SUGAR FACTORY MATERIAL BALANCE CALCULATIONS WITH THE AID OF A DIGITAL COMPUTER

by A.M. Guthrie

Abstract

The mathematical models used to compute the materials balance at the various stations in a sugar factory are described and the overall logic of the computer program to prepare a factory materials balance is discussed. The use of the program to study the effect on the factory of varying one process parameter is illustrated and other applications of the program are discussed.

Introduction

The author was involved in several attempts to compute heat balances for sugar factories. Before a heat balance computation can be attempted it is essential that a reasonably accurate materials balance for the factory be available. In every case, the final heat balance could only be described as a rough approximation to average conditions as a result of difficulty experienced in arriving at a sufficiently accurate materials balance. These cases were only investigated for average conditions. It would obviously be desirable if the investigation could also be carried out for extreme conditions, for example, high and low fibre content of cane, and high and low throughput. Any attempt to do this manually, however, would be prohibitively time-consuming and expensive.

It was noted particularly that in the calculation of the materials balance for the boiling system a method of successive approximations was almost essential. This section of the factory involves the greatest amount of calculation and the digital computer is particularly suitable where this type of iterative approach to a solution can be adopted. The speed of the computer enables the complete materials balance calculation to be performed in a matter of minutes. Hence, it becomes an economical proposition to take approximate input data to perform the computation and then refine the results by adjusting the data until an acceptable solution has been obtained.

A computer program to calculate the materials balance of a sugar factory was, therefore, written with provision for extension to compute heat balances and steam balances although this extension has not yet been attempted. Experience in the application of the program lead to its extension to cover all possible footings systems in the boiling house which are used in the Natal industry and certain footings systems which are used elsewhere. In addition, it was realised that the program could be of considerable assistance in other applications and the output was, therefore, adapted to give considerably more information than was available from the original version of the program.

Definitions

In any attempt to write a mathematical model of the nature described it is essential that all terms used be precisely defined in order to avoid confusion. The following definitions were used for the principal parameters used throughout the materials balance program. Certain of these definitions differ from those laid down for factory chemical control. Minor changes to definitions were made for convenience in programming.

Brix — the ratio of the weight of soluble solids in a solution to the total weight of the solution.

Purity — the ratio of the weight of sucrose to the total weight of soluble solids in the solution.

Exhaustion — the ratio of the weight of sucrose in sugar made to the weight of sucrose in the massecuite from which it is obtained.

Mud Solids Ratio — the ratio of the dry weight of insoluble solids in mud to the total weight of the mud.

Tons Brix — the total dry weight in metric tons of the soluble solids in the solution.

Liming Ratio — the weight ratio of dry lime added to the soluble solids in total juice.

Filter Retention — the ratio of the weight of dry insoluble solids retained on the filter to the total dry weight of insoluble solids in mud after the addition of bagacillo.

Mathematical Models

A. The Milling Station

Computation of the materials balance over the milling station as a whole is relatively trivial. It is appreciated that a lot of research work is being devoted to modelling the precise performance of a milling tandem but this is a very much more complex problem than the simple material balance. The input data required by this section of program is the weight of cane crushed per hour, the sucrose and fibre content of the cane as ratios, the imbibition ratio on fibre, the extraction, the moisture on bagasse, the purity of mixed juice, the suspended solids in mixed juice and the purity of last expressed juice. From this data it is possible to compute the brix and weight of mixed juice, the brix and purity of residual juice in bagasse and the total weight of bagasse.

