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COAL WASHERY DESIGN - I
THE E. M. R. PROCESS

J. VISMAN

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COAL WASHERY DESIGN - I
THE E. M. R. PROCESS

by

J. Visman*

ABSTRACT

The process described here is designed for the beneficiation of coal, especially highly friable coals of the type found in western Canada. The main components of the E. M. R. process comprise the following four unit operations: selective feed preparation; scalping in bulk using water as a medium; oil-assisted drying of coal slimes; and water recovery. The system operates with a closed water circuit and avoids thermal drying, thus preventing pollution of the air and of water at the source. It provides for the optional treatment of middlings by special methods, e.g. the liberation of intergrown coal by grinding and separation by heavy-medium methods, tabling, etc. A wide variety of separators can be used, and this provides the flexibility of choice needed for producing optimum results at a maximum profit per ton of pithead coal (run-of-mine). A closed water system is maintained for all combinations.

A general method for determining steady-state conditions is introduced. This procedure is essential for the advance calculation of slimes recirculation and its control, especially if the process must turn out metallurgical grades from highly variable raw coal.

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Direction des mines

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par

J. Visman [1]

RESUME

Le procédé décrit ci-après est destiné à améliorer la qualité du charbon, en particulier des charbons très friables comme ceux que l'on extrait dans l'ouest du Canada. Les principales étapes du procédé de l'E.M.R. sont les quatre opérations suivantes: préparation selective de l'alimentation; élimination des impuretés en gros, à l'aide de l'eau; séchage des boues de charbon à l'aide d'huile; et récupération de l'eau. Le système fonctionne en circuit d'eau fermé et permet d'éviter le séchage thermique, donc d'éviter de polluer l'air et l'eau à la source. Cette méthode permet également de traiter, si on le désire, les mixtes à l'aide de procédés spéciaux, par exemple en récupérant le charbon par broyage et par séparation suivant le procédé de différenciation des poids, ou par sélection mécanique sur table, etc. On peut utiliser des types de séparateurs très divers, ce qui laisse toute la latitude de choix nécessaire pour obtenir les meilleurs résultats possibles avec un rendement maximum par tonne de charbon extrait directement (charbon tout-venant). On utilise un système de circulation d'eau en circuit fermé pour toutes les méthodes employées.

On a introduit une méthode générale permettant de déterminer les conditions de stabilité. Cette méthode est indispensable pour calculer à l'avance la remise en circulation des boues et le contrôle de cette opération, tout particulièrement si l'on doit produire à l'aide de cette méthode des charbons métallurgiques à partir de charbons bruts de qualité très variable.

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INTRODUCTION

The problems of coal beneficiation are many but, if one had to describe 'washery trouble' with friable coals by a single expression, the word would be degradation. The amount of minus 28-mesh fines that is accumulated during transport from the pit, in storage bins, and during feed preparation is usually double the amount found in the pithead coal. In the wash plant, additional fines are formed during processing, fines that elude desliming screens and so contribute to the build-up of slimes in the wash-water circuit.

These slimes interfere with the recovery of heavy medium. The consumption of magnetite rises, not infrequently, from less than 2 lb/ton to over 8 lb/ton. Dewatering screens are soon overloaded by fines, the moisture contents of centrifuge products increase and coal freezes in the cars during the winter season. These problems are so well known that no more need be said of them.

The general solution of the fines problem is covered by three points:

1) Scalp the prepared feed by bulk cleaning, using water as a medium, and apply more precise methods only on the middlings, if needed.

2) Keep plant volume small to reduce the residence time of slimes, the degradation of particles, as well as the capital cost.

3) Remove slimes from the circuit and recover the water. Agglomeration of coal slimes with small amounts of oil has been actively studied as a means of controlling slimes build-up and of eliminating the need for thermal drying. This method, once promoted for other reasons (ash reduction), is again in favour because of its economic and technical advantages.

The above three points describe, in essence, the E. M. R. process. Control of recirculating loads and - for design purposes - the predictability of the steady state at each point in the circuit are the key to its practical solution in each plant. Contrary to doubts expressed by some, the process permits the use of a considerable variety of equipment types. Bulk cleaning with water as a medium can be done in jigs, on tables, with water cyclones, etc. For recleaning of middlings (deslimed), two entirely different principles can be followed: depending on the liberation size of the intergrown coal, the middlings can be ground and recirculated; if it is more profitable to do so, a sharp cut can be made on the uncrushed middlings, in a heavy-medium section of the plant that is "plugged in" to the main process as a back-up, by means of a cone separator, bath, or a cyclone.

Though the above principles are not new, it is evident that their re-embodiment in any processing plant presents a new set of conditions and requirements. Different properties of the coal and different quantities of products require a synthesis of the main function, at the maximum returns per ton run-of-mine (abbr. $/t.rom.). Conventional thinking in terms of any special equipment or method needs to be broadened by considering the interaction of all the equipment within the frame of these main functions:

F e e d p r e p a r a t i o n, including blending, storage, screening and crushing of the raw coal and the optional selective grinding of middlings;

C l e a n i n g, the beneficiation of the prepared feed, and the beneficiation and recovery of effluent solids;

D r y i n g, the dewatering and final moisture reduction of all products, including reject, to buyer specifications and to environmental requirements;

C l a r i f y i n g, the recovery of reconditioned wash water.

Effective integration of these unit operations includes control of the recirculation of water and solids. In this publication, a computer procedure is introduced whereby steady-state conditions can be calculated for groups of separators whose error curves are known. This includes density error curves and size error curves.

INTEGRATED PROCESS

The general objective is to separate friable coal by wet-mechanical means and to produce dry clean coal to specification, dewatered reject for stockpiling, and reconditioned plant water for recirculation, at a maximum return in $/t. rom.

The diagram on Fig. 1 shows the master plan of an integrated washery for friable coal without limiting the process to any specific method of beneficiation or type of equipment. The emphasis is on the recirculation of middlings and slimes because, for friable coals, the control of recirculating products is a point of major importance.

The problem of build-up may be circumvented by eliminating the fines from the feed (by dedusting, for example) or by sending the effluent solids to a pond. Neither of these examples applies when the minus 28-mesh fines constitute over 30 percent of the feed to the cleaning section. There has always existed a tendency in the coal industry 1) to preserve a large average particle size and 2) to operate on a "once-through" basis; but the maximum particle size is limited, particularly for metallurgical coals whose average ash content has to be reduced to the very minimum and where a s h d i s t r i b u t i o n has to be controlled (hard, high-ash particles are detrimental to coke quality because of their different shrinkage on cooling). The advantage of a "once-through" operation - though valid as a target - is lost if the amount of fines is large. It is also lost if the amount of middlings is large and no end-use for a middlings product exists.

Control of Recirculating Products

The quantitative appraisal of slimes and middlings recirculation will now be discussed in some more detail, as a means of estimating and controlling build-up in an integrated plant.

Referring to Fig. 2, what happens, in essence, when a product from separator B is fed back to another separator A (or set of separators) whence it returns in part to B, can be described mathematically as accumulating a converging series of increments of diminishing size approaching a limit that is known in process engineering as the steady state. When this state of equilibrium is reached, the build-up (recirculating load) can be expressed as $\lambda = F'/F$ -- 1)

where λ = recirculation coefficient,

F = new feed to plant or system (A+B), in tph of solids,

F' = feed to separator A, in tph solids.

Equation (1) provides the basic relationship for calculating the build-up of solids in a system of separators shown in elementary form on Fig. 2. In this example, the overproduct[1)]O of separator A is fed into separator B; underproduct U and overproduct OO leave the system, while underproduct OU recirculates to the feed of separator A.

Under steady-state conditions, the new feed (F) to the system equals U + OO and the recirculation coefficient can be found from

$\lambda = (F + OU)/F$ --2)

where OU represents the underproduct solids flowrate of separator B.

Equation 2 applies as well for the flowrates of homologous fractions of F and OU. Thus λ can, for instance be calculated for the 48 to 100-mesh fraction that forms part of the minus 1/4-inch feed to the system.

The relative amounts of this fraction in each product (O, U, OO and OU) are found from the size consist of the new feed F, and from the densimetric error curves[2)] for the 48 to 100-mesh fractions of separators A and B respectively. The work involved in calculating the fractional values and the overall value of λ from the error curves of a series of interlocked separators is time-consuming but manageable with an engineering desk computer. The details of this procedure are written up in a separate publication by J. L. Picard (1). The build-up in mixed systems of gravity separators and classifiers, including a maximum of five units, can be computed without complications. Larger numbers of units require a larger computer.

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1) Synonym for 'overflow' and 'overflow product'; used in coal preparation terminology to describe the entire product as well as its components, e.g. overproduct solids flowrate, overproduct pulprate, overproduct slimes flowrate.

2) Synonymous with partition curve, distribution curve.

The resultant overall value of λ for a separator system provides the information from which the throughput capacity of each unit can be determined.

Computer techniques for washery design provide the possibility of comparing two washery circuits and selecting the one with the lower recirculation ratio. It provides a means of checking the build-up for a range of feed compositions and of checking the possibility that a separator may get overloaded to the point where its separating efficiency will be affected. At E. M. R., the effect of separating efficiency of individual units has been studied in context with the overall result of the integrated process. The error curve of a separator (A) may be better than that of separator (B); yet, two separators (B) may produce a better overall error curve than separator (A) at the expense of a controlled degree of recirculation but at a lower overall cost per ton run-of-mine.

Research on all aspects of beneficiation, including dewatering with oil and centrifugal drying, was directed towards achieving the maximum return in $$ per ton rom., a parameter that does take into account the yield of clean coal and the cost at which it is attained. This method of 'counting the cost' provides the specific information for any individual separator in relation to other separators within a coal washery. Thus, the optimization of the above main functions (Fig. 1) can be achieved. General guidelines for washery design can then be checked for specific applications. For example, it is often advantageous to separate the majority of the clean coal by scalping the raw feed in bulk, using a low-cost method. A performance evaluation, illustrated by the graph shown on Fig. 3, provides the information for designing the cleaning section for a given set of conditions and requirements. It is noted, firstly, that the curves for actual yield and ash content become more steeply inclined as the cutpoint is reduced; and secondly, that these curves, in fact, turn back when the separating efficiency indicated by increasing values of the probable error (r) becomes too low.

