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by

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ABSTRACT

The signal flowgraph technique is utilized to represent the flowsheet of a coal preparation plant. The flowsheet is assumed to be composed of one or combination of density separators and/or size separators. A formula is used to establish the relationships between the end products and feed as well as between intermediate products (in case of recirculation) and feed. Several typical coal washing circuits as well as existing coal preparation plant flowsheets are considered to illustrate the effectiveness of the proposed technique. The proposed method eliminates the tedious and time-consuming calculations of performance predictions using the step by step approach and simplifies computer programming for modelling purposes.

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UTILISATION DE LA SIGNALISATION DANS L'ORGANIGRAMME D'UNE USINE DE PRÉPARATION DU CHARBON

par

A.I.A. Salama* et M.W. Mikhail**

La représentation par signaux est utilisée dans l'organigramme d'une usine de préparation du charbon. On présume que l'organigramme comprend un ou des appareils de séparation de densité ou de séparation gravimétrique. On utilise une formule pour établir les rapports entre le produit fini et la matière première et entre les produits intermédiaires (dans les cas de recirculation) et l'alimentation. Plusieurs circuits de lavage de charbon et les organigrammes des usines de charbon démontrent l'efficacité de la méthode proposée. Cette méthode élimine les calculs longs et fastidieux concernant les prévisions sur la performance qui nécessitent une approche par étapes et simplifie la programmation informatique du modelage.

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INTRODUCTION

Prediction of coal preparation plant performance is essential at early stages of mine development in order to estimate potential recovery and quality of products. Economic and feasibility studies also depend to a great extent on performance predictions for flowsheet design and optimization. In this paper density separators: Heavy Medium Cyclone (HMC), Heavy Medium Bath (HMB), table and jig are considered. It is noted, however that the same principles can apply also to size separation (1). To assist in performance prediction for a coal preparation plant utilizing density separators and size separators, the method of signal flowgraph is used to determine the relationships between the process variables such as density separator feeds, overflows and underflows. The method starts by assigning nodes to the process variables in the flowsheet and using the partition ratios for the different density separators to establish the relationship between the adjacent nodes. However, the overall relationship between end products and feed or intermediate process variables (where there is recirculation) can be determined using Mason's Rule (2) (see Appendix A). These relationships are used to determine performance predictions for given float-sink data or size distribution. The method avoids tedious calculations and also simplifies computer programming for modelling purposes.

Typical two-product and three-product circuits with and without recirculation are used to demonstrate the signal flowgraph method. The signal flowgraphs for the CBDC (Cape Breton Development Corporation) coal preparation plant in Sydney - N.S. and Luscar-Sterco coal preparation plant in Alberta are developed and the relationships between end products and feed are determined.

DENSITY SEPARATORS SIGNAL FLOWGRAPH

In an ideal density separation, particles of density less than the relative density of separation d_p report to the clean product, while particles of density greater than d_p report to the reject. If the ratio of recovery in the reject of particles with density d is plotted against density d then, a step function is obtained with ordinate 0 for d less than d_p and with ordinate 1.0 for d greater than d_p, as shown in Fig. 1. However, in the non-ideal case which is found in practice, some clean coal particles report to the reject and some reject particles report to the clean product. In this case the plot of the ratio of feed reporting to the reject against the mean value of each density fraction, is called the separation curve (SC); also known as distribution curve, partition curve, or error curve, whose ordinate, representing the ratio of feed reporting to the reject is known as the partition ratio (P).

In the case of the HMC separator Fig. 2, the raw feed is F, the feed to the cyclone is X, and since there is no recirculation X=F. The raw feed and the cyclone feed are thus represented by nodes F and X and with X=F the branch between F and X has a gain of 1. Since by definition the partition ratio P is the ratio of the reject to the cyclone feed, then the branch between nodes X and R (reject) will have gain of P and the branch gain from node X to node C will be (1-P).

Figure 3 shows that for two-product jig separation, with no recirculation the signal flowgraph is similar to the HMC signal flowgraph developed above. In fact, this would be true for any separator in the same configuration. However, for three-product separation, two partition ratios P_1 and P_2 are required to represent the primary and secondary cuts. Following the same line of reasoning as for the two-product HMC separation, the signal flowgraph for three product jig separation can be readily determined, Fig. 3. Figure 3 shows that, as for the two-product separation, an identical process configuration yields an identical signal flowgraph regardless of the device.

FLOWSHEET SIGNAL FLOWGRAPH DEVELOPMENT

To facilitate signal flowgraph development for a given coal preparation flowsheet, we start by assigning nodes to all the different processes feeds, overflows and underflows. We then utilize the signal flowgraphs developed in the previous section as the basis for determining the overall flowsheet signal flowgraph. This can best be illustrated by considering a few typical circuits and existing ones in the CBDC coal washing plant in Sydney, N.S., and the Coal Valley washing plant in Alberta.

TWO-STAGE HMC (NO RECIRCULATION)

In this circuit, shown in Fig. 4, the underflow of HMC_1 is fed to HMC_2 and thus the circuit variables are identified as F, X, C_1, Y, C_2, and R. The branches joining F, X, C_1 and Y are identical to the those shown in Fig. 2, except P_1 replaces P. To account for the second cyclone, the additional nodes Y, C_2 and R and the partition ratio P_2 are introduced. The nodes are joined in the same way as for the primary cyclone.

The gain formula (Eq A-2) described in Appendix A can be used to derive the gain relationships. Since there are only forward paths and no feedback loops in this signal flowgraph, then $\Delta=\Delta_i=1$ and the following are obtained:

$$(C_1/F) = (G_1\Delta_1)/\Delta = G_1 = 1-P_1 \qquad \text{Eq 1}$$

$$(C_2/F) = (G_2\Delta_2)/\Delta = G_2 = P_1(1-P_2) \qquad \text{Eq 2}$$

$$(R/F) = (G_3\Delta_3)/\Delta = G_3 = P_1P_2 \qquad \text{Eq 3}$$

Using Eqs. 1-3, it can be shown that

$$(C_1/F) + (C_2/F) + (R/F) = 1, \qquad \text{Eq 4}$$

which can be used as a verification for the derived gain relationships.