B. Clarification

In order to model the clarification station, it was decided to use three main input parameters, the ratio of lime added to brix in total juice, the purity of clarified juice, and the mud solids ratio. It is assumed that the total quantity of sucrose over the clarifier remains unchanged. The lime added by definition will reduce the purity of the juice arriving at the clarifier. It is assumed, therefore, that the purity rise between limed juice and clarified juice is caused by the reaction between the lime and certain of the soluble non-sugars in the solution to form insoluble material. Hence the total insoluble material in the clarifier comprises the insoluble solids brought in with mixed juice plus any insoluble material caused as a result of the action of lime on non-sucrose. This insoluble material will be mixed with the total quantity of sucrose and soluble non-sucrose in clear juice. In order to obtain the separation of mud from clear juice it is assumed that no insoluble solids are carried over to the clear juice. A material comprising clear juice and insoluble solids in the ratio specified by the mud solids ratio is, therefore, drawn off and remaining material is assumed to be clear juice.

C. Filter Station

Input parameters required to specify reactions at the filter station are the ratio of added bagacillo to mud solids, the filter retention, the ratio of sucrose and moisture to filter cake and the ratio of wash water to filter cake. If the factory is using the diffusion process with a press water clarifier, then the effects of press water clarification are computed in the same way as normal clarification, and the press water muds are added to the muds from the main clarifier before the addition of bagacillo. Bagacillo in the ratio specified by the ratio bagacillo to mud solids is added to the muds and a new series of figures computed for mud solids, brix, tons brix and purity of juice in the mud. The bagacillo is assumed to have the same composition as the bagasse and the quantity used is deducted from the total bagasse made.

Insoluble solids in the filter cake are then computed from the filter retention and the sucrose, non-sucrose and moisture in the filter cake are computed from the input data. The remaining solution together with the insoluble solids not retained by the filter, and the filter wash comprise the filter returns.

D. Evaporation

As far as material balance computations are concerned, the only requirement in the evaporation station is that the brix of the juice is increased to that of syrup, the amount of evaporation to achieve this being computed. No detail of concentration between individual vessels in the evaporator is taken into account, as this is more a problem for the heat balance computation.

E. Pan Boiling

For the purposes of the materials balance calculation the three processes of pan boiling, crystallization and centrifuging can be regarded as a single operation. A feed of known brix and purity is taken to a pan, water is removed to obtain the required massecuite brix, sugar of a given purity is removed from the massecuite to obtain the required exhaustion and the residual material comprises the molasses made at the station.

F. Double Curing

In a first order attempt to model the operation of double curing, it is assumed that the B molasses used acts purely as a vehicle and it is not, therefore, taken into account in the model process. Given the purity of C sugar made from the C station and the purity of the double cured sugar it is assumed that two products result from the double curing operation, namely, a sugar of the purity of the double cured C sugar and a runoff at the brix of C molasses and purity of B molasses. The total quantity of the first C sugar is, therefore, divided in the above proportions and the runoff returned to C feed.

G. Affination

The mathematical model of the affination stage, where this is employed, follows very closely that of the double curing operation. In this instance input parameters required are the purity of the raw sugar, the purity of the affinated sugar and the purity of the affination runoff. The total hourly feed is divided in the above proportions and the runoff returned with refinery returns to mixed juice.

Program Logic

The logic for the milling or diffusion stations is relatively simple and follows directly the mathematical models described for this station. There is no necessity for iterative procedures as the results can be directly described in the form of simple equations.

Clarification Station

The input to the clarification station can only be determined when the filter returns which are a function of the muds produced are known. Hence an iterative technique is used in solving the material balance in the clarification station.

In the first instance the mixed juice obtained from the milling station is taken to the clarification station and divided according to the mathematical model described above. The muds are taken to the filter station and a value computed for filter returns. The tons brix in filter return is stored, the return added to mixed juice and the clarification and filtration computation repeated. On each iteration the quantity of filter return is compared with that from the previous iteration. When on two successive calculations the total tons brix in the filter return agrees to within 0,1% it is assumed that an acceptable accuracy has been obtained and the computation terminated. The complete procedure usually requires between 8 and 10 successive approximations and requires less than two seconds of computer time. A flow sheet for the clarification station computation is included in Figure 1.