It is commonly accepted that a sharper gravity is always more economical because of the resultant higher yield. Adverse experience in the field has shown that this rule should be checked carefully, especially where it concerns the beneficiation of highly friable coals.

SCALPING IN BULK, USING WATER ONLY

Scalping in bulk is the recovery of a substantial portion of clean coal by washing the raw feed "in bulk", that is, all sizes together. The reject and the slimes are recleaned in order to recover additional coal, if present.

Application of water-only methods for the scalping, in bulk, of friable coal offers the advantages of simplicity and low cost. A recent article by A.A. Terchick (3) on this subject is of interest. One of the oldest methods used for this purpose is jigging. Large jigs are often used to treat the entire size range, including coarse coal with a top size up to 5 in., the finer sizes being retreated to provide an acceptable product. Similarly, for smaller top sizes, up to 5/8 in. tabling in bulk is often practised. Water cyclones of the compound type are used for bulk cleaning raw coals with a top size of up to 2 1/2 in. The compound water cyclone thus handles a range of top sizes intermediate between those of the table and the jig.

Depending on the type of coal and the end use of the product, water-only methods may or may not be sufficient. In some instance, if a very low cutpoint is required, scalping may not be feasible, as is illustrated in the example on Fig. 3 for the curve representing a probable error $r \geq 0.20$. It is noted that, as the cutpoint decreases, the ash % of the coal tends to increase again for large r-values, owing to the high percentage of near-gravity[1)] material present in the low-density fractions of the feed. In many cases, however, a combination of scalping and retreatment of middlings and fines is preferable; and in some cases, water-only methods by themselves are sufficient to attain the desired end product.

Control of the recirculating products and effluent solids depends, as has been demonstrated above, on the error curves of all separators, including those of screens and centrifuges; and on the stability of these error

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1) Defined as the weight fraction of coal contained in the $d \pm 0.1$ density fraction, where d = density cutpoint.

curves under build-up conditions. The latter requirement is the one most commonly overlooked when plant sections are not properly integrated at the design stage. Consequently, a spate of troubles awaits the coal preparation superintendent during start-up and later on, if the capacity of the plant needs to be increased.

CONTROL OF RECIRCULATING SOLIDS

In-plant products that are returned to the feed, either directly or indirectly, contribute to the build-up that determines the minimum capacity of each separator under steady-state conditions.

The procedure for calculating the recirculation coefficient λ, mentioned earlier (eqn. 1, p. 4, can be found for any arrangement of separators, as illustrated by the decision flowchart on Fig. 4. With this chart, combinations of up to five separators for sorting and sizing can be handled, using an engineering desk computer. An example is presented on Fig. 5. Though this example illustrates a compound water cyclone circuit, it is clear that the procedure applies to any method or combination of methods for cleaning coal. The program can, of course, be amplified if more than five separators are involved. This requires a computer with a larger memory bank.

The essential information shown on Fig. 5 comprises, for each size fraction, the fractional partition numbers (R_i) of each separator (including gravity separation[1]), the yields[2] of the gravity separators, and the size consist of the prepared raw feed to the washery. The partition numbers represent the separator's size error curve under conditions within the normal range of operation. Once the overall value of λ is found, the capacity of each separator can be determined for the plant, as it will be operating in the steady state.

With friable coals, the slimes content can build up to intolerable levels when recirculation is not kept in check by special means. One method of containing the build-up is that of oil agglomeration, to be described in more detail in a separate section below (p. 14). Oil added to the circuit is absorbed by the hydrophobic coal particles, and small agglomerates are

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1) Every gravity separator operates to a certain extent as a classifier.

2) The yield figures account for the effect of the gravity separation on the recirculation and build-up of middlings, in each size fraction.

formed that can be effectively screened out on a 28-mesh dewatering screen. Recoveries of over 95% can be obtained for coals of which, for example, 40% would pass through the 28-mesh screen if no oil were used. The affinity of the oil is selective; it does not affect the clay and high-ash silt. Thus, the agglomeration of coal slimes has the additional advantage of effecting a significant ash reduction of the coal slimes reporting to the clean coal product. For oxidized coals and for the low-rank coals, oil agglomeration is less effective or not effective at all. The size error curves of dewatering screens depend, therefore, on the type of coal and amount of clay present when oil agglomeration is used, and the partition numbers are found from a test, if no prior information is available.

Control of the slimes and middlings removes most, if not all, of the objections that can be raised against the recirculation of solids as a beneficiation procedure. Where friability is in evidence, the recirculation of solids is a dominant factor which, to say the very least, can never be ignored. In many cases it overrides the differences between methods of beneficiation.

OPTIONAL TREATMENT OF MIDDLINGS

Once the recirculation as a whole is under control, middlings problems, if present, can be solved in a straightforward manner. Three options will be briefly discussed. The first possibility is to return the middlings to the feed. This method has the advantage of simplicity and the retreatment of the middlings adds to the overall separating efficiency of the plant. Calculation of λ will indicate the feasibility of this choice as far as the build-up of middlings in the steady state is concerned.

The second option is to screen out the middlings on a dewatering screen and to send them back after liberating the intergrown carbon by grinding. This is, in fact, a method of improving the cleaning characteristics of the plant feed by selective treatment of the pre-sorted middlings. It can be seen as a form of feed preparation which may reduce or eliminate the need for retreatment of the middlings by more sophisticated means. In this case the build-up is calculated on the basis of a feed whose middlings have been ground in advance.

The third option is to rewash the dewatered uncrushed middlings of a water-only washery circuit in a separate section of the plant by a more efficient method.

Because higher efficiency generally means higher cost, the question arises, what combination of methods will produce the highest returns per ton of mined coal for any given case. A cost-profit calculation (p.17) will indicate which method is to be preferred from the economic point of view.

THE E. M. R. PROCESS

The beneficiation of friable coals requires that the methods for cleaning, dewatering, etc. be matched with one another so that control of the recirculating solids is established and the plant produces the specified product at the maximum return per ton of mined coal.

The process developed by the Department of Energy, Mines and Resources provides the means whereby these two requirements can be met when fines are present in large quantity.

The essential features of the E. M. R. process are: A combination of a bulk cleaning method for the entire feed, using water only; controlled recirculation of solids; the dewatering of coal slimes with oil; the drying of all products by centrifugal force; and the recovery of plant water.

The principal equipment used consists of cyclones and screens, complemented if necessary with other equipment. The process flowsheet is shown on Fig. 6. The four main sections will be discussed in relation to the above requirements of fines control and process economics.

Pre-treatment of Feed Coal

Raw coal is treated in the manner shown on the flowsheet, Fig. 6. The following two features are noted: firstly, the raw coal can be crushed to a finer product with topsizes ranging from 2 1/2 to 1/4 inch, in preparation for the bulk cleaning step; secondly, middlings pre-sorted in the cleaning section can be returned to the pre-treatment section after dewatering and selective grinding. As a result, the washability characteristics of the feed can be improved by liberation of carbon from the intergrown coal and shale. This advantage is to be balanced against the increasing difficulty of cleaning particles of diminishing size, but taking into account the beneficial effects of oil agglomeration as well.

The Cleaning Section

The prepared feed is cleaned with water as a medium, using compound water cyclones in single- or two-stage operation. The C. W. cyclone which is made in sizes ranging from 2-in. to 24-in. in dia. (95-142 stph raw coal capacity)[1] has been described in more detail elsewhere (4). It is a special type of water cyclone that operates on the hindered settling principle, not unlike the jig. In the presence of slimes an artificial medium is developed and maintained under steady-state conditions, thus creating a system that - like the jig - has characteristics of a true heavy-medium process, as pointed out by H. L. L o v e l l (2). Commercial C. W. cyclones are known to carry 1 1/2 times their nominal capacity in recirculating slimes in addition to their normal new feed. Operational data of six C. W. cyclone models are presented on Table 1.

The flowsheet of a two-stage C. W. cyclone circuit is shown on Fig. 7. The main characteristics of this circuit are, a) four products, including the effluent, are produced with a single pump and sump; b) the pulp divider, a cyclonic device producing injection water under pressure; it is an optional feature, saving a pump and a sump; c) automatic control of pressures within the circuit, which also provides instantaneous cutpoint control to compensate for the small but often persistent variations in feed composition; d) remote adjustment of the vortex finder position for re-setting the C. W. cyclone cutpoint when a different coal is to be washed; e) a dual mix-tank of compact construction with controlled internal circulation that prevents p l u g g i n g. This tank holds the water and solids of the entire circuit when the pump is not operating. The use of a single pump and sump eliminates the problem of "matching" the flow rates that is common with pumps operating in series. In this two-stage circuit the impeller of the pump is the only moving part.

An exploded view of the C.W. cyclone is presented on Fig. 8. In view of other published information, only a brief recapitulation will be given here of its main features. The compound cone section, which is the essential part of the separator, is available in three different models (types L, M, and S), the choice depending on the type of feed material and the cutpoint required. The vortex finder is available in two diameters and is adjustable in height. The vertical distance between the lower orifice edge of the vortex

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1) A 36-in. C.W.C. (260-390 stph raw coal cap.) has recently been added to the series available to industry.

finder and the triconical bottom, called "vortex finder clearance", is the major controlling factor with respect to the cutpoint. For compound water cyclones the efficiency of separation is substantially independent of the cutpoint over the entire range of 1 to 2.5 specific gravity (4).

