Theory and Economics of Diffusion

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First of all, what are the objectives of diffusion?

1. As completely as possible transfer the sugar from the cossette of the beet to the solution phase or diffusion juice.

2. Leave in the diffused pulp the maximum of nonsugars. This selective extraction of sugar in diffusion constitutes one of the two purification steps in current processing methods generally employed in the beet sugar industry, the other being defecation.

3. Accomplish the above two objectives with a minimum of dilution of the sugar.

The objective in process control is to find the equipment and process conditions which accomplish the most profitable compromise of these objectives. To evaluate where we stand today on this diffusion job, we need to know what is being accomplished with respect to each of the above enumerated objectives and at what cost.

To illustrate what is being accomplished with respect to completeness of transfer of sugar in the cossettes to the solution phase or diffusion juice, the three chain diffusers at the Nyssa, Nampa, and Twin Falls plants of The Amalgamated Sugar Company were calculated for the 1953-54 campaign to date of writing. They show the values illustrated in Table 1. This calculation assumes no unknown loss in the diffuser.

To illustrate what *is* being accomplished with respect to diffusion elimination on the same three diffusers refer to Table 2.

Table I.

Factory	Percent Non-sugar Elimination in Diffusion
Nampa	21.9%[1]
Twin Falls	20.9%[2]
Nyssa	16.2%[2]

[1] Cossette purity by spindle method, diffusion juice by refractometer, cossette purity by Waring blendor method.

[2] Both cossette and diffusion juice purity based on refractometer brix. Cossette purity by Waring blender method.

Table 2.

Factory	% Input Sugar in Outgoing Diffusion Juice	Draft by Sugar Content	Daily Slicing Performance Tons/24 Hour
Nampa	99.03	128	3443
Twin Falls[1]	99.09	135	5295
Nyssa	98.78	133	2842

[1] 19-Cell Diffuser.

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Looking at diffusion from the standpoint of the amount of dilution suffered to accomplish the above listed results, we use Nampa as the example. In the beets processed at Nampa, there existed 4.94 pounds of water per pound of sugar content. In the diffusion juice realized the water content per pound of sugar had been increased to 7.16 pounds. In other words, a dilution of 2.22 pounds of water per pound of sugar was sacrificed to bring about this 99 percent translocation of sugar to the liquid phase. If there existed an expulsion method in which the marc of the beet could be squeezed absolutely dry and free of sugar, the juice would have 2.22 pounds of water less per pound of sugar content.

Admittedly these next figures are an over-simplification, but they illustrate the cost of this diffusion dilution and portray the economic benefits which would result from the perfect sugar separation—if it could be found—in relation to the present continuous diffusers. Using a figure of 2.1 pounds of water evaporated per pound of steam and a "to burner" fuel cost of 41c/1,000,000 BTU and a boiler efficiency of 85 percent, the material cost of evaporating this extra 2.22 pounds of water per pound of sugar, which results from diffusion dilution, is .051c. On top of this would come the capital, maintenance, and overhead costs of this additional steam producing and evaporating equipment—which might be expected to raise the cost of evaporating this additional 2.22 pounds of water per pound of sugar to 0.075c or 7.5c per 100 pounds of sugar in cossettes.

This then would represent the possible magnitude of saving of the perfect diffuser, provided—

1. it could be installed and operated as cheaply as present diffusers,
2. it would realize as great a non-sugar elimination as that accomplished by present diffusers, and
3. it would leave the by-products equally recoverable. These last two provisions provide a stiff challenge to any new improved sugar extraction method.

A clear-cut concept of the cost of current operating methods is usually most valuable in directing efforts towards most profitable avenues of improvement in any processing problem. Following this reasoning let's look at current costs of diffusion first, and then look at some values of non-sugar elimination to see which avenue appears most valuable in improving diffusion, and also how much sacrifice of one might be justified to gain on the other.

First, look at some operating costs on the present Silvers diffusers. It is necessary to make some assumptions to set up these costs, so the following costs in Table 3 will be used.

If the assumptions of Table 3 are valid, then for current conditions it is evident that if either the capital cost or operating cost of the total diffusion bill could be reduced say 25 percent, the saving would be of the order of 2c per bag of sugar.