Boiling House

The operations in the boiling house are probably the most complex in a sugar factory and this is also the part of the process where the greatest number of variations are likely to occur between different factories. Contrary to the normal approach used in manual computation where it is the accepted practice to work backwards from the final molasses, the facilities

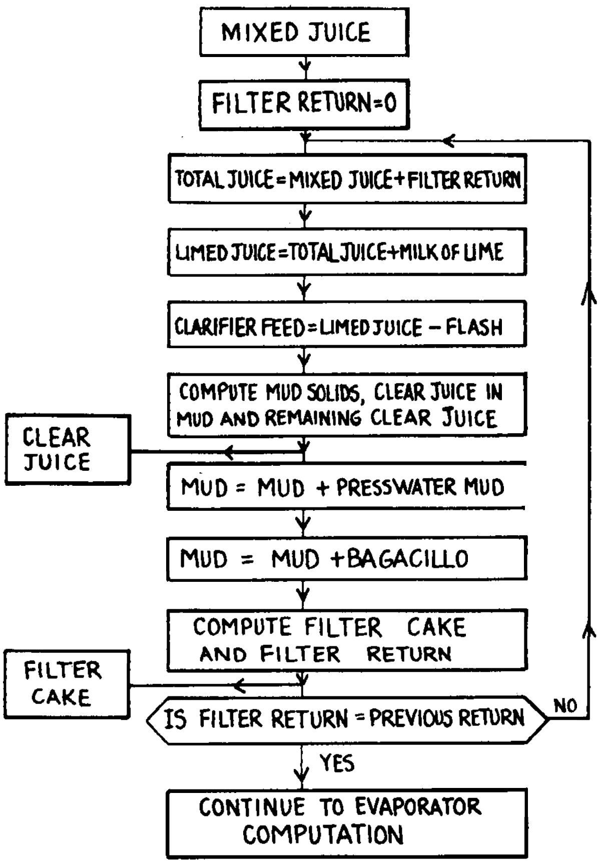


Fig. 1 Logic Diagram — Clarification.

available on the computer enable us to work forward from syrup. During the first computation through the system it is assumed that there are no footings or returns. The syrup is taken as the feed to the A pans, the A molasses made from this boiling is taken as feed to B pans and the B molasses made is used as feed for C pans. Input figures of exhaustion and molasses brix are used to compute the molasses and sugar made.

From this first computation through the system, figures are obtained for the massecuite quantities and for the quantities of sugar, both B and C, available for remelt, magma, etc.

The quantities of feeds, remelts, etc obtained from the first calculation through the system are then used to compute footings for the second computation. This process is repeated until on two successive computations the quantity of C sugar made differs by less than 0,03%. It has been found that this iteration normally converges after 7 to 9 computations through the system. Where there is no refinery this concludes the computation apart from the output phase. However, where a refinery is attached to the raw factory it is now necessary to compute the refinery balance on the basis of input sugar from the first computation on the raw house in order to find the quantity of refinery return to be added to the total syrup. In this case after each refinery computation the raw house computation is repeated on the basis of the previous figures for total feed to A pans plus the refinery returns until on two successive computations the refinery returns differ by less than 0,03%.

Refinery

If the raw factory is refining as well a first order approximation of the refinery boiling process is available. No attempt has been made at this stage to model the actual carbonatation, or the other refining processes. It is merely assumed that a slight purity rise, which is required as one of the input parameters, occurs between remelting of the input sugar and the feeding of the refined liquor to the first refined boiling. It is further assumed that a straight boiling process is used with the molasses from the previous boiling forming the footings to the next boiling. The same basic pan boiling model is used as in the raw house for each refined boiling. The program allows for one to four refined boilings, and for backboiling of a proportion of the runoff from the first boiling until a constant purity for the first runoff is obtained.