TWO STAGE HMC (WITH RECIRCULATION)

In this circuit, shown in Fig. 5, the underflow of HMC_1 is fed to HMC_2 and the overflow of HMC_2 is fed to HMC_1. The nodes corresponding to the process variables are F, X, C, Y and R. The signal flowgraph of this circuit is similar to that of two-stage HMC with no recirculation except that the branch (Y, C_2) is replaced by the feedback branch (Y, X) whose gain is $(1 - P_2)$. In this case, we have only one feedback loop, whose gain is $[P_1(1-P_2)]$. The signal flowgraph $\Delta = [1-P_1(1-P_2)]$. Note that the path between F and C (F, X, Y, X, C) is not a forward path since node X is traversed twice. The forward paths (F, X, C) and (F, X, Y, R) have common nodes with the feedback loop (X, Y, X) and therefore, $\Delta_1 = 1$. Applying the gain formula (Eq A-2), the following equations are obtained:

$$(C/F) = (G_1\Delta_1)/\Delta = (G_1/\Delta) = [1-P_1]/[1-P_1(1-P_2)] \qquad \text{Eq 5}$$

$$(R/F) = (G_2\Delta_2)/\Delta = (G_2/\Delta) = [P_1P_2]/[1-P_1(1-P_2)] \qquad \text{Eq 6}$$

again using Eqs. 5-6 it can be shown that:

$$(C/F) + (R/F) = 1 \qquad \text{Eq 7}$$

If the amount of recirculation relative to feed is required then the ratio (Y/F) must first be determined using the gain formula:

$$(Y/F) = (G_3\Delta_3)/\Delta = P_1/[1-P_1(1-P_2)$$

then the recirculation relative to feed (Rec):

$$\text{Rec} = (1-P_2)(Y/F) = [P_1(1-P_2)]/[1-P_1(1-P_2)] \qquad \text{Eq 9}$$

Alternatively, the recirculation relative to feed can be obtained from the ratio (X/F):

$$(X/F) = (G_4\Delta_4)/\Delta = 1/[1-P_1(1-P_2)] \qquad \text{Eq 10}$$

where the recirculation relative to feed Rec = [(X - F)/F] = [(X/F) - 1], and substituting

Eq 10,

$$Rec = [1/(1-P_1(1-P_2))]-1 = [P_1(1-P_2)]/[1-P_1(1-P_2)] \qquad \text{Eq 11}$$

we arrive at the same expression as in Eq 9.

The ratio (R/F) expressed in Eq 6 is by definition the overall partition ratio of this circuit. Therefore, by applying this ratio to the float-sink data of a coal, a prediction of yield and quality of clean coal and reject can be obtained.

EXISTING COAL PREPARATION PLANTS CIRCUITS

The CBDC coal preparation plant circuit is shown in simplified form in Fig. 6. In this circuit, two feed coals F_1 and F_2 from two different seams are fed to two separate HMC circuits. The overflows of HMC_1 and HMC_2 are combined to give clean product C_1 (metallurgical coal) and the underflows are combined and fed to a secondary cyclone HMC_3. The overflow of HMC_3 constitutes clean product C_2 (thermal coal), and the underflow is the reject (R). In this circuit, the process variables are thus F_1, X_1, F_2, X_2, C_1, Y, C_2, and R. The corresponding nodes are shown in Fig. 6 where extra nodes are added for clarity. The flowsheet signal flowgraph has no closed loops, therefore, $\Delta = \Delta_1 = 1$. Since this graph has two independent input variables F_1, F_2, the end products are calculated in terms of F_1 and F_2 as:

$$C_1 = \frac{G_1\Delta_1}{\Delta} F_1 + \frac{G_2\Delta_2}{\Delta} F_2 = [1-P_1]F_1+[1-P_2]F_2 \qquad \text{Eq 12}$$

$$C_2 = \frac{G_3\Delta_3}{\Delta} F_1 + \frac{G_4\Delta_4}{\Delta} F_2 = [P_1(1-P_3)]F_1+[P_2(1-P_3)]F_2 \qquad \text{Eq 13}$$

$$R = \frac{G_5\Delta_5}{\Delta} F_1 + \frac{G_6\Delta_6}{\Delta} F_2 = [P_1P_3]F_1 + [P_2P_3]F_2 \qquad \text{Eq 14}$$

The two independent input variables F_1 and F_2 are normalized quantities relative to the overall feed $F = F_1 + F_2$.

The Luscar-Sterco coal preparation plant circuit is considered, where units 1, 4 and 6 are density separators and units 2, 3, 5, 7 and 8 are size separators, Fig. 7. Since the flowsheet is composed of a combination of size and density separators, then the feed must be characterized by certain size ranges with density distribution within each size range whenever applicable. The circuit signal flowgraph developed is shown in Fig. 8. The signal flowgraph has no closed loops, therefore, $\Delta = \Delta_i = 1$. Applying the gain formula (Eq A-2), the following relationships are obtained:

$$\begin{aligned} C/F = \sum_{i=1}^{5} G_i = \; & (1-P_2)(1-P_{11}) + (1-P_2)P_{11}(1-P_{12})(1-P_3)(1-P_4) + \\ & (1-P_2)P_{11}(1-P_{12})P_3P_5(1-P_6)P_7P_8 + P_2(1-P_3)(1-P_4) + \\ & P_2P_3P_5(1-P_6)P_7P_8, \end{aligned} \qquad \text{Eq 15}$$

$$\begin{aligned} R/F = \sum_{i=1}^{11} G_i = \; & (1-P_2)P_{11}P_{12} + (1-P_2)P_{11}(1-P_{12})(1-P_3)P_4 + \\ & (1-P_2)P_{11}(1-P_{12})P_3(1-P_5) + (1-P_2)P_{11}(1-P_{12})P_3P_5P_6 + \\ & (1-P_2)P_{11}(1-P_{12})P_3P_5(1-P_6)(1-P_7) + \\ & (1-P_2)P_{11}(1-P_{12})P_3P_5(1-P_6)P_7(1-P_8) + P_2(1-P_3)P_4 + \\ & P_2P_3(1-P_5) + P_2P_3P_5P_6 + P_2P_3P_5(1-P_6)(1-P_7) + \\ & P_2P_3P_5(1-P_6)P_7(1-P_8). \end{aligned} \qquad \text{Eq 16}$$

To verify these relationships, let us compute the expression [(C/F) + (R/F)] using Eqs. 15 and 16, we get

$$C/F + R/F = 1.$$

which is true.

CONCLUSIONS

A technique for the representation of coal preparation flowsheet is introduced. The technique utilizes the signal flowgraph method to develop the overall flowsheet signal flowgraph. A gain formula is used to determine the relationships between end products and feed as well as between intermediate products and feed. The proposed technique is general and can be implemented on computer, which in turn simplifies computer programming for modelling purposes.

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2. Shinners, S.M. "Modern Control System Theory and Applications" (Second Edition); Don Mills, Canada, Addison-Wesley; 1978.