The probable errors for five models are shown as a function of particle size and particle specific gravity on Fig. 9. The probable error values refer to single-stage operation and apply generally for C. W. cyclones operating within the ranges shown on Table 1. Lower efficiencies may be found when flat particles occur in significant amounts, as happens when the coal has been deformed ("slickensided") by mountain movements and breaks into fragments of lenticular shape when mined. These flaky particles also tend to be extra friable. Further details on the CWC error curve are given in the appendix.

If it is required to reclean the slimes fraction - e. g. with finely divided pyrite and high-ash silt being present - wet gravity separation by means of tables, froth flotation, or small-bore water cyclones, is added as a back-up. On the process flowsheet, this slimes beneficiation circuit is shown to receive its feed from the middlings dewatering screen and from the classifier overflow. The circuit shown schematically on Fig. 6 consists of a multiple 2-in. C. W. cyclone unit followed by a multiple 2-in. classifier cyclone unit for dewatering the coal product; the effluent returns to the circuit. This arrangement is essentially the same as that shown for the bulk product shown on Fig. 7, except that the CWC — I underflow is not retreated, but discarded.

The Drying and Clarifying Sections

This is the part of the washery where control of the slimes[1] recirculation is established. In the drying section, where the dewatering screens and centrifuges are located, the "coarse" fractions of the products are permanently removed from the circuit. A considerable amount of undersize

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1) Slimes are defined here as substantially minus 28-mesh material.

particles may be removed with the coarse fractions, preferably as much as the moisture content of the load-out products permits. By thus permitting part of the fines[2] to discharge with the coarser coal, a considerable proportion of it is permanently removed from the system at this stage. The quantities involved are found from tests or from prior knowledge; and this information, expressed in the form of size error curves, can then be used for steady-state calculations as discussed above (p. 9 and Fig. 5).

The fines passing through the clean-coal dewatering screens generally constitute the bulk of that size fraction in the new feed to the plant (and which includes clay and silt as well). This slimes fraction is conditioned with a small amount of light oil which causes the coal to agglomerate into aggregates, most of which will remain on a 28-mesh screen and discharge with the overproduct. This process, for which patents are pending, is incorporated in the Clarifying Section shown on Fig. 6.

The conditioned coal slimes are removed from the effluent on a 28-mesh screen and the effluent is subsequently aerated to float off the remnant of oil-conditioned coal from the high-ash silt. This coal fraction is either sent back to the same screen (as shown on Fig. 6) or discharged directly into the high-speed centrifuge.

The clay and silt remaining in the effluent are densified and dried in a three-step procedure shown on Fig. 6, by -

a) slugging cyclones, followed by a screen for dewatering the bulk of the slimes and discharging; this is really a scalping operation for the removal of fine reject material; it is an optional, low-cost separator;

b) a clarifier; this can take the form of a static thickener, an inclined settler, a pond or any method whereby reconditioned wash water is returned to the plant; solids contents of this water may range between 0 and 500 ppm;

c) a high-speed centrifuge for final dewatering of the clay.

Several recirculation sub-circuits are involved in the drying and clarifying sections that contribute to the overall steady-state flow pattern. Two examples are discussed in part II of this publication, to which the reader is referred for further information (1).

2) Fines are broadly defined as the material typical of any dewatering screen underproduct.

Table 1. Capacities and Flowrates of Compound Water Cyclones and Classifier Cyclones

		Top Size of feed		Dry Feed* tph			Average Flowrate of Water*			Inlet Pressure (minimum)			Maximum % Solids		Average Sp Gr	
		m.m	mesh/inch	metric**	long** (gross)	short** (net)	m3/hr**	USGPM**	IGPM**	kg/cm2 (atmos)	psi	ft. head	wt.%	vol.%	solids	pulp
Mult.2"	Coal			3-6***	3-6***	3-7***	31-62***	174-348***	145-290***	0.4-1.7	6-25	14-58	7	5	1.5	1.03
CWC-2M	Sand	1.5	10 m.	6-12	6-12	7-14	36-72	200-400	167-334	0.5-1.7	8-25	18-58	12	5	2.5	1.08
ClC-2M	Ore			8-16	8-16	9-18	36-71	200-400	167-334	0.5-1.7	8-25	18-58	16	5	3.5	1.13
4"	Coal			0.5	0.5	0.5	6	37	23	0.2	3	8	7	5	1.5	1.03
CWC-4	Sand	5	3/16	0.8	0.8	0.9	6	27	23	0.3	4	8	12	5	2.5	1.08
ClC-4	Ore			1.1	1.1	1.3	6	27	23	0.3	4	9	16	5	3.5	1.13
8"	Coal			3-6	3-5	3-6	35	154	128	0.5	7	16	7-14	5-10	1.5	1.03-1.05
CWC-8	Sand	10	3/8	9	9	10	33	146	122	0.6	8	18	22	10	2.5	1.15
ClC-8	Ore			13	13	14	33	146	122	0.6	9	20	18	10	3.5	1.25
12"	Coal			15	15	17	92	403	335	0.8	11	25	14	10	1.5	1.05
CWC-12	Sand	19	3/4	25	25	28	92	403	336	0.8	12	27	22	10	2.5	1.15
ClC-12	Ore			36	35	39	92	403	335	0.9	13	29	28	10	3.5	1.25
24"	Coal			86-129	85-127	95-142	518-489	2279-2153	1898-1792	1.5	21-22	50-51	14-21	10-15	1.5	1.05-1.08
CWC-24	Sand	38	1 1/2	143-216	141-212	158-238	518-489	2280-2153	1898-1792	1.6	24-25	54-58	22-31	10-15	2.5	1.15-1.23
ClC-24	Ore			201-301	198-296	222-232	518-489	2279-2154	1898-1793	1.8-2.0	26-28	59-65	28-38	10-15	3.5	1.25-1.38
36"	Coal			238-356	234-350	262-392	1426-1348	6282-5932	5229-4940	2.3	32-33	74-76	14-21	10-15	1.5	1.05-1.08
CWC-36	Sand	62	2 1/2	395-594	389-585	436-655	1427-1347	6282-5932	5231-4939	2.5-2.6	35-38	81-87	22-31	10-15	2.5	1.15-1.23
ClC-36	Ore			555-830	546-817	611-914	1427-1348	6281-5935	5230-4942	2.7-3.0	38-42	88-97	28-38	10-15	3.5	1.25-1.38

* When using narrow vortex finder reduce solids flowrates and water flowrates by one third.
** Figures apply to CWC and ClC with wide vortex finder.
*** Feed inlet pressure 25 psi.

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PROCESS ECONOMICS

The direct economic benefit of a coal mining operation can be expressed as a function of the total cost per ton run-of-mine ($/ton rom.), the proceeds per ton rom., and the yield of marketable products that are of a quality stipulated by contract and assessed by mutually acceptable methods of analysis and testing.

When the difference between the proceeds per ton rom. and the cost per ton rom. is defined as 'profit' (short for 'gross returns'), the cost-profit relationship can be protrayed for varying yields as shown on Fig. 10.

The J-shaped curve AA typifies the cost[1)] of a metallurgical-grade coal worth $10.00 per ton f.o.b. cars. This cost is constant below the actual yield (85%) but rises steeply to a very high value as the theoretical yield (90%) for this grade of coal is approached by means of more efficient cleaning methods. The proceeds[2)] is a straight line B that intersects the cost curve twice. In area (1) the distance between curves AA and B indicates the profit per ton rom. as indicated by P_1 when only a two-product separation is made. A higher profit P_2 is obtained if a better, more expensive cleaning process is employed.

If the reject is recleaned to produce 10% middlings for steam raising worth $6/ton, the cost curve moves over, on the right-hand side, to AA' and, within area (2), it indicates that the profit per ton rom. P_3 has risen above the profit P_2 gained by two-product separation. The cost of this three-product beneficiation rises sharply as the actual yield of coal and middlings approaches the theoretical yield of 95%.

Additional profit can conceivably be extracted from the reject, e.g. by recovery of pyrite (at a concentrate grade of say, 28-34% S) as shown schematically by curve AA". The overall profit per ton rom. as shown by P_4

---

1) Cost of mining and cleaning raw coal, in $/ton rom. = total cost of mining and preparation, in $, divided by the tonnage of rom. processed (during a specified period).

2) Proceeds, in $/t rom. = total proceeds in $, divided by the tonnage of rom. processed (during a specified period).

in area (3) on the graph exceeds the profit of the three-product separation. This graph shows that the choice of a coal cleaning device or process is to be judged by its efficiency, in context with its profit per ton rom.

Profit Evaluation for Plant Design

The basis for profit evaluations is the series of equations shown on Table 2, with individual items being identified on Table 3; the former also shows the computation of cost, proceeds, and profit estimates. Alternative situations can be studied by repeating the computation with modified values for items a, b, c, ---- u.

Examples 1, 2.

The profit-evaluation procedure is exemplified on Table 3 by two sets of data, for a 100-tph and a 1000-tph CWC plant, respectively. The figures apply to the combined Main Beneficiation, Drying, and Clarifying sections. In both designs, a three-product separation (coal, middlings, reject) is attained. Coal slimes are dewatered with oil to a resultant overall, free-water content of 6% in the load-out coal. The pre-treatment section of the process is not included in the figures shown on Table 3; and the cost of mining the coal is assumed to be the same for the small plant as for the big plant.

Table 2 - Equations for Calculating Cost, Proceeds and Profit

Cost of processing in $/ton r.o.m.	
	$A = B + C + D + E + F + G$ *
Labour	$B = 100\ em/a(100-f)$
Materials	$C = 100\ n/abcd\ (100-f) + o$
Power	$D = 100\ gs/a\ (100-f)$
Depreciation	$E = 100\ (k/i + l/j)/abcd(100-f)$
Interest	$F = (k + l)\ p/abcd\ (100-f)$
Supervision & Administration	$G = 100\ q\ (1 + {}^{r}/100)/abcd\ (100-f)$
Proceeds	$u = (u_1h_1 + u_2h_2 + u_3h_3)/100$
Profit	$P = u - (A + t)$

* Symbols on Table 3.