Options Available

The program has been written to allow the following variations in the sugar making process:

a. For the extraction of the sucrose from cane either straight milling or normal milling-cum-diffusion with or without clarification of press water.

b. Options in the boiling house allow for the boiling of a pre-determined quantity of Syrup, A molasses or B molasses into the footings of the A pans, B pans and C pans. In addition B sugar may be bagged for sale, remelted with either clear juice or water and returned to total syrup, or used as a magma with A molasses as an A footing. In the last case only the specified proportion of magma is used in the footing, and any surplus is remelted either with water or clear juice for return to total syrup. C sugar may be double cured or not, as desired. Any proportion of the resultant sugar may be retained for disposal and the balance may be remelted with water, or clear juice for return to total syrup, or it may be used to form a magma with B molasses to form a footing for the B boiling. Any surplus C magma is used as a footing for the A boiling. In addition, provision is made for placing a target purity on the C massecuite. In this case the amount of A molasses necessary to raise the C pan feed to the target purity is computed and used in the computations. If, however, it is found that the B molasses purity is above the target purity for the C massecuite, the B molasses is accepted by the program as the purity of the feed to the C boiling.

c. Refinery options include:
   (i) Affination before remelt or straight remelt of any desired proportion of the raw sugar made. If the affination option is adopted then the affination runoff is fed back with refinery returns to the total juice.
   (ii) From 1 to 4 refined boilings may be used, each successive boiling being fed with runoff from the previous boiling.
   (iii) A predetermined proportion of the runoff from the first refined boiling may be back-boiled to the feed of the first boil-

ing in which case the program will repeat the computation around the first boiling until the runoff purity becomes constant. All refinery runoff is returned to total juice.

Illustration of the Modelling Application

Using the sugar factory material balance program, 4 analyses were carried out to determine the effect on the boiling house of varying exhaustions of A massecuite.

Basic data selected was for an average Natal factory during the 1970/71 season as obtained from the analysis of laboratory reports for the season in the S.A.S.T.A. Congress Proceedings. A crushing rate of 100 tons cane per hour at 13,61% sucrose and 15,34% fibre was selected. This gave 14,9863 tons brix in clear juice per hour. The boiling house was operated on a B magma system using 20% magma on A massecuite as a footing. C sugar was double cured and remelted with clear juice for return to syrup. Surplus magma was also remelted. The C boiling was maintained constant by using A molasses in the footing to adjust C massecuite purity to 59,38 giving in every case 3,876 tons of 85 brix final molasses which resulted in a loss of sucrose in molasses of 9,58%.

The A exhaustions used were 57,45; 61,99; 65,74 and 69,01 while B and C exhaustions of 63,13 and 61,79 were used in each case. For the range of A exhaustions analysed the purity of B molasses was always below that of the C massecuite making it possible to maintain a constant C boiling by adding A molasses to the footing.

The principal results are shown in the composite graph in Figure 2. By increasing A exhaustion the total massecuite quantity was reduced from 1,852m^3 per ton brix in mixed juice to 1,3806m^3 (Am-c 1,087m^3 to 0,92m^3 and B m-c 0,507m^3 to 0,203m^3) while the total evaporation in the pan station, excluding movement water, was reduced from 15,55 tons water to 12,49 tons water.

Under the conditions described improved exhaustion of A massecuite from 57,45 to 69,01 resulted in a decrease of 15% in the quantity of A massecuite handled, 60% in the quantity of B massecuite and 19,8% in the amount of water evaporated in the panhouse. It had no effect on the C station or on the molasses loss.

A sample computer printout for the analysis with 61,99 exhaustion of A massecuite is included in Figure 3.

Discussion

The above illustration of one of the modelling applications of the sugar factory material balance program shows how the program may be used to determine quantitatively the effect of alterations in specific parameters controlling the sugar manufacturing process. The parameter selected for variation may be one which is partially or wholly under the control of factory staff or may be one which is dictated by the quality of the input material. In either case it is possible to prepare a graph to determine the effect of these variations on the process and possibly to do further computations to find out whether it is possible to counteract adverse effects by varying other parameters.