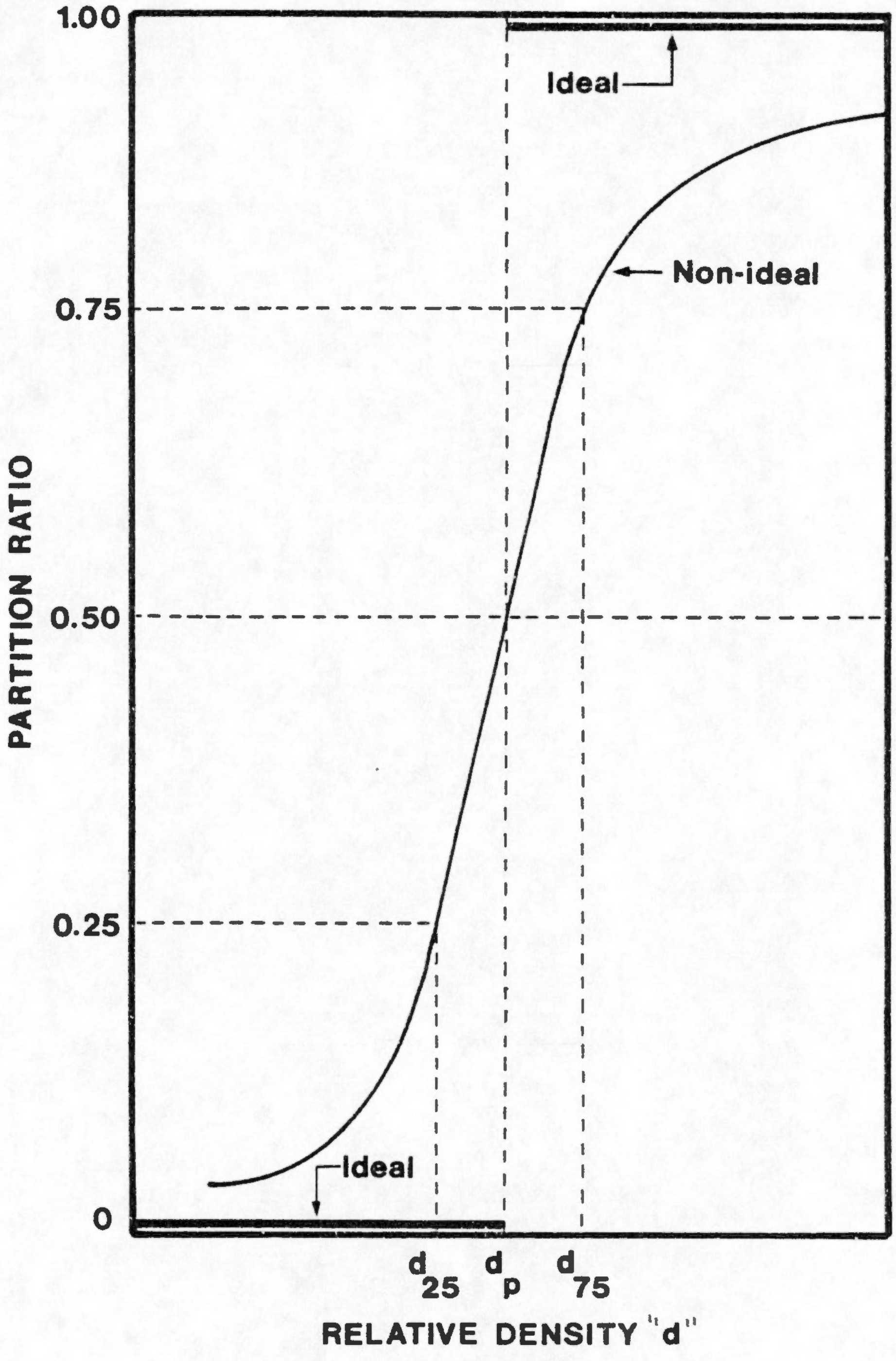


Fig. 1 - Density separation curve