Table 3 - Cost Analysis of E.M.R. Process

Item	Description	Unit	Symbol	Plant 1 100 tph	Plant 2 1.000 tph
Plant feed	Raw coal to cleaning plant	tph	a	100	950
Hr/shift	Operating hrs. (incl. down time)	hr/shift	b	7 1/2	7 1/2
Shifts/day	Oper'g shifts (incl. repair sh.)	sh/day	c	2	2
days/yr	Operating days only	days/yr	d	250	250
Av. no. men on shift	Men/shift (incl. operators, oilers, repair men etc.)	men/sh.	e	3	4
Down time	Stoppages due to breakdown etc.	%	f	6	6
Power	Installed capacity or equivalent	cap.	g	700	4600
Yield	of 2- and 3-product separation	%	h	85 and 5	85 and 5
Life	Expected lifetime of machinery	yr	i	5	5
"	Ditto, of other equip & bldgs	yr	j	10	10
Cost of	Mechanical & electrical installations	$	k	429,000	4,704,821
" "	Buildings, incl. site preparation, utilities hook-up	$	l	160,000	1,309,000
" "	Labor (wages & social chgs.)	$/man hr	m	7	7
" "	Materials (repairs, maintenance, ≃ k + 1/30)	$/yr	n	20,000	200,000
" "	Flotation reagents, oil, etc.	$/t.rom.	o	0.16	0.12
" "	Capital int rate (flat equiv)	%	p	10	10
" "	Supervision	$/yr	q	15,000	15,000
" "	Admin. (as % of supervision)	%	r	5	5
" "	Power	$/kwh	s	0.01	0.01
" "	Raw coal at pithead or washery[1)]	$/t rom.	t	6.50	6.50
Proceeds	Clean coal, fob cars & middlings	($/ton of (products sold	u	10 & 6	10 & 6
Labor	-incl. all social charges	$/t rom.	B	0.22	0.03
Materials	-incl. maintenance & supplies	"	C	0.22	0.18
Power	Electrical or other, expressed as kwh	"	D	0.07	0.05
Depreciation	Mach., bldgs & other equip	"	E	0.29	0.32
Interest		"	F	0.17	0.18
Supv.& adm	Salaries of mgr. etc.; cost of admin = r% of supervision	"	G	0.03	0.00
	Total cost of cleaning[2)]		A	1.00	0.76
Profit	2-product separation	$/t rom.	P_2	1.00	1.23
	3-product separation[3)]	"	P_3	1.30	1.53
	4-product separation	"	P_4	-	-

Remarks: 1) The cost of raw coal at the washery (t) includes feed preparation (crushing, storage, and conveying), expressed in $/t. rom. (run-of-mine).

2) The total cost of cleaning (A) includes the cost of producing clean coal, middlings, and reject; dewatering of clean coal to 6% moisture (free water-only content), middlings to 19% moisture and reject to 22% moisture; and the cost of water recovery for recirculation.

3) The profit of the 3-product separation represents the combined profits of clean coal and middlings.

Table 3 illustrates (see itemized costs B to G) that the combined costs of depreciation and interest constitutes the largest portion - 46% and 65% of the total cost - for Plant 1 and Plant 2, respectively. It is noted that these figures increase when the Pretreatment Section referred to on Fig. 6 is included in the overall plant cost.

CONCLUSIONS AND RECOMMENDATIONS

The examples presented in the previous section are typical of an integrated coal washing plant, for a wide range of capacities between 100 tph and 1000 tph. The conclusions that can be drawn from the foregoing discussion apply generally to coals that are difficult to clean, especially highly friable coals.

1) The processing of friable coals requires s l i m e s c o n t r o l based on a detailed knowledge of the sizing effect of all separators involved.

2) Capital cost is the main cost item affecting the profit/ton rom.[1)] of a coal processing plant. The investment in $/tph installed capacity for the processing of friable coals can be kept at a level comparable to that required for "easy" coals by an appropriate c o m b i n a t i o n of conventional methods; for example, a low-cost bulk cleaning method, augmented by a special method for the retreatment of middlings, can be employed.

3) The scalping in bulk, using water-only methods, s i m p l i f i e s the control of slimes recirculation and tends to reduce the cost of operation. Scalping can be combined with other methods where required, e.g., the selective grinding and retreatment of middlings, or alternatively, H. M. separation of middlings. Tabling can be used to advantage for pyrite removal; other methods can be added on as required.

4) The well-known advantage of H. M. methods - that of high separating efficiency - is off-set by several limitations that stem from the following p a r a d o x : in H. M. circuits, especially those where cyclones are used for cleaning small particles, ash reduction is achieved by first adding to the raw coal expensive "ash" in the form of say, magnetite; and subsequently removing it again at considerable cost. Effective application of heavy media at both low and high densities (below 1.50 and over 1.80 sp. gr.) becomes a delicate operation when slimes are abundant and the coal is f l a k y and f r i a b l e . Difficulties experienced in the field

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[1)] rom. (run-of-mine) = pithead coal, or coal as mined.

confirm the fallaciousness of the contention that a higher separating efficiency is by itself a cure-all for the beneficiation of any coal.

5) The over-abundance of clay and the presence of oxidized coal common to the flaky, distorted coal seams of Western Canada tend to reduce the effectiveness of froth flotation. Water-only methods such as jigging, tabling, and cycloning and other densimetric bulk-cleaning procedures can be used to advantage for the simultaneous ash reduction of coarse and fine coal. Tables and cyclones are capable of removing ultra-fine pyrites from coal slimes with great efficiency because of the large differential in apparent density between pyrite and shale.

6) A design method is introduced for implementing the main functions of a coal processing plant, i.e., pretreatment, cleaning, drying, and clarifying. The general application of this method in coal washery design is recommended, in particular for the processing of highly friable coals.

7) A flexible process is introduced which permits the combination of a wide variety of separators to suit the conditions and requirements for a given mine. The E. M. R. process is recommended for coals that exhibit a high and variable ash content, a variable ash distribution, and a tendency for degradation.