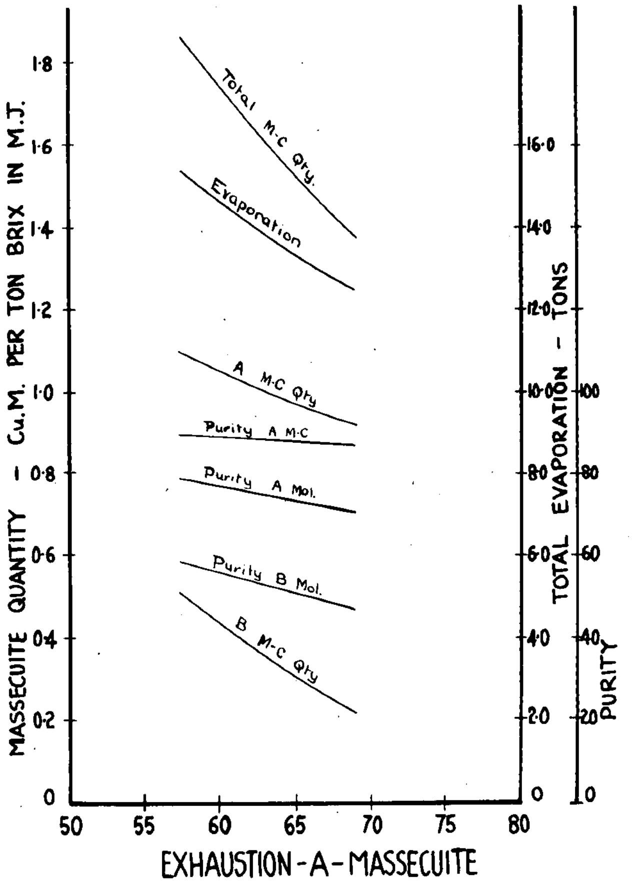


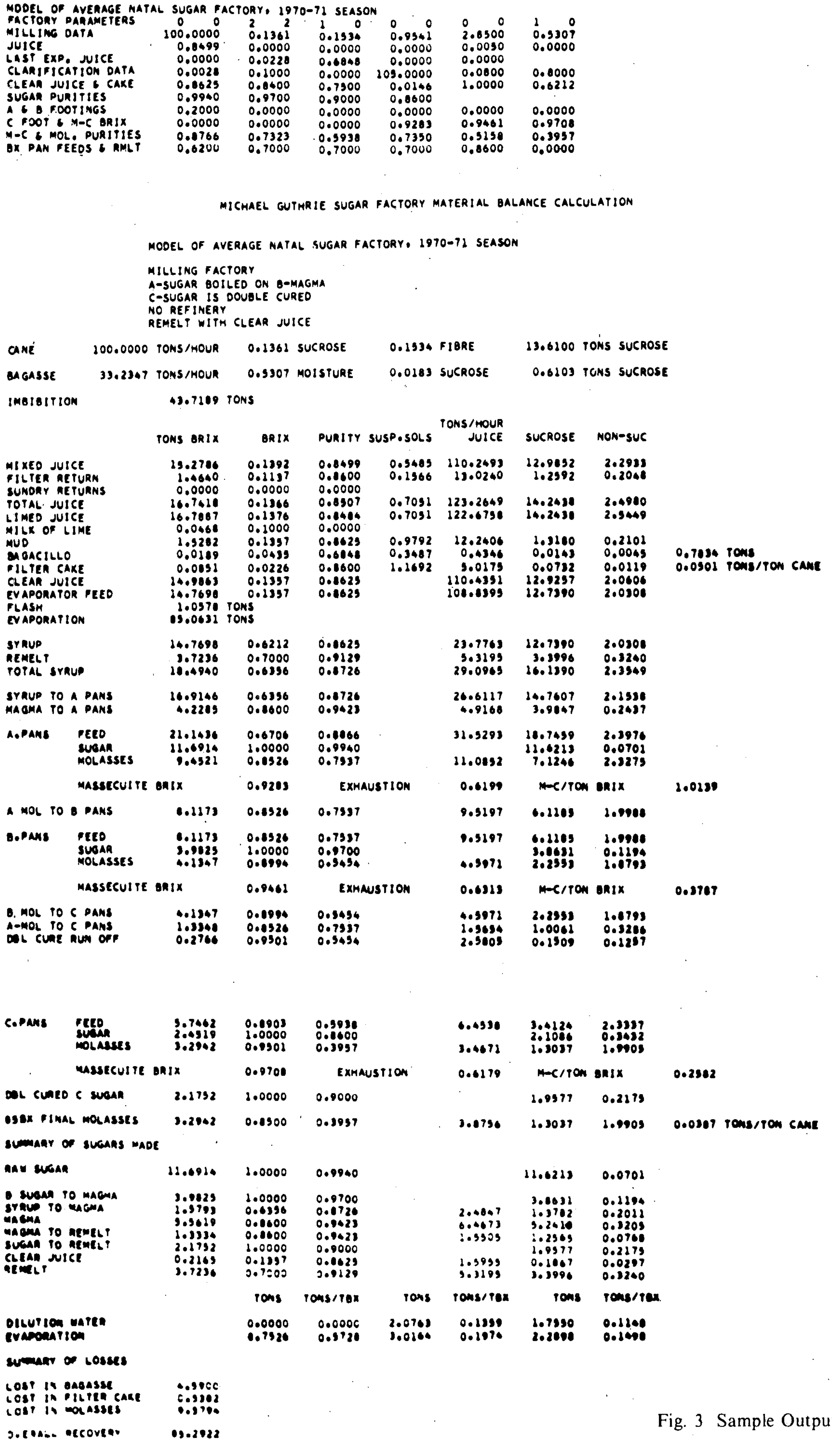
Fig. 2 Effects of varying A Exhaustion.