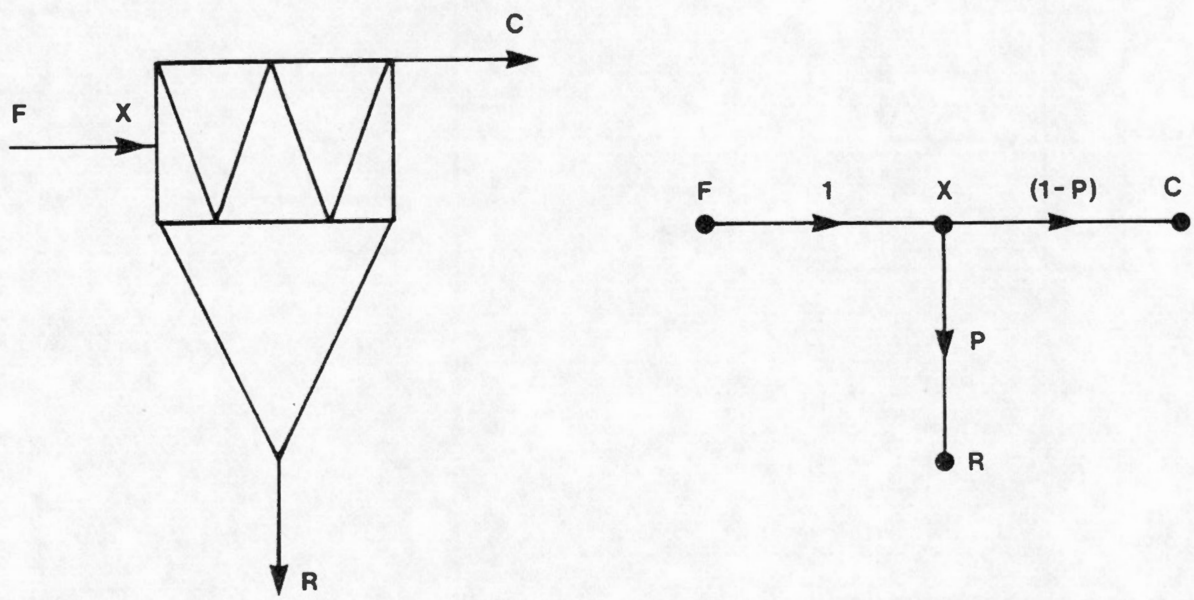
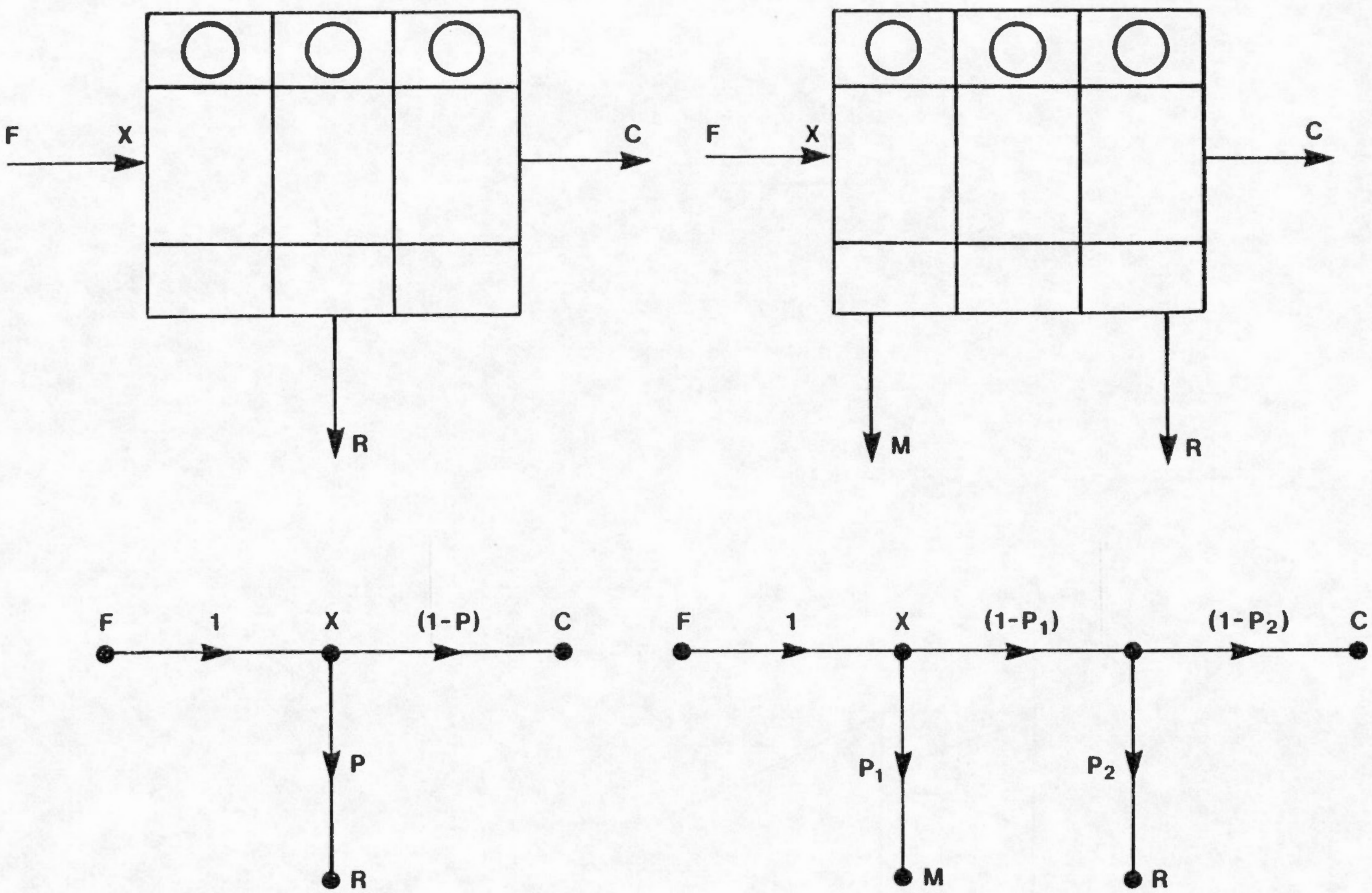


