
A · CAR WASH PRODUCT 1
B · CAR WASH PRODUCT 2
C · CAR WASH PRODUCT 3
FINAL DRY SUBSTANCE
OUT OF SPECIFICATION
HIGHER SACCHARIDES
DEXTROSE
MALTOSE
MALTO-TRIOSE
FINAL EVAPORATOR RATE
A
B
C
TIME .2 HRS/STEP
PERCENT OF SACCHARIDE IN SYRUP
25%
50%
75%

EXHIBIT III RAIL CAR LOADINGS

LOADINGS FOR DAY 4

CAR NO	RAW TIME	TIME FNSHD	DS LBS	% DS	% DEX	% MALT	% MALTRI	% UPS	% DE	PRODUCT	BE'(100F)
1	73.75	1.75	161941.7	79.8	8.1	30.9	24.4	36.5	43.0	OS	42.6
2	74.79	2.79	80539.8	79.3	9.5	38.7	22.0	29.8	46.6	OS	42.2
3	77.05	5.05	161766.1	79.3	10.1	41.8	21.1	27.1	48.0	3	42.2
4	79.09	7.09	80788.5	80.1	9.7	42.8	21.7	25.8	48.3	3	42.6
5	80.80	8.80	81029.0	80.0	9.4	43.3	22.2	25.1	48.3	3	42.6
6	83.65	11.65	160301.5	80.0	9.3	43.3	22.4	25.0	48.3	3	42.5
7	84.69	12.69	80543.4	79.8	9.4	42.7	22.4	25.6	48.1	3	42.4
8	86.29	14.29	81148.1	79.9	9.3	42.5	22.4	25.8	48.0	3	42.5
9	88.70	16.70	162201.7	79.8	9.3	42.6	22.5	25.5	48.0	3	42.5
10	90.00	18.00	80596.1	79.8	9.4	43.0	22.8	24.8	48.3	3	42.4
11	93.25	21.25	161248.9	80.0	9.4	42.9	22.7	25.0	48.3	3	42.5
12	94.96	22.96	80201.9	80.0	9.1	42.6	22.2	26.1	47.8	3	42.6

LOADINGS FOR DAY 5

CAR NO	RAW TIME	TIME FNSHD	DS LBS	% DS	% DEX	% MALT	% MALTRI	% UPS	% DE	PRODUCT	BE'(100F)
1	96.10	0.10	80393.0	80.0	9.1	42.5	22.0	26.4	47.7	3	42.6
2	98.75	2.75	160594.0	79.9	9.4	42.8	21.9	26.0	48.0	3	42.5
3	101.40	5.40	160348.2	79.9	10.0	43.3	21.7	25.0	48.7	3	42.4
4	105.47	9.47	160544.2	79.9	23.7	40.5	17.5	18.2	57.8	OS	42.1
5	108.09	12.09	161900.3	79.8	38.2	37.5	13.0	11.3	67.3	4	41.7
6	110.70	14.70	161478.7	79.6	39.2	35.9	12.5	12.5	67.4	4	41.6
7	113.65	17.65	161649.6	80.0	39.4	35.4	12.3	12.9	67.4	4	41.8
8	115.25	19.25	81027.6	80.0	39.2	35.3	12.1	13.3	67.2	4	41.8
9	116.85	20.85	80996.9	80.0	39.2	35.3	12.1	13.4	67.1	4	41.8
10	118.45	22.45	80959.3	80.0	39.3	35.4	12.4	12.9	67.3	4	41.8
11	120.00	24.00	80043.9	80.0	39.5	35.8	13.4	11.2	67.9	4	41.8

LOADINGS FOR DAY 6

CAR NO	RAW TIME	TIME FNSHD	DS LBS	% DS	% DEX	% MALT	% MALTRI	% UPS	% DE	PRODUCT	BE'(100F)
1	121.07	1.07	80370.8	80.0	39.6	36.0	14.0	10.5	68.1	4	41.8
2	123.65	3.65	161196.2	79.8	39.4	35.9	13.8	10.9	67.9	4	41.7
3	125.71	5.71	160120.1	79.3	39.0	35.7	12.7	12.6	67.2	4	41.4
4	126.75	6.75	80604.3	79.6	39.0	35.6	12.4	13.0	67.1	OS	41.6
5	130.42	10.42	160698.1	79.6	39.3	30.1	7.6	23.0	64.4	1	41.7
6	132.70	12.70	161187.6	79.7	39.6	28.8	6.3	25.3	63.9	1	41.8
7	135.05	15.05	160212.2	80.0	40.6	29.7	6.5	23.2	65.1	1	41.9
8	137.15	17.15	161117.0	79.8	40.4	29.5	5.8	24.3	64.7	1	41.8
9	139.80	19.80	162236.8	79.9	39.9	29.0	4.5	26.6	63.8	1	41.9
10	140.92	20.92	80962.2	80.0	39.8	29.1	5.3	25.8	63.9	1	41.9
11	143.45	23.45	160288.1	79.9	39.6	29.1	6.8	24.5	64.1	1	41.9

LOADINGS FOR DAY 7

CAR NO	RAW TIME	TIME FNSHD	DS LBS	% DS	% DEX	% MALT	% MALTRI	% UPS	% DE	PRODUCT	BE'(100F)
1	146.02	2.02	161320.8	79.5	39.3	28.9	6.5	25.2	63.7	1	41.7
2	148.60	4.60	161216.5	79.8	39.1	28.6	6.0	26.3	63.3	1	41.9
3	149.64	5.64	80385.5	79.8	39.7	29.1	5.6	25.6	63.9	1	41.8