Turning attention now to the values of non-sugar elimination related to processing costs, it was stipulated at the beginning of this presentation that any evaluation of new sugar extraction processes for beets should include careful comparison of the ability of the competitive process to give non-sugar eliminations equal to present diffusers and leave the by-products— pulp—equally recoverable.

Table 3.—Estimated Cost of Beet Diffusion, Silver Chain Diffuser.

Assume	
Tons beets sliced per year =	300,000
Tons sliced per day =	3,250
Capital Cost	
12-foot—Scroll & Wheel Diffuser	$300,000
Building for Diffuser	75,000
Annual Amortization	
Diffuser (25-year schedule)	12,000
Diffuser Building (40-year schedule)	1,875
Annual Maintenance Cost	
Diffuser	18,500
Diffuser Building	2,500
Labor (Including Knife Station)	
With company contributing payments	**15,407**
Steam	
Only that lost in radiation and heat in pulp. (Heat in juice considered part of evaporation.) Cost at 48c/1,000,000 BTU	**12,900**
Supplies	
Knives, routers, etc.	6,000
Total Diffusion Cost per Year =	$ **69,182**
Total Diffusion Cost/Ton Beets =	23.1c
At 280 pounds sugar sacked/ton beets	
Total Diffusion Cost per Bag of Sugar =	8.2c

Table 4.—Narapa Non-Sugar Elimination—1952 Campaign.

	Percent Elimination
Total Non-Sugars (Double Enzyme T.P.)	21.05%
Raffinose	None
Invert Sugar	57.75%
Ash	7.71%
Amine Compounds	33.16%

What does this mean? The three factories used herein as examples had. diffuser non-sugar eliminations for the current campaign to date of writing ranging from 16.2 percent to 21.9 percent. For a more detailed analysis of the non-sugars eliminated through diffusion refer to Table 4. These represent carefully composited samples taken and immediately frozen twice each shift for the duration of the 1952 campaign at the Nampa, Idaho, factory and analyzed on a weekly basis.

Some of the disappearance of invert sugar is undoubtedly through bacterial assimilation which imparts other bacterial end products as a partial replacement.

The non sugars enumerated in Table 4 are not currently removable to any large extent through carbonation. Therefore, if they are not eliminated *in* diffusion, they proceed through the process to form molasses.

Any sugar separation process—such as steam explosion—which is evaluated against conventional diffusion must be carefully examined with respect to non-sugar elimination. For example, two-thirds of a pound more of non-sugars left in deficated juice extracted from a ton of beets will result in the loss of roughly a pound of sugar in molasses. At today's nets for sugar and molasses, this loss of value approaches one-quarter of the total cost of diffusion enumerated in Table 3. Look at it another way: For factories of the 3500 ton class each one one-hundredth of one percent of additional non-sugars percent on beets going through to the sugar end, represents a loss of revenue of $50-$65 per day, depending on the sugar net and molasses price that fits your area. This is a half-cent or better per bag of sugar for each one-hundredth of a percent non-sugars percent on beets.

These thoughts lead to the question of whether the possibilities of improvement of diffusers or diffusion have been exhausted. Our feeling is that we cannot answer this question with any assurance since the industry knows very little factually of the effects of the different variables of diffusion.

Our search for reliable information on diffusion led us to the conclusion that about all that is known of diffusion mechanics is the result of observations of commercial practice. Since the raw material is variable from hour to hour and day to day, reliable comparative data is almost impossible to obtain in plant operation. To the contrary, many witches' tales have grown up among operating personnel because at some time they may have tried some adjustment which actually had an adverse effect, but due to a simultaneous change of beets, a contrary conclusion was drawn. Some of these persist for years. It is difficult to combat them since no reliable information exists with which to counter.

Another factor contributing to the slow development of knowledge with respect to diffusion is the yard stick of evaluation. The yard stick of evaluation is purity, and due to the fact that this measures sucrose and sucrose is highly predominant—large and significant changes of non-sugars do not show up dramatically and tend to be overlooked.

Take a specific example of a factory which—during the first week of campaign—had a diffusion juice true purity of 88.29, and on the sixteenth week had a true purity of 85.53. The purity was 2.76 points higher at the beginning of campaign on fresh beets. We know that's appreciable, but does it strike you as forcefully as when you see that the non-sugars per 100 pounds of sugar increased from 13.26 to 16.92, an increase in non-sugars of 27.6 percent. Another way of looking at this is that the non-sugars were increased by 3.66 pounds/100 pounds of sugar. If carbonation removes 25 percent of these, there still exists an increase of 2.75 pounds of non-sugars going to molasses, which will carry with them into molasses approximately 4.13 pounds of sugar.