Fig. 2 - Heavy medium cyclone signal flowgraph



a) two product separation b) three product separation

Fig. 3 - Jig signal flowgraph

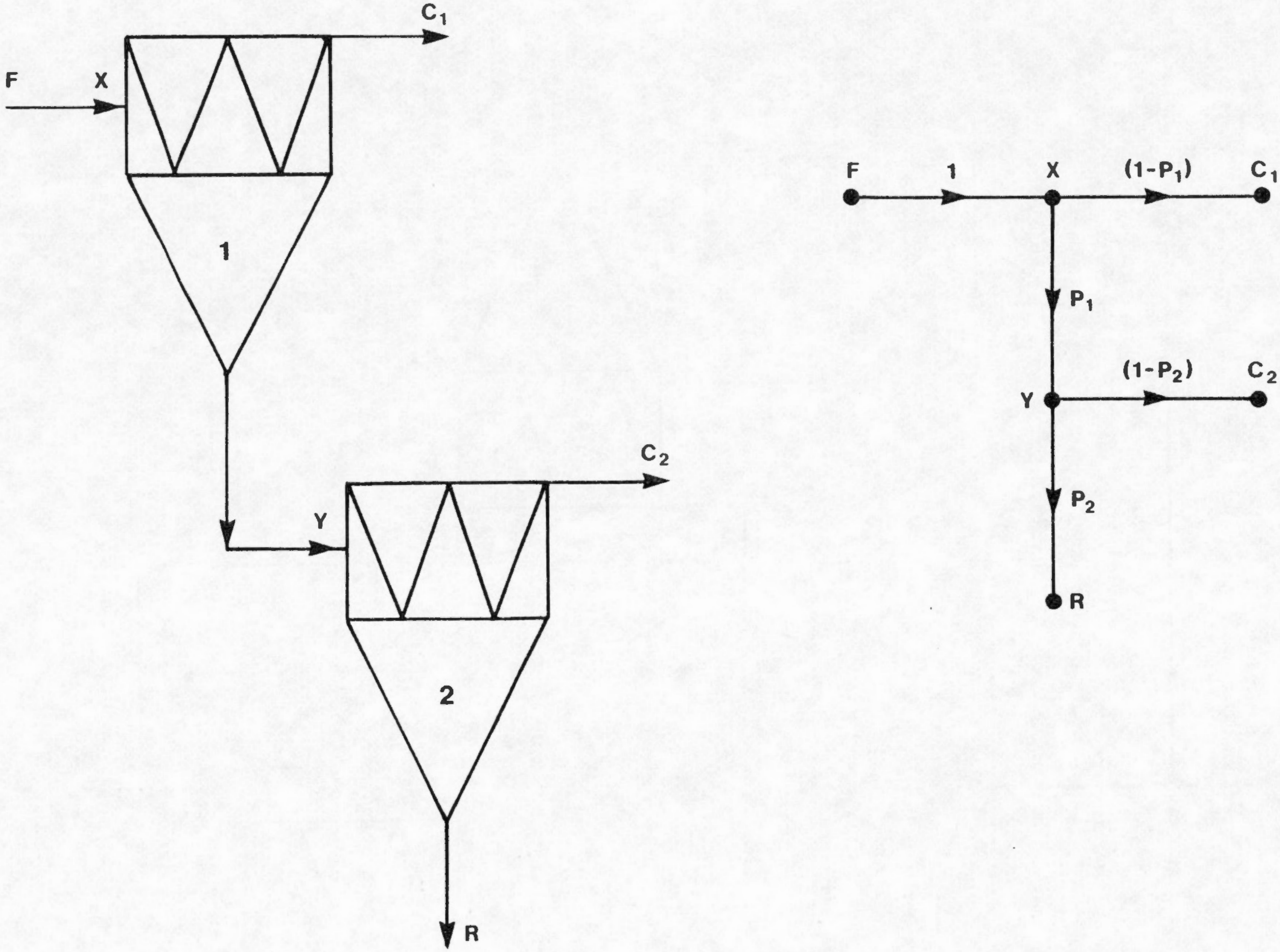


Fig. 4 - Two stage heavy medium cyclone signal flowgraph

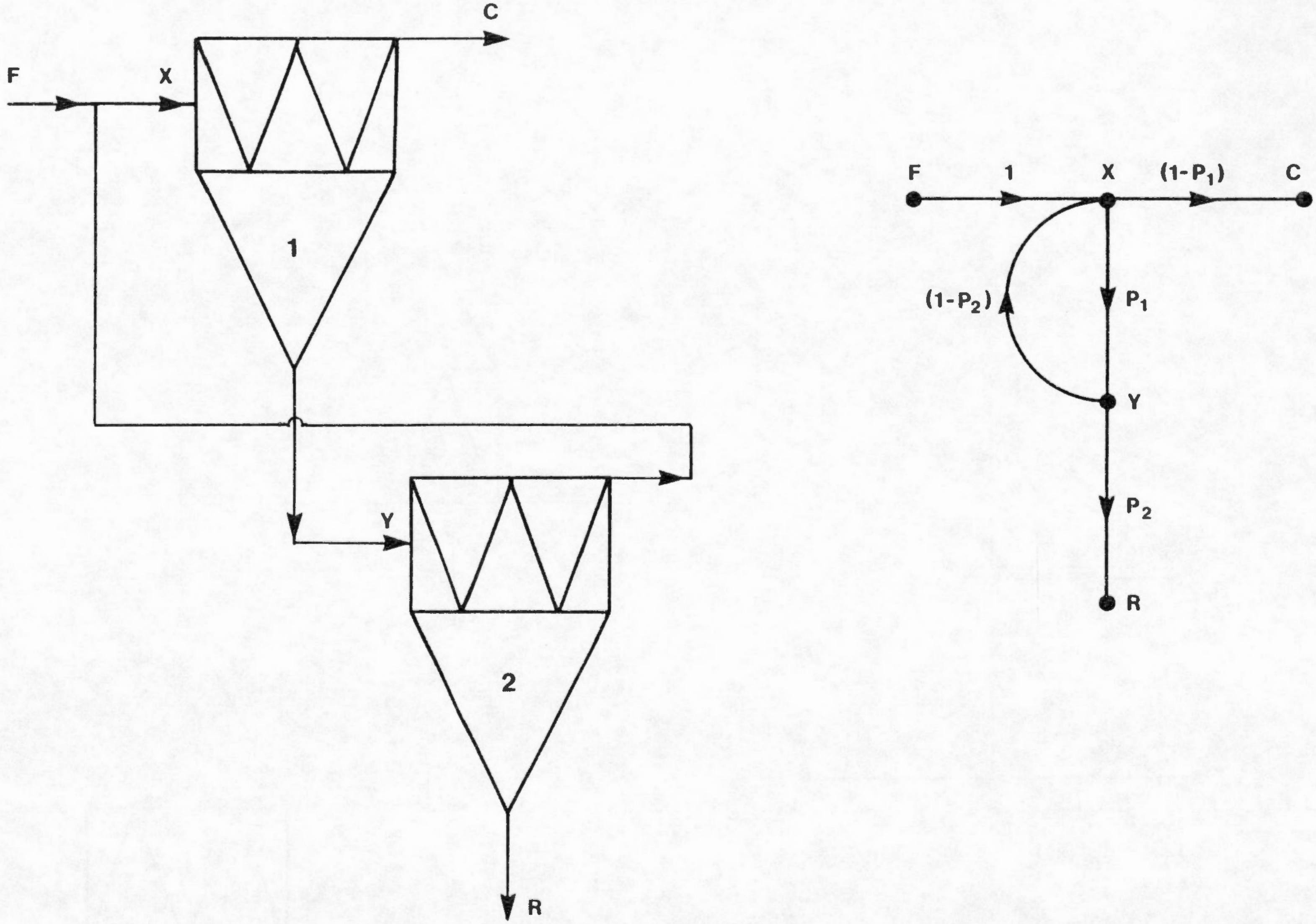


Fig. 5 - Two stage heavy medium cyclone with recirculated middlings signal flowgraph