The second use of the program is to model the performance of an actual factory. Experience in the use of this program has indicated that invariably the parameters given by factory management in the first instance do not give a material balance which agrees with the reported laboratory figures. Because of the speed of the program, which takes approximately three minutes in total to run, it is possible to vary certain parameters until a model is obtained which agrees with laboratory figures. Hence the actual process being used may be evaluated and from this action may be taken to ensure that the optimum process is adopted.

Where one specific parameter is in doubt, it is possible to repeat the analysis with this parameter set at various figures both greater and less than the figure expected and the results graphed in order to obtain an approximation to the actual value of the parameter.

Where it is desired to do a heat and steam balance computation for a sugar factory, the basic data supplied by the material balance program makes the remaining calculations relatively trivial. It is also simple to investigate the effects of high and low fibre and sucrose content on the heat and steam balance of the factory as the extra material balance computations are quickly and simply done with the aid of the program.

The materials balance program can also be of the utmost assistance when planning extensions to



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MODEL OF AVERAGE NATAL SUGAR FACTORY, 1970-71 SEASON
FACTORY PARAMETERS       0    0      2    2      1    0      0    0      0    0      1    0
MILLING DATA        100.0000     0.1361      0.1534      0.9541      2.8500      0.5307
JUICE                 0.8499     0.0000      0.0000      0.0000      0.0050      0.0000
LAST EXP. JUICE       0.0000     0.0228      0.6848      0.0000      0.0000
CLARIFICATION DATA    0.0028     0.1000      0.0000    105.0000      0.0800      0.8000
CLEAR JUICE & CAKE    0.8625     0.8400      0.7500      0.0146      1.0000      0.6212
SUGAR PURITIES        0.9940     0.9700      0.9000      0.8600
A & B FOOTINGS        0.2000     0.0000      0.0000      0.0000      0.0000      0.0000
C FOOT & M-C BRIX     0.0000     0.0000      0.0000      0.9283      0.9461      0.9708
M-C & MOL. PURITIES   0.8766     0.7323      0.5938      0.7350      0.5158      0.3957
BX PAN FEEDS & RMLT   0.6200     0.7000      0.7000      0.7000      0.8600      0.0000
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                         MICHAEL GUTHRIE SUGAR FACTORY MATERIAL BALANCE CALCULATION