With this as background, it was felt that the only way we could learn more about diffusion was to build a small controllable diffuser, so that a given set of cossettes can be split into several fractions. Then changing one variable on these successive portions of cossettes, the specific effect of the change of this variable can be determined without introducing error from a change of beets or a change of other process variables. Central Laboratory has been working on this problem for two campaigns now. They have successfully developed a continuous diffuser, which is controllable and which duplicates very closely the results under given conditions obtained with these same conditions in a factory diffuser.

A substantially greater problem has been that of developing analytical procedures sensitive enough to reflect the small changes of various classes of non-sugars.

Basing conclusions on work with synthetic solutions and also on reproducibility of results on factory products, it has been concluded that for total non-sugar grouping the sucrose purity by the double enzyme method is most accurate. *In* our district, it appears that the other polarimetric materials than sucrose present are close enough to compensating to make apparent purity a satisfactory tool for most screening work. It was further concluded that the raffinose results—by the double enzyme method at the level which raffinose exists in diffusion products—are not sufficiently accurate to be usable.

In the work so far, rather than attempt to quantitatively measure the individual constituents of the beet, classes of non-sugars are grouped to measure the diffusion behavior of these groups.

The grouping used currently for evaluation and the method employed are as follows:

Invert Sugar	TASCO modification of the Layne-Enyon Method
Ash	The sulfated, uncorrected method
Amine Compounds	TASCO modification of the Gunning Method
Percent Coagulables	Figures are determined at about 2 and at 11 pH. The product in question is adjusted to maximum flocculation with either hydrochloric acid or calcium hydroxide. The product is then centrifuged in a graduated vial in which the volumetric percentage of coagulables thrown down can be read directly. These are taken as a representation of the quantity of coagulables to be removed by carbonation.

In undertaking a problem such as this diffusion problem where no variable optimums can be assumed to be known and where the number of effective variables is so numerous, a large amount of repetitious work is involved. First, assumed conditions must be adopted for all but one variable. After the optimum is found for that variable under those conditions a second variable is approached. When the second variable optimum is fixed, it is often necessary to go back and recheck the first variable to determine whether the optimum on variable 1 holds under the optimum for variable 2. Due to this complexity and the large number of variables involved, the pilot diffuser work is far from completed.

It has been encouraging, however, that an apparatus and methods have been developed which demonstrate consistently reproducible patterns of results and in which the variables can be controlled within reasonable tolerances.

The diffuser and its operation will not be described in great detail here. The apparatus is a true counter-current diffuser with perforated flights, drawing the cossettes counter through the diffusion tube to the flow of diffusion liquor. The diffusion tube is 3 inches inside diameter with an effective length of 126 inches. The initial 15 percent of diffusion length is provided with separate heating control so that the region can be heated differentially from the rest of the diffuser. The final 85 percent of diffusion length is in a controllable temperature bath, readily controlled in any range up to boiling temperatures. In the 85 percent of final diffusion travel, variable speed oscilation of the diffuser tube is provided to develop variable mechanical agitation. Provision is made for such factors as control of temperature and flow rate of battery supply, prescalding of cossettes, etc. Variable speed of the diffuser chain is provided. A weighed amount of cossettes is placed in each diffuser flight section so that uniform cossette loading is maintained.

The results herein enumerated are only exemplary of the type obtained demonstrating some of the findings to date.

Table 5—Diffusion Temperature Constant Throughout.

Diffusion Conditions:

Beets—fresh, 15.8% Sugar
Draft—135
Retention Time—36 Minutes

	Averages of 3 Sets of Tests				
	65° C.	70° C.	75° C.	80° C.	85° C.
Diffusion Juice Brix	12.04	12.45	12.37	12.38	12.63
Pulp, % Sugar	0.45	0.40	0.29	0.29	0.33
% Non-Sugar Elimination	17.1	19.9	18.1	15.9	8.2
% Ash Elimination	15.7	17.4	17.5	17.1	18.1
% Amine-Compound Elimination	34.5	34.4	33.9	37.7	39.6
% Invert Elimination	34.4	39.8	48.4	48.4	36.6