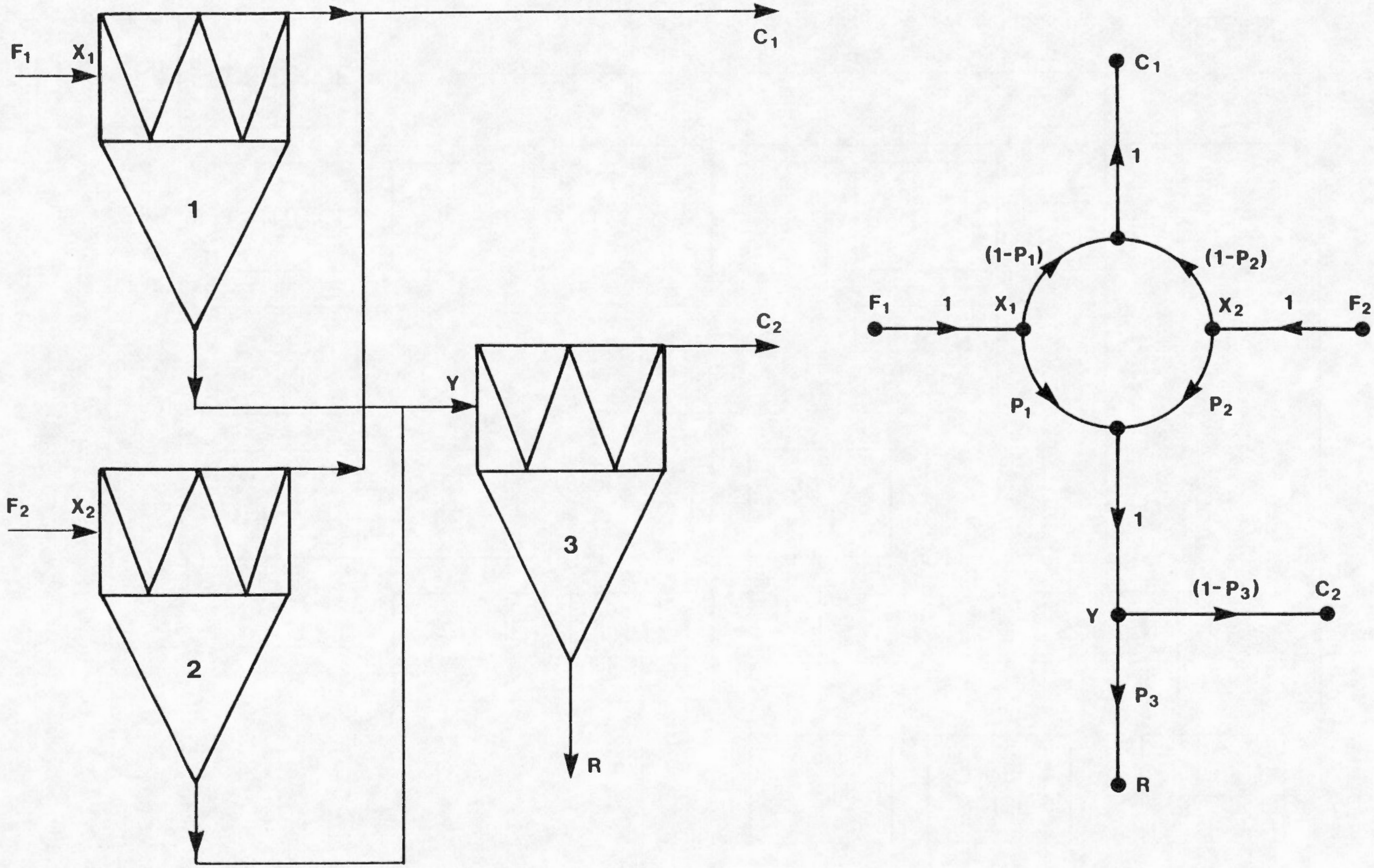


Fig. 6 - Devco coarse cleaning section signal flowgraph

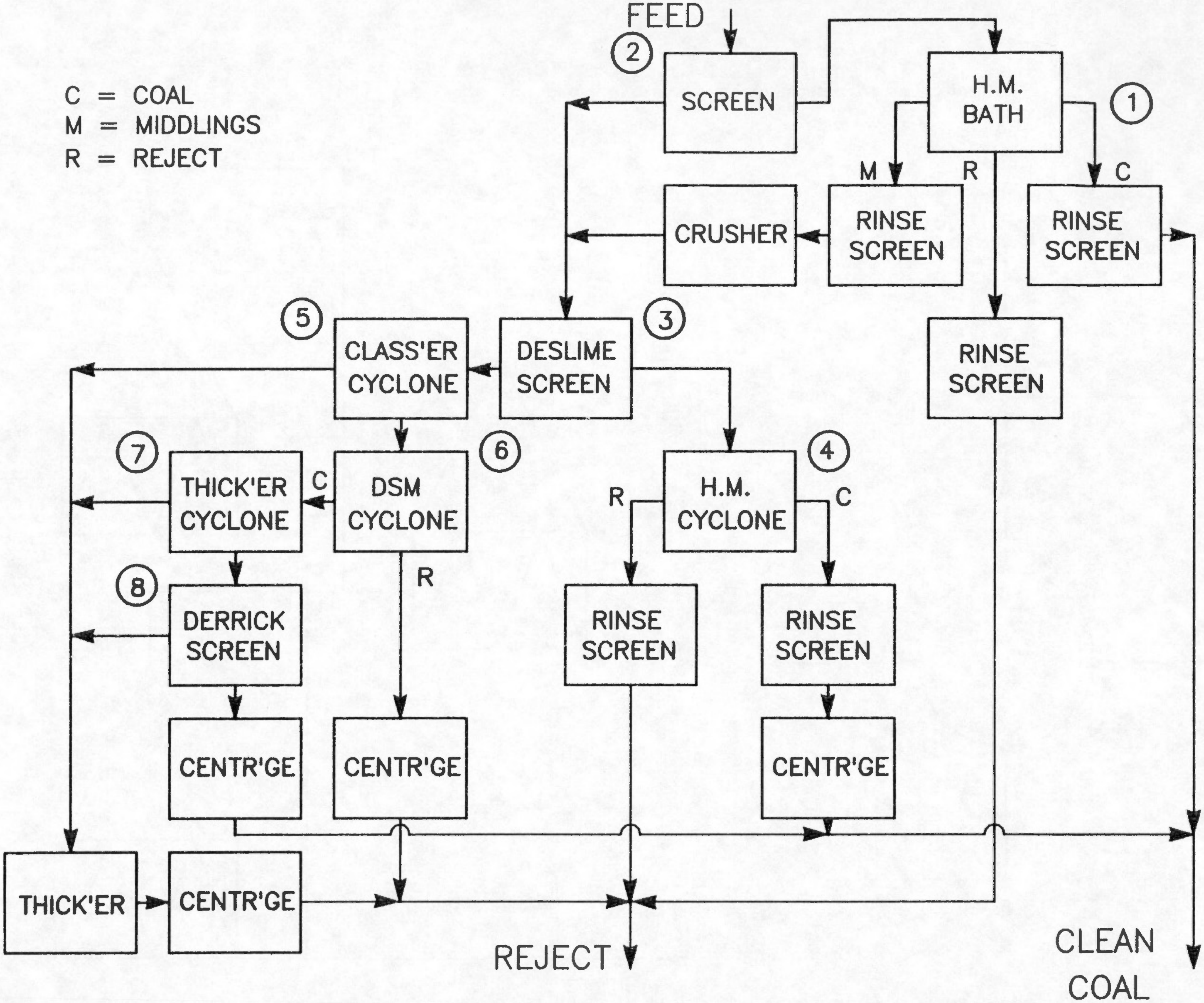


Fig. 7 - Luscar-Sterco plant flowsheet

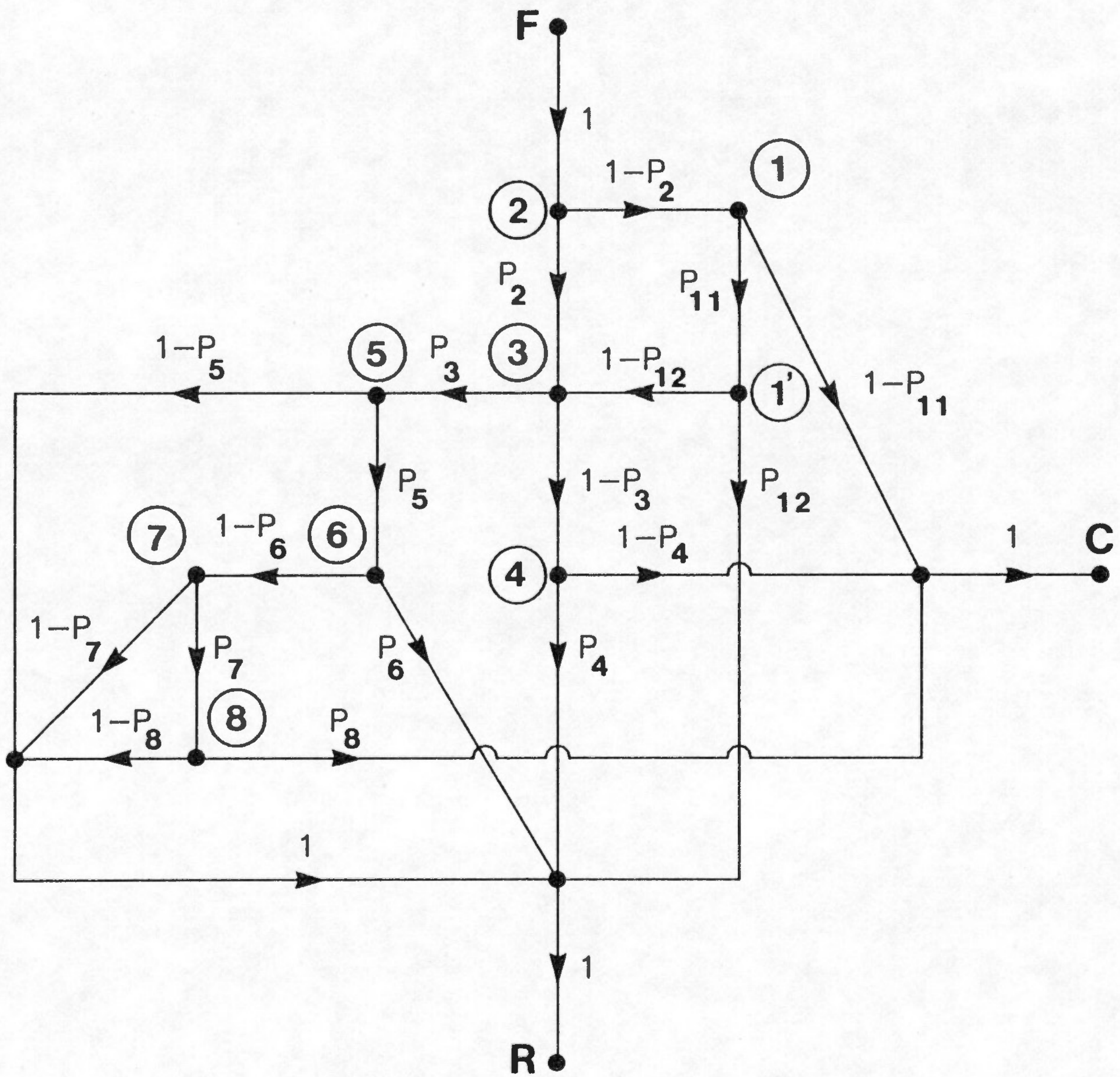


Fig. 8 - Signal flowgraph of Luscar-Sterco plant flowsheet

APPENDIX A

GAIN FORMULA - "MASON'S RULE"

SIGNAL FLOWGRAPH

The signal flowgraph is a pictorial representation of a process where interrelationships exist between its variables. The process variables are assigned some nodes and the interrelationships or gains between the variables are assigned to the branches joining these nodes. The process variable at a given node N is determined by the sum of products of all incoming process variables multiplied by their corresponding gains relative to N. The following definitions are essential before stating the gain formula known as the "Mason Rule":

FORWARD PATH

A forward path is a path from the input node I to the output node O, where no node is traversed more than once. If for example, in Fig. A-1, the input node I is node X_1 and the output node O is node X_8, then there are two forward paths: (X_1, X_2, X_3, X_6, X_8) and (X_1, X_2, X_3, X_5, X_6, X_8). It should be noted that (X_1, X_2, X_3, X_4, X_3, X_6, X_8) is not a forward path since node X_3 is traversed more than once.

FORWARD PATH GAIN G_i

The forward path gain G_i is the product of all branch gains along a forward path i. In Fig. A-1, the forward path (X_1, X_2, X_3, X_6, X_8) has a gain $G = g_1\ g_2\ g_6\ g_{11}$.

FEEDBACK LOOP

A feedback loop is a path from a certain node which ends up at the same node where no node is traversed more than once. Referring to Fig. A-1, there are three feedback loops (X_2, X_3, X_2), (X_3,X_4, X_3) and (X_6, X_7, X_6). It should be noted that (X_3, X_5, X_6, X_3) is not a feedback loop.

FEEDBACK LOOP GAIN

The feedback loop gain is the product of all gains around a feedback loop. The feedback loops in Fig. A-1, have gains ($g_2\ g_3$), ($g_4\ g_5$) and ($g_9\ g_{10}$).

NON TOUCHING LOOPS