                  MODEL OF AVERAGE NATAL SUGAR FACTORY, 1970-71 SEASON

                  MILLING FACTORY
                  A-SUGAR BOILED ON B-MAGMA
                  C-SUGAR IS DOUBLE CURED
                  NO REFINERY
                  REMELT WITH CLEAR JUICE

CANE         100.0000 TONS/HOUR    0.1361 SUCROSE      0.1534 FIBRE        13.6100 TONS SUCROSE

BAGASSE       33.2347 TONS/HOUR    0.5307 MOISTURE     0.0183 SUCROSE       0.6103 TONS SUCROSE

IMBIBITION              43.7189 TONS

                                                             TONS/HOUR
                  TONS BRIX       BRIX     PURITY SUSP.SOLS      JUICE    SUCROSE    NON-SUC

MIXED JUICE         15.2786     0.1392     0.8499    0.5485   110.2493    12.9852     2.2933
FILTER RETURN        1.4640     0.1137     0.8600    0.1566    13.0240     1.2592     0.2048
SUNDRY RETURNS       0.0000     0.0000     0.0000
TOTAL JUICE         16.7418     0.1366     0.8507    0.7051   123.2649    14.2438     2.4980
LIMED JUICE         16.7887     0.1376     0.8484    0.7051   122.6758    14.2438     2.5449
MILK OF LIME         0.0468     0.1000     0.0000
MUD                  1.5282     0.1357     0.8625    0.9792    12.2406     1.3180     0.2101
BAGACILLO            0.0189     0.0435     0.6848    0.3487     0.4346     0.0143     0.0045     0.7834 TONS
FILTER CAKE          0.0851     0.0226     0.8600    1.1692     5.0175     0.0732     0.0119     0.0501 TONS/TON CANE
CLEAR JUICE         14.9863     0.1357     0.8625              110.4351    12.9257     2.0606
EVAPORATOR FEED     14.7698     0.1357     0.8625              108.8395    12.7390     2.0308
FLASH                1.0578 TONS
EVAPORATION         85.0631 TONS

SYRUP               14.7698     0.6212     0.8625               23.7763    12.7390     2.0308
REMELT               3.7236     0.7000     0.9129                5.3195     3.3996     0.3240
TOTAL SYRUP         18.4940     0.6356     0.8726               29.0965    16.1390     2.3549

SYRUP TO A PANS     16.9146     0.6356     0.8726               26.6117    14.7607     2.1538
MAGMA TO A PANS      4.2285     0.8600     0.9423                4.9168     3.9847     0.2437

A.PANS     FEED     21.1436     0.6706     0.8866               31.5293    18.7459     2.3976
           SUGAR    11.6914     1.0000     0.9940                          11.6213     0.0701
           MOLASSES  9.4521     0.8526     0.7537               11.0852     7.1246     2.3275

           MASSECUITE BRIX      0.9283        EXHAUSTION         0.6199     M-C/TON BRIX          1.0139

A MOL TO B PANS      8.1173     0.8526     0.7537                9.5197     6.1185     1.9988

B.PANS     FEED      8.1173     0.8526     0.7537                9.5197     6.1185     1.9988
           SUGAR     3.9825     1.0000     0.9700                           3.8631     0.1194
           MOLASSES  4.1347     0.8994     0.5454                4.5971     2.2553     1.8793