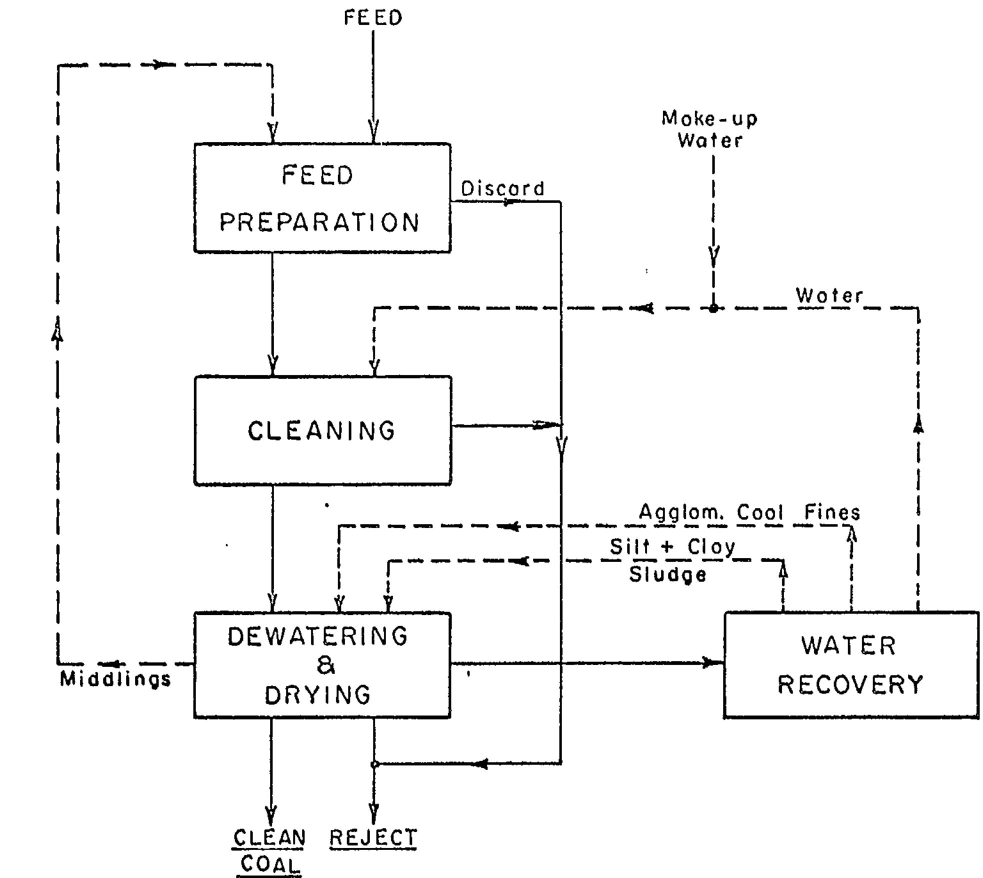


Fig. I - Ground Plan of Integrated Wash Plant

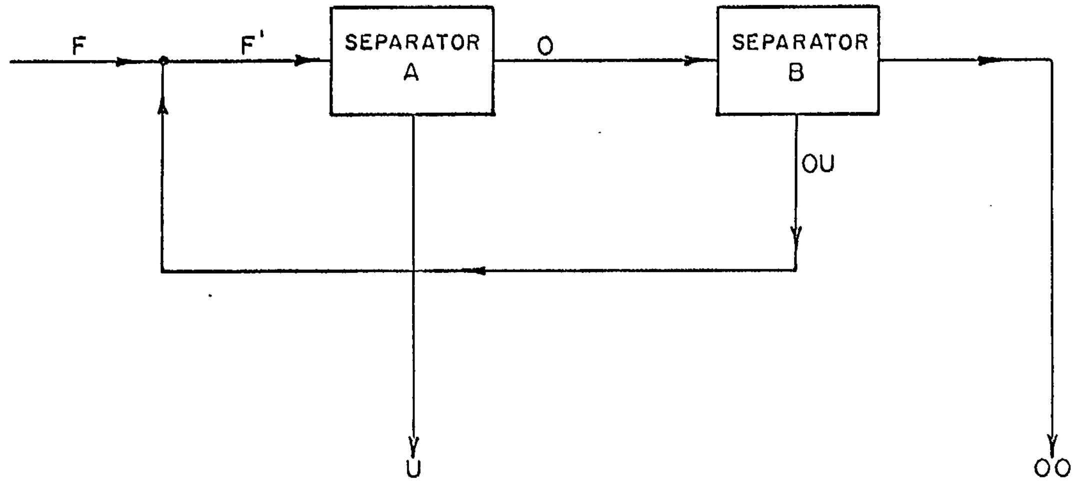


Fig. 2 - Recirculation Model

Fig. 3 - Performance Evaluation Curves for 1/4" - 200 m. Coal

r = probable error
d_p = gravity cut point

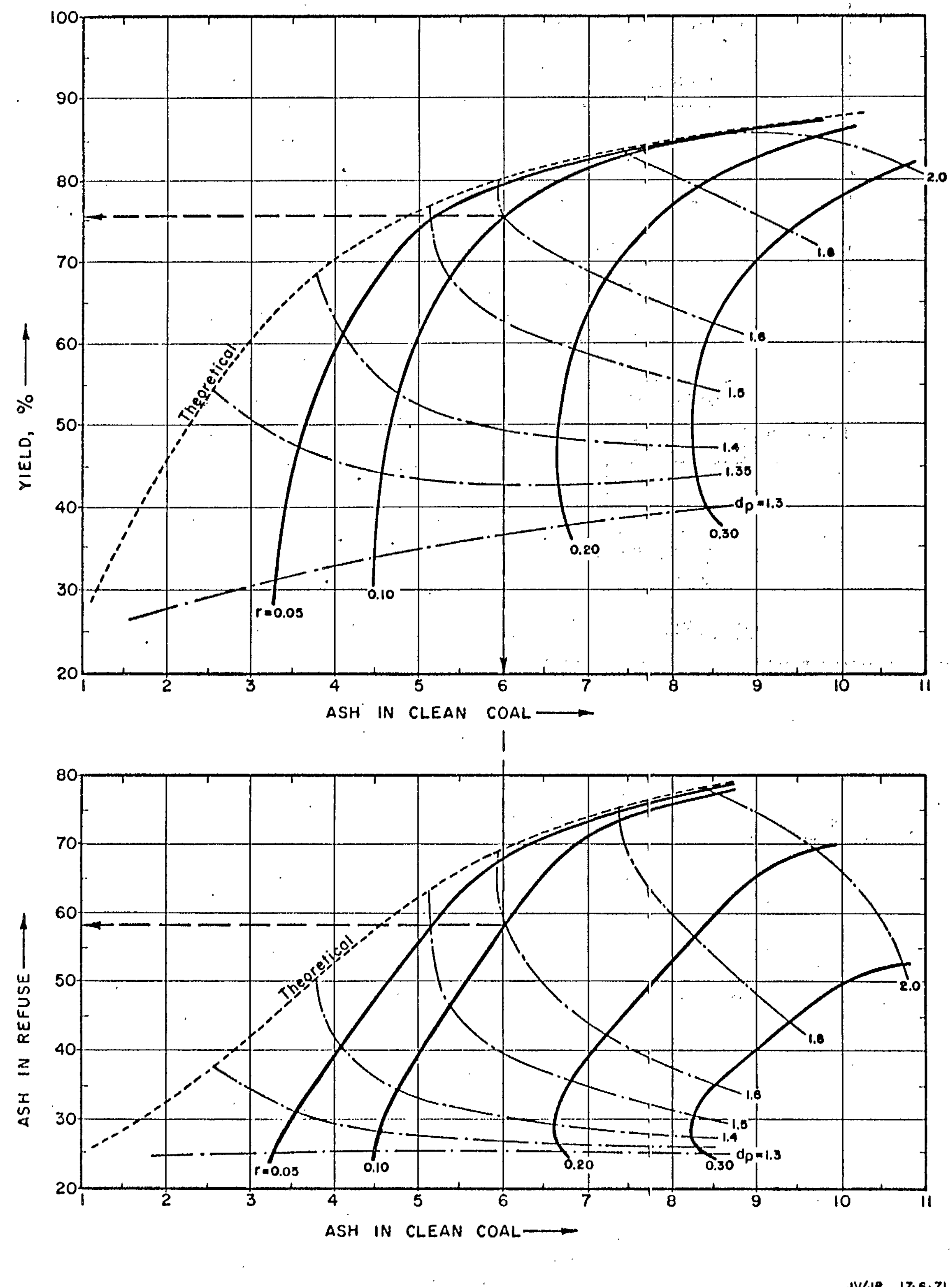


Fig. 4 - Decision Flowchart for Calculation of Recirculation Factor, λ and Overall Partition Number, R.

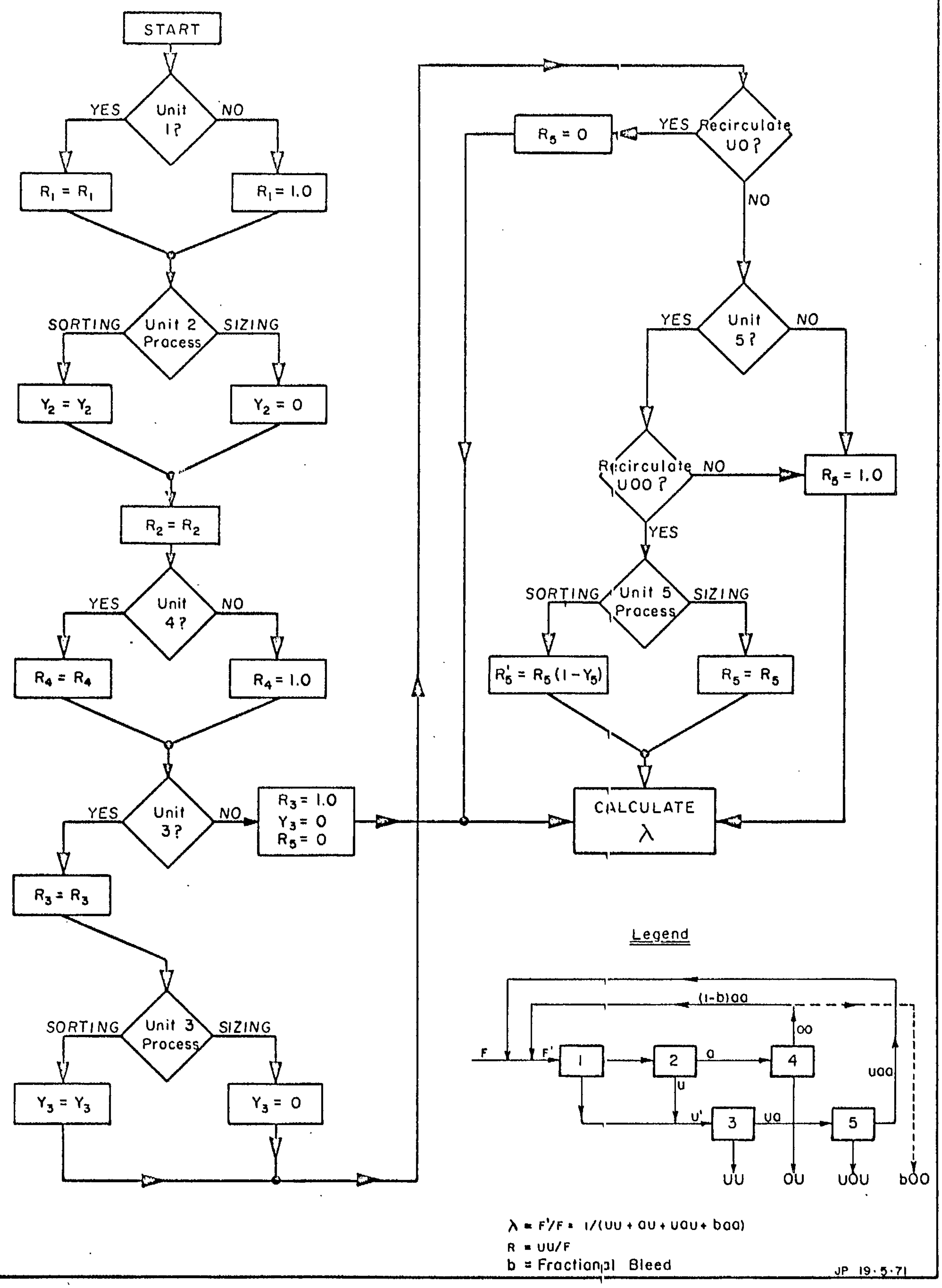
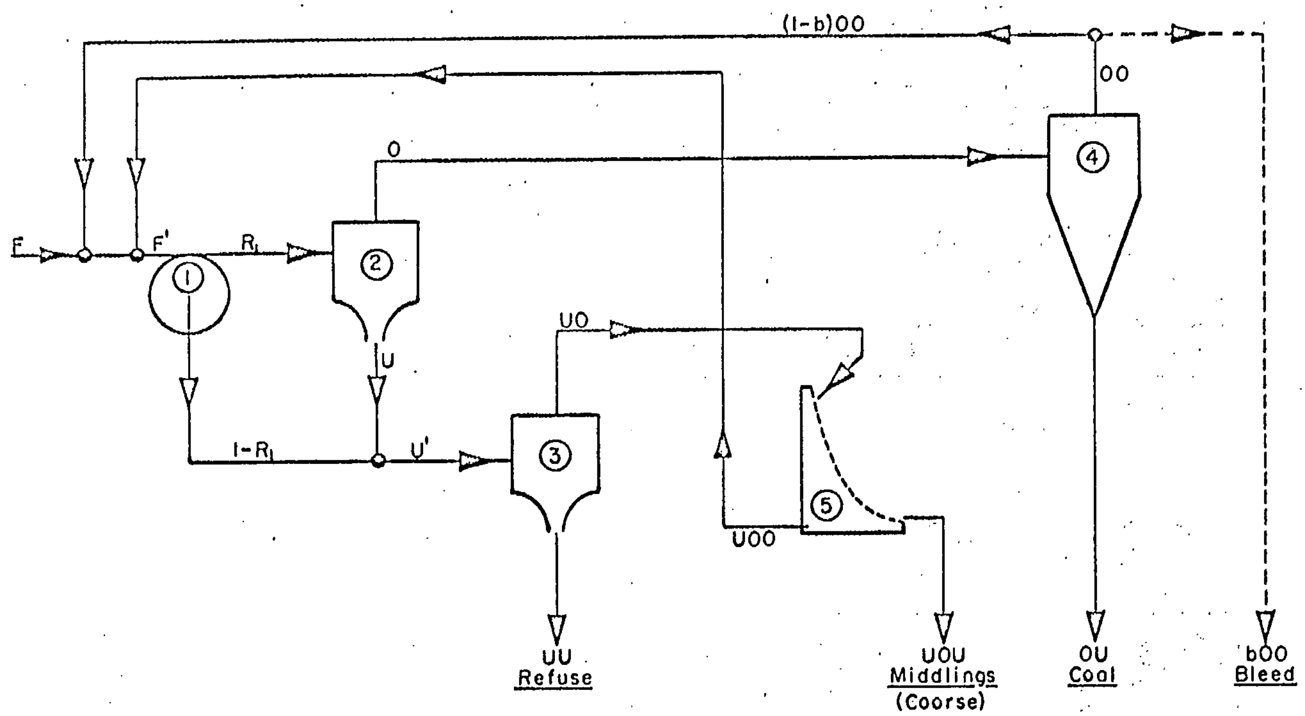