Referring to Table 5, these data as shown are the average of three sets of tests. In other words, the results were replicated three times and averaged. It should be pointed out that for a series of tests the beets to be used are washed and axially segmented lengthwise of the beet, with one segment being thrown in each pile up to the number of tests planned. Each pile has an equal wedge segment of each beet to eliminate any chance of variability of raw material. The samples are immediately placed in vapor tight plastic bags in a refrigerator until test time when they are totally cut to cossettes, mixed, and diffused. The samples evaluated are taken after the diffuser has reached equilibrium. Recent tests on marc value indicate that some drying of pulp is taking place in the draining section of the diffuser so the exhaustion is greater than shown. No correction for this drying was made in the tests reported herein. In this series the temperature was raised in the first 15 percent of diffusion travel to the given value and maintained constant at this level throughout the remainder of diffusion. In other words, this is as nearly as possible a constant temperature diffusion. The maximum over-all non-sugar elimination of this series manifests itself at a diffusion temperature of 70° C. with maximum exhaustion being manifest at 75-80° C. It is worth noting that the ash elimination is not significantly sensitive to temperature. The elimination of amine constituents is significantly higher at temperatures of 80° C. and above. It is also interesting to note that the amine constituents are the class of non-sugars eliminated to the highest degree. Factory tests have borne this out.

The apparent invert eliminations shown herein are very high, but show no pattern of trend with temperature. It should be pointed out that diffusion juice from the experimental diffuser shows no lactic formation, so that bacterial fermentation cannot be credited with the invert disappearance. Thermal alteration of invert, however, is a probable factor in the high apparent invert elimination.

For a time in the earlier diffusion studies raffinose was followed with erratic results, which were traced back to the weakness of the analytical method. No appreciable raffinose elimination was observed, and this has been confirmed on factory samplings.

A continuing effort has been made to evaluate the acid and alkali coagulatable factors in the diffusion juice to measure their pattern of elimination. Only recently has what is now considered a satisfactory method been developed. So far, they demonstrate no appreciable elimination of acid coagulatable factors and the alkali cogulatables have shown from "no elimination" to a "small, negative elimination."

Table 6.—Diffusion Temperature Varying in First 15% of Cossette Travel, Remaining Portion of Diffuser at 70° C.

Diffusion Conditions:
Beets—fresh, 16.4% Sugar
Draft—135
Retention Time—36 Minutes

	Averages **of** 3 **Sets of Tests**			
	Entire Diffuser	**First** 15	**of Cossette Travel**	
	70° C.	**80° C.**	85° C.	**90° C.**
Diffusion Juice Brix	12.30	13.25	12.85	13.63
Pulp, % Susrar	0.46	0.43	0.40	0.29
% Non-Sugar Elimination	17.9	23.7	24.4	21.0
% Ash Elimination	9.1	13.5	12.7	11.9
% Amine-Compoumd Elimination	30.5	32.3	33.5	31.6
% Invert Elimination	32.9	48.8	43.9	40.2

Referring now to Table 6, this series was set up to test the merit of holding the head end of the diffuser at a higher temperature than the rest of the diffuser. This is the conventional method of operating, but the question was how much higher temperature, if any, on the head end would derive the optimum result. Since the series in Table 5 demonstrated optimum uniform temperature diffusion at 70° C, this series reported in Table 6 was set up to heat *in* the first 15 percent of travel to temperatures of 80, 85, and 90° C, with the remainder of diffusion travel held at 70° C. in all cases. A duplication of the 70° C. uniform diffusion was also placed in this series for direct comparison. It's worth mentioning here that Table 5 anticipates that higher temperature on the head end might give improved elimination by virtue of raising amine elimination due to the short high-temperature exposure, without keeping this high temperature long enough to reap all its detrimental effects.

The results in Table 6 bear out these hopes. They show in all cases an improved non-sugar elimination over the constant temperature diffusion, the optimum occurring with a head end heating temperature of 85° C. This series was conducted with freshly dug beets, as shown.

The increased amine elimination with increased head end temperature is demonstrated. The sugar-in-pulp reduction associated with the higher head end temperatures should not be overlooked.

Table 7.—Pre-Scalding Cossettes to 85° C. with Steam and Diffusing at Various Temperatures.