Feedback loops which do not have nodes in common are referred to as non-touching loops. Fig. A-2 illustrates the cases of two touching loops (a), three touching loops (b), two non-touching loops (c) and three non-touching loops (d). The signal flowgraph of Fig. A-1 has two touching loops (X_2, X_3, X_2) and (X_3, X_4, X_3) and two sets of two non-touching loops: (X_3, X_4, X_3), (X_6, X_7, X_6) and (X_2, X_3, X_2), (X_6, X_7, X_6).

SIGNAL FLOWGRAPH Δ

Signal flowgraph Δ is related to the structure of the signal flowgraph and is defined as:

Δ = 1 - Sum of feedback loops gains + sum of products of "two non-touching loops" gains - sum of all products of "three non-touching loops" gains + ...

The signal flowgraph shown in Fig. A-1, indicates that

$$\Delta = 1-(g_2g_3+g_4g_5+g_9g_{10})+(g_4g_5\cdot g_9g_{10}g_2g_3\cdot g_9g_{10})-0 \qquad \text{Eq A-1}$$

FORWARD PATH Δ_i

The forward path Δ_i has the same definition as the signal flowgraph Δ, except that all the feedback loops which have common nodes with the forward path i are excluded. Since all the feedback loops shown in Fig. A-1 have common nodes with the forward paths (dotted lines), then $\Delta_i = 1$.

GAIN FORMULA

The signal flowgraph gain formula known as the "Mason's Rule" (2) which expresses the relationship between an output node O (output process variable) and an input node I (input process variable) is given by:

$$(O/I) = \sum_i (G_i \Delta_i)/\Delta \qquad \text{Eq A-2}$$

where $\sum$ is the summation of all possible forward paths from the input node I to the output node O. For example, if we wish to determine the overall gain from node X_1 to node X_8 in Fig. A-1, we find only two forward paths from X_1 to X_8:

$(X_1, X_2, X_3, X_6, X_8)$ with $G_1 = g_1 \, g_1 \, g_6 \, g_{11}$

$(X_1, X_2, X_3, X_5, X_6, X_8)$ with $G_2 = g_1 \, g_2 \, g_/ \, g_8 \, g_{11}$

Since the feedback loops have common nodes with the forward paths, then

$\Delta_1 = 1 \qquad \Delta_2 = 1$

The signal flowgraph Δ is given by:

$$\Delta = 1-(g_2g_3+g_4g_5+g_9g_{10})+(g_2g_3g_9g_{10}+g_4g_5g_9g_{10})-0 \qquad \text{Eq A-3}$$

Then:

$$\frac{X_8}{X_1} = \sum_{i=1}^{2}(G_i\Delta_i)/\Delta = \frac{(g_1g_2g_6g_{11})+(g_1g_2g_/g_8g_{11})}{1-(g_2g_3+g_4g_5+g_9g_{10})+(g_2g_3g_9g_{10}+g_4g_5g_9g_{10})} \qquad \text{Eq A-4}$$

This completes the development for the signal flowgraph given in Fig. A-1.