Fig. 5 - Example I. Five-separator Cambination



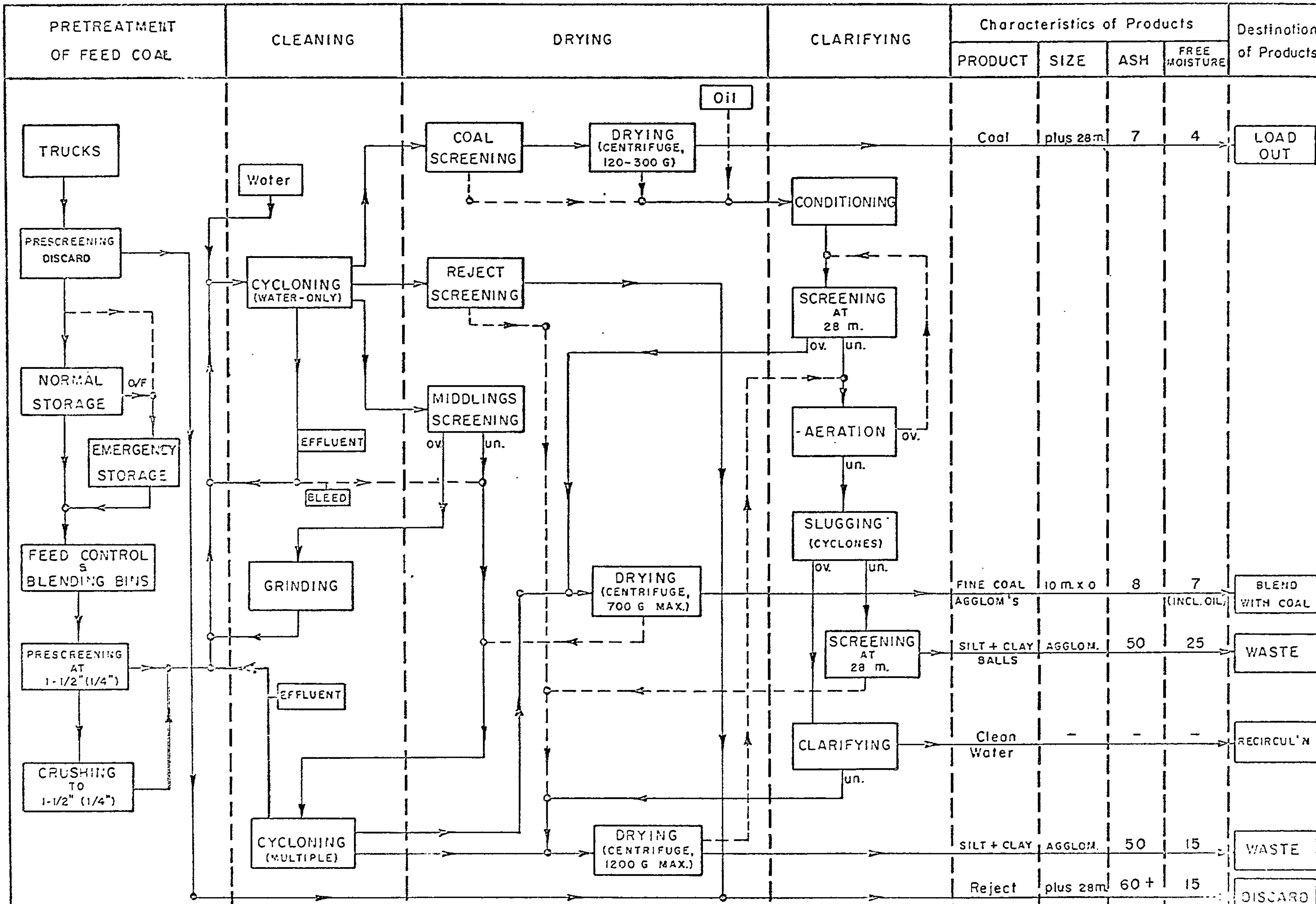
b = 0

UNIT	Pulp Divider	CWC-12	CWC-12	Cl.C-12	28 m. Sieve Bend	Yield[1] Unit 2	Yield[1] Unit 3	Recircul'n[2] Factor	Size Consist of Feed, F wt, %
PROCESS	Sizing	Sorting	Sorting	Sizing	Sizing				
Size Fraction \ P.N.	R_1	R_2	R_3	R_4	R_5	Y_2	Y_3	λ	
>4000μ	0.95	1.0	1.0	1.0	1.0	0.25	0.15	1.0	
4000-2000	0.78	1.0	1.0	1.0	1.0			1.0	
2000-1000	0.65	1.0	1.0	1.0	1.0			1.0	
1000-500	0.58	1.0	1.0	1.0	1.0			1.0	
500-250	0.54	1.0	1.0	1.0	0.75			1.03	
250-150	0.52	1.0	1.0	1.0	0.30			1.10	
150-100	0.51	1.0	1.0	0.90	0.18			1.14	
100-80	0.50	0.94	0.94	0.71	0.14			1.23	
80-60	0.50	0.78	0.78	0.50	0.12			1.51	
60-40	0.50	0.56	0.56	0.30	0.11			2.15	
<40	0.50	0.26	0.26	0.11	0.10	0.25	0.15	4.49	
Mean						0.25	0.15		100.0

NOTES: 1) THE VALUES FOR Y_2 AND Y_3 ARE HERE SHOWN AS CONSTANT OVER THE ENTIRE RANGE OF SIZES. IN PRACTICE, DIFFERENT VALUES MAY BE EXPECTED. THESE WILL AFFECT λ_i IF THE DIFFERENCES FROM THE AVERAGE ARE LARGE.

2) THE MEAN VALUE OF λ IS OBTAINED BY WEIGHTING THE INDIVIDUAL VALUES IN PROPORTION TO THE SIZE CONSIST VALUES FOR EACH FRACTION (LAST COLUMN).

Fig.6- E.M.R. Process Flowsheet [1]



1) Water-only Cyclones + Oil-dewatering process, Dept. of Energy, Mines and Resources, Canada.

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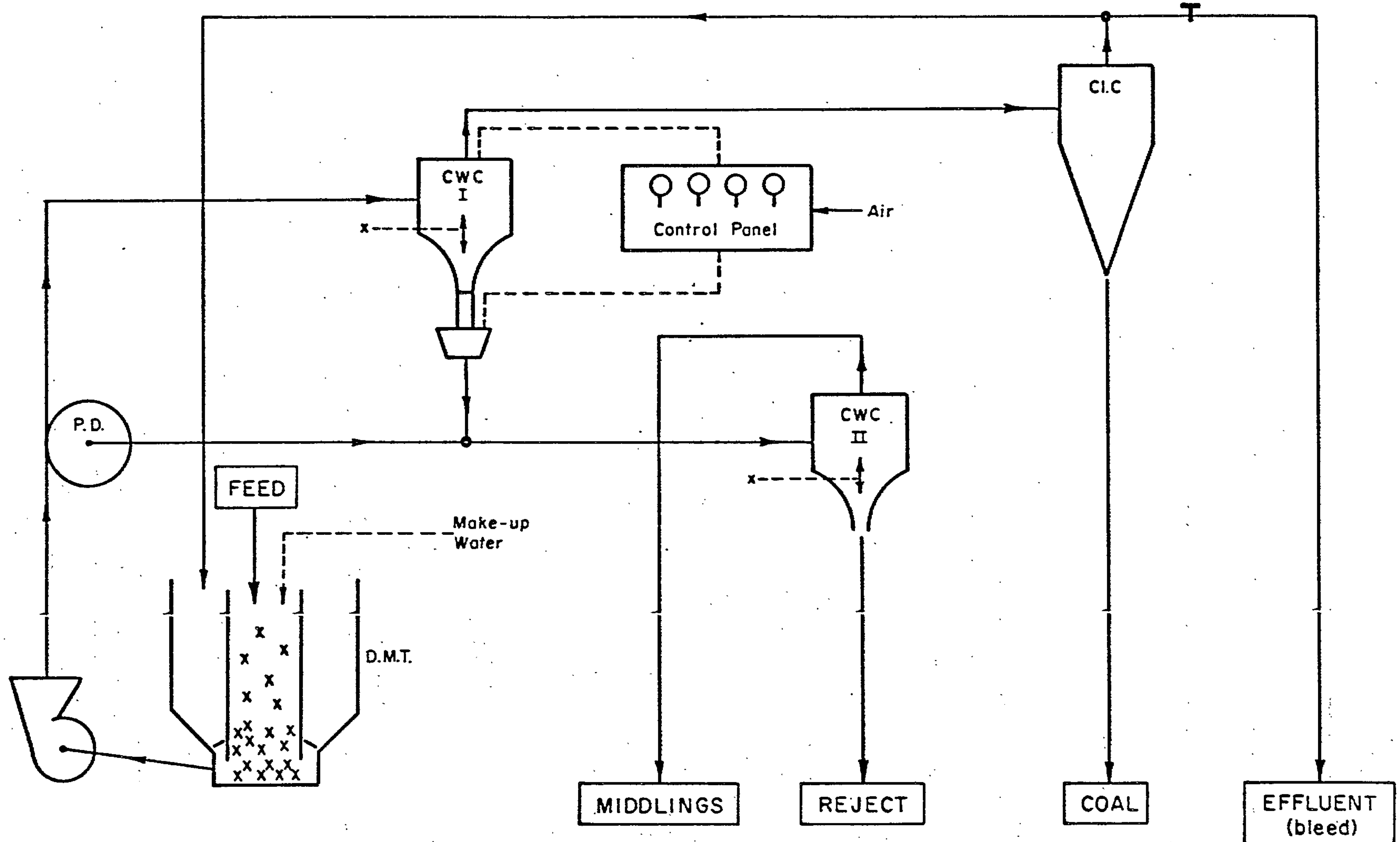
Fig. 7 - Compound Water Cyclone Automatic Two-stage Circuit