           MASSECUITE BRIX      0.9461        EXHAUSTION         0.6313     M-C/TON BRIX          0.3787

B.MOL TO C PANS      4.1347     0.8994     0.5454                4.5971     2.2553     1.8793
A-MOL TO C PANS      1.3348     0.8526     0.7537                1.5654     1.0061     0.3286
DBL CURE RUN OFF     0.2766     0.9501     0.5454                2.5805     0.1509     0.1257




C.PANS     FEED      5.7462     0.8903     0.5938                6.4538     3.4124     2.3337
           SUGAR     2.4519     1.0000     0.8600                           2.1086     0.3432
           MOLASSES  3.2942     0.9501     0.3957                3.4671     1.3037     1.9905

           MASSECUITE BRIX      0.9708        EXHAUSTION         0.6179     M-C/TON BRIX          0.2582

DBL CURED C SUGAR    2.1752     1.0000     0.9000                           1.9577     0.2175

85BX FINAL MOLASSES  3.2942     0.8500     0.3957                3.8756     1.3037     1.9905     0.0387 TONS/TON CANE

SUMMARY OF SUGARS MADE

RAW SUGAR           11.6914     1.0000     0.9940                          11.6213     0.0701

B SUGAR TO MAGMA     3.9825     1.0000     0.9700                           3.8631     0.1194
SYRUP TO MAGMA       1.5793     0.6356     0.8726                2.4847     1.3782     0.2011
MAGMA                5.5619     0.8600     0.9423                6.4673     5.2418     0.3205
MAGMA TO REMELT      1.3334     0.8600     0.9423                1.5505     1.2565     0.0768
SUGAR TO REMELT      2.1752     1.0000     0.9000                           1.9577     0.2175
CLEAR JUICE          0.2165     0.1357     0.8625                1.5955     0.1867     0.0297
REMELT               3.7236     0.7000     0.9129                5.3195     3.3996     0.3240

                                  TONS   TONS/TBX       TONS   TONS/TBX       TONS   TONS/TBX

DILUTION WATER                  0.0000     0.0000     2.0763     0.1359     1.7950     0.1148
EVAPORATION                     8.7526     0.5728     3.0164     0.1974     2.2898     0.1498

SUMMARY OF LOSSES

LOST IN BAGASSE      4.5900
LOST IN FILTER CAKE  0.5382
LOST IN MOLASSES     9.5794

OVERALL RECOVERY    85.2922
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Fig. 3 Sample Output.

a factory or investigating bottlenecks in an existing factory.

Where discrepancies are found between laboratory reports and actual performance, the program provides a quick and simple means of comparing the effect of varying certain parameters obtained from laboratory analyses which may be suspect in order to determine their most likely values. Thus a well planned series of analyses may provide the necessary data to assist in pinpointing those areas of the laboratory technique in sugar factory reporting which would offer the greatest return from detailed investigation.

The author is aware of the considerable amount of research being devoted to dynamic modelling of the sugar factory processes. This is a field which in the long term will provide enormous benefits to the industry in better process control and greateryields. However, it is the author's belief that a far greater insight into the inter-relation of parameters controlling the process may be obtained from the application of a first order static model of the type described which may considerably assist the sophisticated modellers in expediting their work.

Conclusion

A computer program for calculating the material balance of a sugar factory on the assumption that it is a continuous process with constant controlling parameters has been described. It is realised that this does not approach the actual situation with rapidly varying qualities of input material and the batch process existing in the boilinghouse. However, it is contended that the speed and simplicity with which this analysis can be carried out provides a useful tool both for investigating the current problems in existing factories and for assisting in preparing future dynamic models in the attempt to obtain a more complete mathematical description of the dynamics of the sugar factory.

Lord Kelvin once said, "When you can measure what you are speaking about and express it in numbers you know something about it, but when you can't express it in numbers, your knowledge is of a meagre and unsatisfactory kind". While all parameters in the sugar process are regularly expressed in numbers in voluminous reports we find that many of the numbers are suspect. The facility provided by the computer program described for comparing and inter-relating these numbers could assist us in giving to each of them its due significance.