Diffusion Conditions:
Beets—fresh, 16.3% Sugar
Draft—135
Retention Time—36 Minutes

	Averages of 3 Sets of Tests			
	No Pre-Scald.	Pre-Scalding Cossettes to 85° C.		
	Coss. End[1] 80° C. Rem. 70° C.	Entire Diff. 70° C.	Coss. End[1] 85° C. Rem. 70° C.	Coss. End[1] 80° C. Rem. 70° C.
		*	*	*
Diffusion Juice Brix	13.14	10.72	11.93	11.07
Pulp, % Sugar	0.47	0.39	0.34	0.40
% Ash Elimination	15.0	12.9	13.5	12.6
% Non-Sugar Elimination	19.8	15.7	16.0	16.0
% Amine-Compound Elimination	30.7	35.8	36.2	36.0
% Invert Elimination	52.8	50.0	41.7	49.1

[1] Temperature in diffuser after first 15 percent of cossette travel. * Low brix due to steam dilution.

Table 7 represents a series set up to test the possible benefits of steam prescalding of cossettes on assisting non-sugar elimination. The previously determined optimum of variable temperature diffusion is included in the series for comparison. The prescalding runs demonstrate non-sugar eliminations inferior to the variable temperature diffusion indicating no promise when applied in this manner as a beneficient to over-all elimination. The prescalding results do demonstrate the ability to boost amine elimination. The dilution of the diffusion juice through prescalding is substantial and points up the disadvantage of any direct steam heating employed in diffuser operation.

Table 8.—Use of Pulp Press Water for Diffusion.

Diffusion Conditions:
Beets—In Storage 42 Days, 17.7% Sugar
Draft—150
Retention Time—40 Minutes

	Typical Data for Single Test		
	Diff. Juice from Pulp Press Water	Diff. Juice from Reg. Water	Pulp Press Water
Diffusion Juice Brix	14.15	1270	0.45
Pulp, % Sugar	0.60	0.31	
% Non-Sugar Elimination	34.5	32.5	
Ash per 100 Sucrose	3.51	3.56	4.21
Amine Compounds per 100 Sucrose	2.25	2.68	6.89
Invert per 100 Sucrose	0.75	0.73	2.03

Table 8 represents a comparative test to examine the effect on non-sugar elimination of returning pulp press water for diffusion. This test is consistent with other repetitions in showing higher purity diffusion juice and higher non-sugar elimination where pulp press water is used for diffusion. While the pulp loss is higher the average of all tests conducted so far show 5.4 pounds of sugar per ton of beets added from pulp press water, compared to 6.2 pounds per ton of beets increased loss of sugar in pulp. We now want to run a similar comparison varying the draft so that more equal pulp losses will occur. In the tests reported in Table 6 straight pulp press water was used for diffusion to accentuate the non-sugar elimination effect.

Table 9.—**Draft Variation Tests.**

Diffusion Conditions:

Beets—Storage 70 days, 15.0% Sugar
Temperature—85° C. first 15% of cossette travel, 70° C. remainder of diffuser
Retention time—45 Minutes

	Averages of 2 Sets of Tests			
	Draft **120**	Draft **130**	**Draft 140**	**Draft 150**
Diffusion Juice Brix	13.07	12.22	11.74	**11.11**
Pulp, % Sugar	0.38	0.23	0.18	0.19
% Non-Sugar Elimination	20.3	17.2	16.0	15.9
% Ash Elimination	16.0	16.2	11.7	14.7
% Amine-Compound Elimination	32.3	28.4	25.5	29.5
% Invert Elimination	46.4	39.1	46.4	39.7

The test work in Table 9 represents a series of tests designed to examine the effects on non-sugar elimination of more completely exhausting the pulp. Factory discussions revolving around this question had persisted for years without a precise answer. Here the opportunity finally presents itself of holding all conditions constant even to the cossettes diffused, with the exception of draft, to vary the degree of exhaustion. The results sharply point up the sacrifice of non-sugar elimination attendant with exhaustion to low pulp levels.

It is hoped that the economic considerations in the forward part of this presentation may assist in pointing the way in balancing considerations of the relative importance of various factors in working toward improved diffusion processes of the future and controlling current diffusers.

While the diffusion studies herein reported are far from complete, it is hoped that they will rouse interest in what may be accomplished in establishing a more sound and factual knowledge of this key unit process of the beet sugar industry.