LEGEND

CWC I = Primary C.W. Cyclone
CWC II = Secondary C.W. Cyclone
Cl.C = Classifier Cyclone
P.D. = Pulp Divider
D.M.T. = Dual Mix Tank
x = remote control of cut point

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FIG. 8 - COMPOUND WATER CYCLONE

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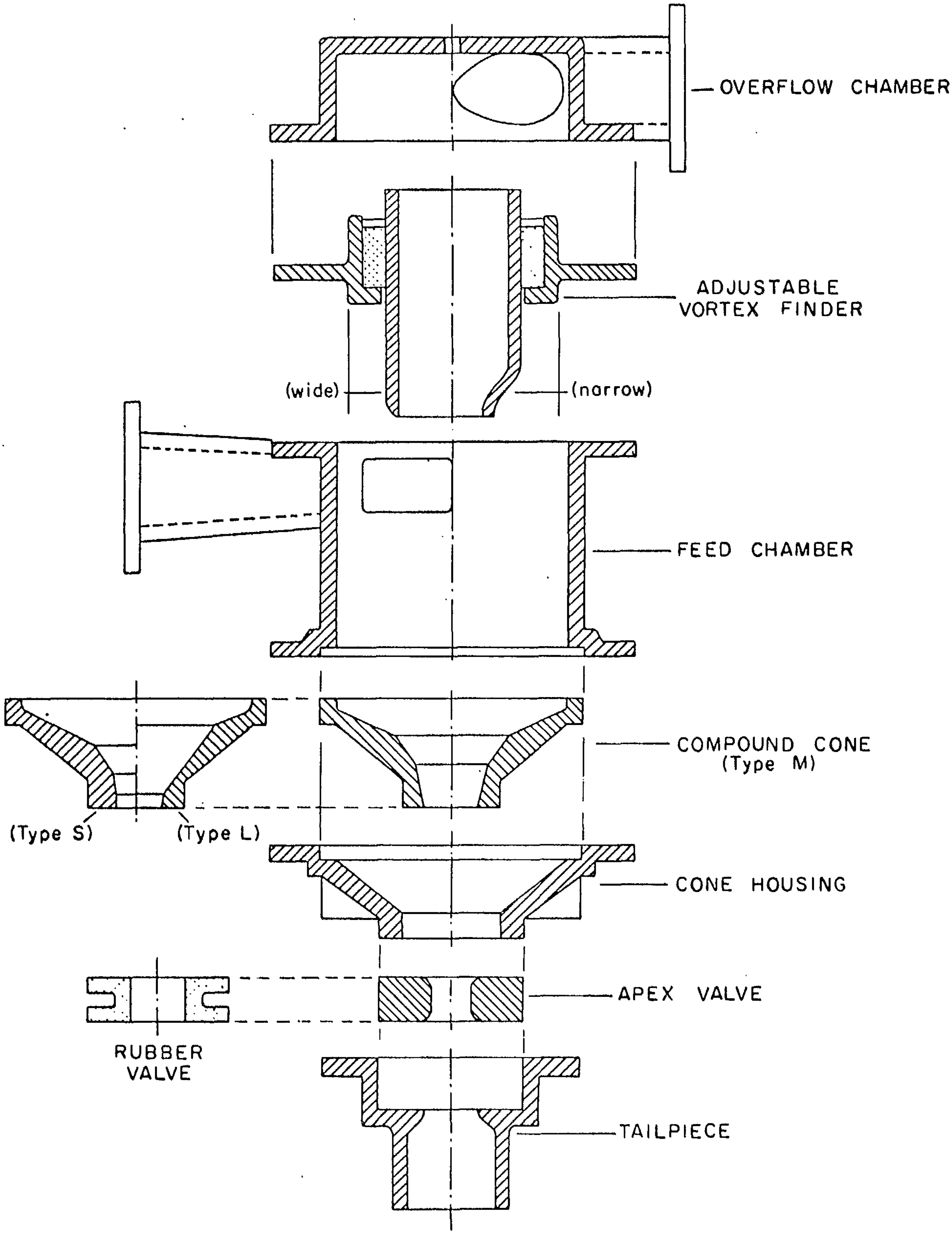

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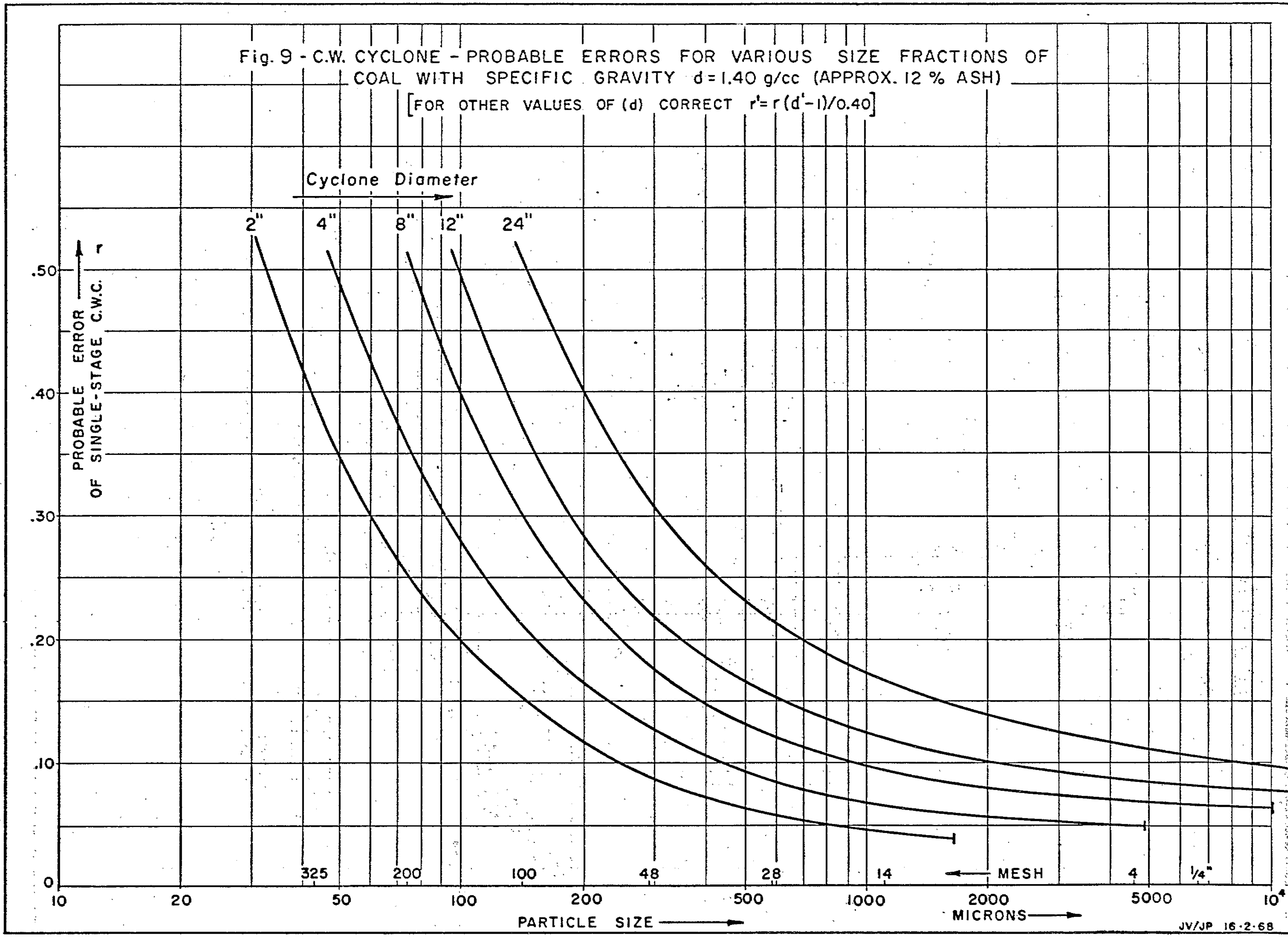

Fig. 9 - C.W. CYCLONE - PROBABLE ERRORS FOR VARIOUS SIZE FRACTIONS OF COAL WITH SPECIFIC GRAVITY d = 1.40 g/cc (APPROX. 12 % ASH)
[FOR OTHER VALUES OF (d) CORRECT $r' = r(d'-1)/0.40$]