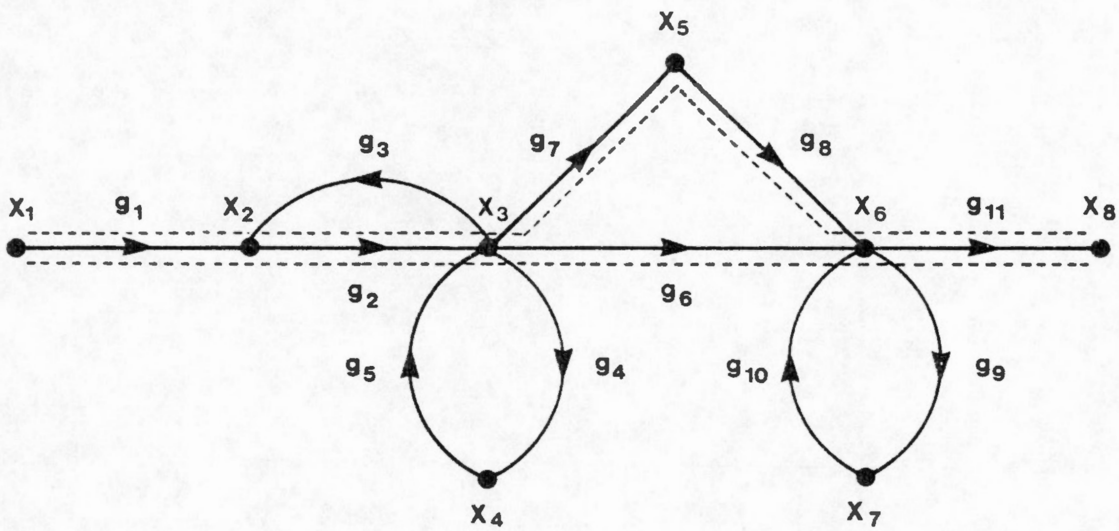
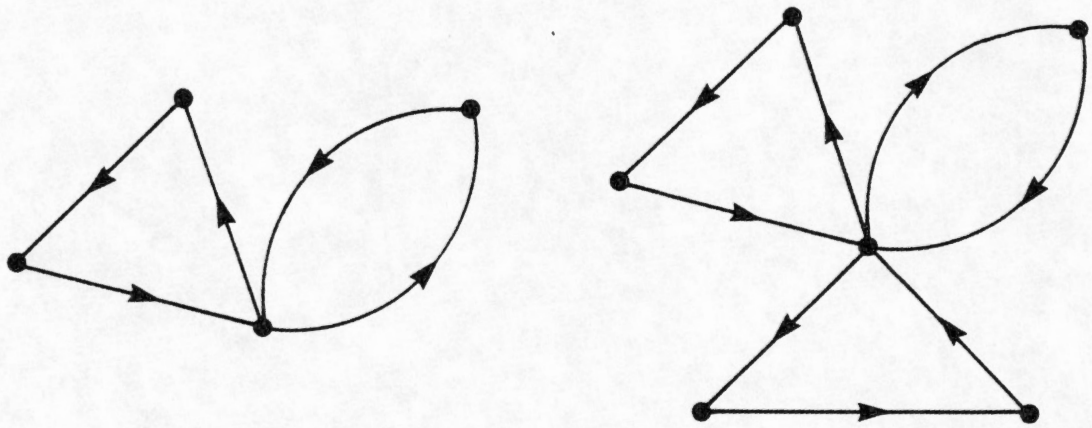
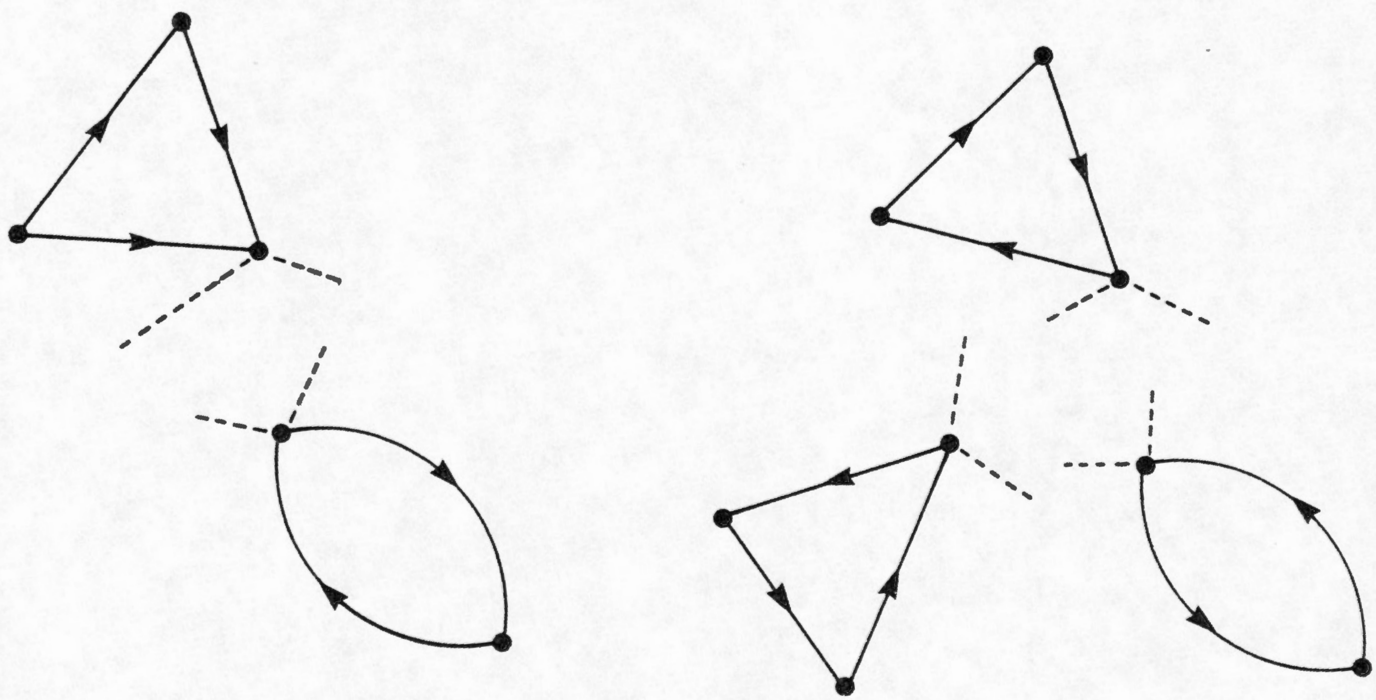


Fig. A-1 - A signal flowgraph



(b)

(a) touching loops



(d)

(c) non-touching loops

Fig. A-2 - Touching and non-touching loops