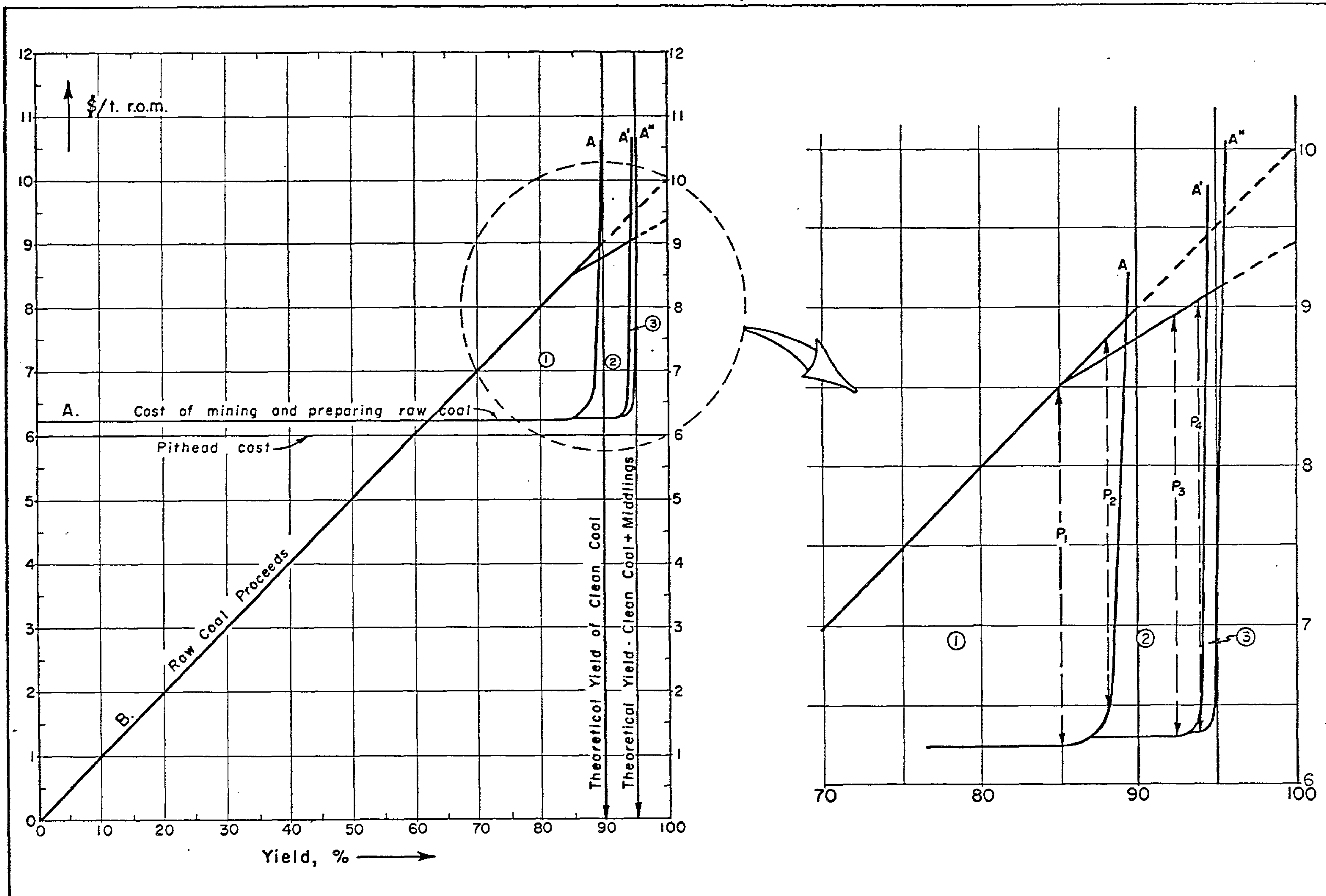

Fig.10- Cost-Profit Chart for Coking Coal Beneficiation

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3) Terchick, A. A., "Comparison of Concentrating Tables, Hydrocyclones and Heavy-Medium Units for Achieving Maximum Sulfur Reduction on 1/4 in. by 28-mesh Coal", paper presented at the Coal Preparation Section, Soc. Min. Engrs. of AIME, (1971).

4) Visman, J., "Bulk Processing of Fine Materials by Means of Compound Water Cyclones", Can. Inst. Mining & Metallurgy, CIMM Bull. Vol. 59, No. 647 (March '66) pp. 333/46; Trans. CIMM Vol. LXIX (1966) pp. 85/98.

5) Yoshioka, N., Hotta, Y. and Mizutani, T., "Classification Efficiency of a Two-Stage Hydraulic Cyclone", Nagaku Kikae 21, 32-36 (1957) (Transl. for Oak Ridge National Laboratory).

APPENDIX

NOTES ON THE SEPARATION EFFICIENCY OF COMPOUND WATER CYCLONES

1) Probable error of the densimetric error curve

Estimates of the overall probable error (r) for the separation in bulk of, for example, a minus 2-inch coal having a mean solids density of 1.50 g/ml are found by calculating its weighted average value from

$$r = \Sigma q_i r_i / \Sigma q_i \quad \text{---------------------------- 3)}$$

where q_i = % weight of size fraction (i)

r_i = probable error of size fraction (i) (see Fig. 9).

Then, the overall value r is corrected for the difference between the solids density 1.50 and the reference value 1.40 as shown on Fig. 9.

$$r' = r \frac{1.50 - 1}{1.40 - 1} = 1.25 \; r.$$

2) Limits of efficient densimetric separation

The upper ends of the r-d curves on Fig. 9 correspond with the particle sizes below which densimetric separation is noticeably affected by size classification. The following practical limits correspond with a probable error $r \approx 0.40$ and apply to C. W. cyclones operating in single stage.

CWC diam in.	Lower limits of particle sizes cleaned by CWC			
	For coal (specific gravity 1.4)		For rock (sp gr 2.5)	For pyrite (sp gr 5.1)
2	325 mesh[1)]	40 microns	28 microns	14 microns
4	200 "	75 "	45 "	30 "
8	150 "	100 "	75 "	60 "
12	100 "	150 "	100 "	80 "
24	60 "	250 "	160 "	140 "

1) The size values correspond with the 95% - point (d_{95}) on the size error curve, i.e. the size of the particles that remain 95% unaffected by the classification effect of the C W cyclone.

The size error curve of a C W cyclone can be determined by a test or it can be calculated in accordance with the method of Yoshioka et al (5).

3. Overall probable error of a standard two-stage CWC circuit

If compound water cyclones are operated in a two-stage circuit by recleaning the underproduct of CWC-I and recirculating the middlings (overproduct of CWC-II) back to the feed, the overall error curve of the circuit is determined by the individual error curves of CWC-I and CWC-II, as follows:

$$R = \frac{R_1 \quad R_2}{1 - R_1 \ (1 - R_2)} \qquad \text{-----------------------------} \quad 4)$$

where R = fractional partition number of the circuit as a whole;

R_1 = " " " " CWC-I

R_2 = " " " " CWC-II

Derivation

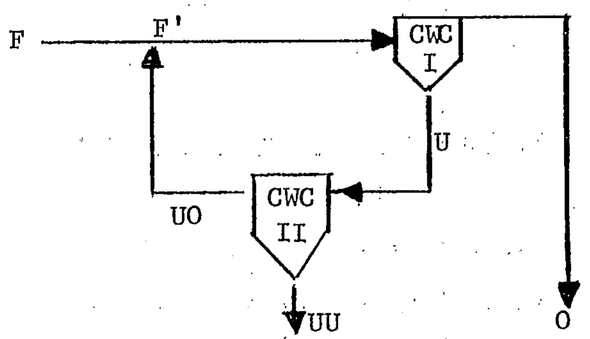
$UU = R_2 \ U$

$U = R_1 \ F^1$

$F^1 = F + UO$

$O = (1 - R_1) \ F^1$

$\therefore \ \frac{UU}{UU+O} = R = \frac{R_1 \ R_2 \ F^1}{(1-R_1+R_1R_2)F^1}$



$R = \frac{R_1 \ R_2}{1-R_1(1-R_2)}$, q. e. d.

4. The densimetric error curves of the C. W. Cyclone

The shape of the densimetric error curve of a single C. W. cyclone depends on its probable error (r) and its cutpoint (d_p).

The abscissa (d_i) of any point on the error curve can be found from

$$d_i = d_p + r \ (A_i + B_i \ d_p) \qquad \text{----------------------------} \quad 5)$$

Eq. 5 is an experimental formula derived from a series of 67 experiments involving the beneficiation of coals, mineral sands and ores, with C. W. cyclone models of different diameters.

Constants A, B are listed for a series of partition numbers PN in the following table:

PN	A	B
0	- 4.21	+ 0.05
1	- 3.81	+ 0.16
2	- 3.50	+ 0.18
5	- 2.70	+ 0.11
10	- 1.82	- 0.03
15	- 1.41	- 0.03
20	- 1.11	- 0.03
25	- 0.76	- 0.10
40	- 0.32	- 0.02
60	+ 0.32	+ 0.03
75	+ 1.26	- 0.11
80	+ 1.92	- 0.32
85	+ 2.84	- 0.63
90	+ 4.29	- 1.14
95	+ 7.42	- 2.39
98	+13.43	- 5.26
99	+17.49	- 7.30
100	+24.34	-10.88

Coordinates calculated with eq.5 are preferably plotted on graph paper with a linear scale for the abscissas (density d_i) and a (normal) probability scale for the partition numbers PN. The curve of best fit, which on this graph paper approaches a straight line, is drawn through the 18 points to compensate for deviations which may occur in view of the wide range of materials and cyclone sizes covered. Noticeable deviations for PN = 98, 99 and 100 may be corrected by extrapolating the straight line, using the linear-probability graph paper mentioned above.