APPLICATION OF OPTIMAL CONTROL TECHNIQUES TO A ROCK CRUSHING SYSTEM

by

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STATEMENT BY AUTHOR

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APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

D. G. Schultz — 7 NOV. 1967

D. G. SCHULTZ — Date

Professor of Electrical Engineering

PREFACE

This thesis has been written with the hope that it will contribute something new to the field of mining. The subject of mining as an electrical engineering thesis may at first appear ill-conceived, but in fact, many applications of electrical engineering bring it into areas with which it is not originally associated. The lack of previous work in this area would bear out the fact that experience in mining alone has been insufficient to provide a suitable solution.

This lack of previous work has required that the author spend much time generating and evaluating possible solutions to the rock-crushing problem. I am particularly indebted to Professor Donald G. Schultz of the Department of Electrical Engineering at the University of Arizona. His critical assistance and suggestions have been invaluable throughout the development of this thesis. Richard Livingston of The Duval Mining Corporation and Lou Lipphart of The Allis-Chalmers Manufacturing Company provided me with much information as to the present state of the art for which I am grateful.

Finally, I owe special appreciation to my wife, Cindy, who typed and proofread this manuscript. Her constant encouragement throughout the entire period of research has been a strong determining factor in its completion.

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ABSTRACT

The basic relationships between feed hardness, crusher setting, horsepower drawn and product size are presented in convenient graphical form. These are used in the light of optimal control theory to evaluate varying degrees of control used with existing rock-crushing systems. Two principal problems exist in these systems: That of maintaining choke-feed in all crushers and that of obtaining the optimal crusher settings in all crushers. The first problem is due to the transportation lag existent between the secondary and tertiary crushers. This problem is resolved by positioning the secondary crusher directly above the tertiary crusher. The optimal setting of the tertiary crusher is obtained by frequent sampling of the tertiary output and adjusting the crusher setting incrementally corresponding to this measurement. An improvement of better than ten percent is postulated by application of these optimal techniques.

For existing systems which have a fixed machinery configuration, a "sub-optimal" solution is presented.

Alternate Performance Indexes are proposed which appear better suited to the overall mining operation than those presently used.

CHAPTER I

INTRODUCTION AND OUTLINE OF CONTENTS

The development of machinery for the crushing of rock in mining operations has been highly refined in terms of the engineering analyses which determine the shape of crusher surfaces, the metals from which the crushers are made and the capacity of individual crushers. To this time, however, little has been done to operate a group of crushers in such a way as to maximize the efficiency of their operation. This paper considers this problem and proposes methods which may be applied to "get the most out" of a series of crushers used in a mining operation. Adequate explanations are given of the crushing problems to be considered as well as the control theory involved, thus allowing the reader who lacks experience in either of these areas to understand the materials presented.

The second chapter of this paper presents the crushing system to be controlled. An explanation is given of each element of the system (screens, hoppers, feeder-trays, etc.) as well as the degree to which each of these elements may be controlled. To clarify later analysis, the dynamics of crushing are discussed, showing the relationship between hardness of feed, crusher setting, and the tons per hour (TPH) of desired product. For those unfamiliar with crushing, these relationships are displayed in a convenient graphical form. This section is concluded with the definition of terms familiar to Optimal Control

Theory such as: State variables, Performance Index, Optimal Policy, Stability, etc. The frequent usage of these terms in the context of this paper requires a careful definition for the reader who may, from past experience, associate a different meaning with these words.

The third chapter is an analytical one. It contains a critical discussion of the varying degrees of system control which have been exercised in current systems. The three systems discussed are: (1) That which has no control; (2) That which controls the rate of feed to the crusher system; (3) That which controls the crusher settings as well as the feed-rate. Frequent reference is made to Chapter II as the inherent disadvantages of each system are discussed in terms of the crushing dynamics and control theory presented there. Particular emphasis is given to the third system, demonstrating that a complex control system still requires a basic understanding of control theory to be of value.

Chapter IV provides a synthesis approach to the optimal control system. First, it is demonstrated that a series of crushers may be constantly choke-fed (filled to capacity yet running as much as 10 percent or more below the actual achievable output. The relative positions of the crushers is shown to play a role in "optimizing" the operation and the best placement of this machinery is presented. A description is given of the manner in which the crusher settings, feeder-trays, etc. should be controlled. In conclusion, these optimal methods are modified for adaptation to any existing system for which the placement of crushers is already determined.

Chapter V summarizes the results of this paper. It is concluded that maximum tonnage of product of a specific size is not the best Performance Index in a mining operation. Alternate Performance Indexes are suggested and the facility with which the ideal system of Chapter IV may be adapted to these is demonstrated.

The concluding chapter points out the areas of additional research which would be beneficial, not only in the area of crushing, but in the control of the entire crushing-grinding-flotation process. These areas include: (1) The acquisition of data relating feed hardness, crusher setting and output; (2) The simulation of a crushing operation on a digital computer; and, (3) The analysis of statistical properties of the size of the feed coming from the quarry.

CHAPTER II

GENERAL CRUSHING PRACTICE AND OPTIMAL CONTROL THEORY

The principal interest of this paper is in controlling the crushing process of a mining operation. Crushing is actually an intermediate step in the reduction of ores to the point where mineral content may be removed, being preceded by the blasting of rock in a quarry and followed by grinding (fine reduction). A typical configuration of crushing machinery is presented with an explanation of each of the elements, viz: screens, hoppers, feeder-trays, etc. The control possibilities of each of these elements are explained as well as the degree to which these options are exercised in current operations.

To best determine the proper control to be exercised it is necessary to discuss the dynamics of crushing. The appropriate relationships between feed hardness, crusher setting, horsepower used, tons per hour (TPH) of output, and so forth, are presented in convenient graphical form.

The final area discussed in this chapter is that of optimal control. The purpose of this paper is to reduce theory to practice. For this reason, and to avoid ambiguity, terms which are familiar to optimal control theory are defined in terms of the specific problem of this paper.

A. Explanation of Crushing Elements

Consider the typical crushing system shown in Fig. 1. The initial feed for a crushing operation originates from blasting in a quarry. These large rocks (12" to 36" in size) leave the quarry and are transported to crusher # 1, generally referred to as the Primary crusher. This crusher then reduces the rocks to 4" to 6" in size and this product is stored in a large bin called the Primary Stockpile.

1. The Primary Crusher

If the Primary Crusher is a gyratory crusher it may be represented as shown in Fig. 2. The "cone" shown in the figure may be adjusted vertically while the crusher is not in operation, thus decreasing or increasing the size of the resultant product, depending on whether the adjustment is made up or down, respectively. In a typical operation the weight of the cone and rock are felt to be too great to allow adjustment while running. Thus it may be said that no control is currently used on the Primary Crusher although the incoming rock may vary in hardness and size.

2. The Primary Stockpile

At least one mining operation (The Duval Corporation mine near Kingman, Arizona) has the capability of controlling the position of feed resulting from the Primary crusher. Although currently not used to the extent of its capabilities, this feed-positioning device which is shown in Fig. 3, allows the operator to position the feed by

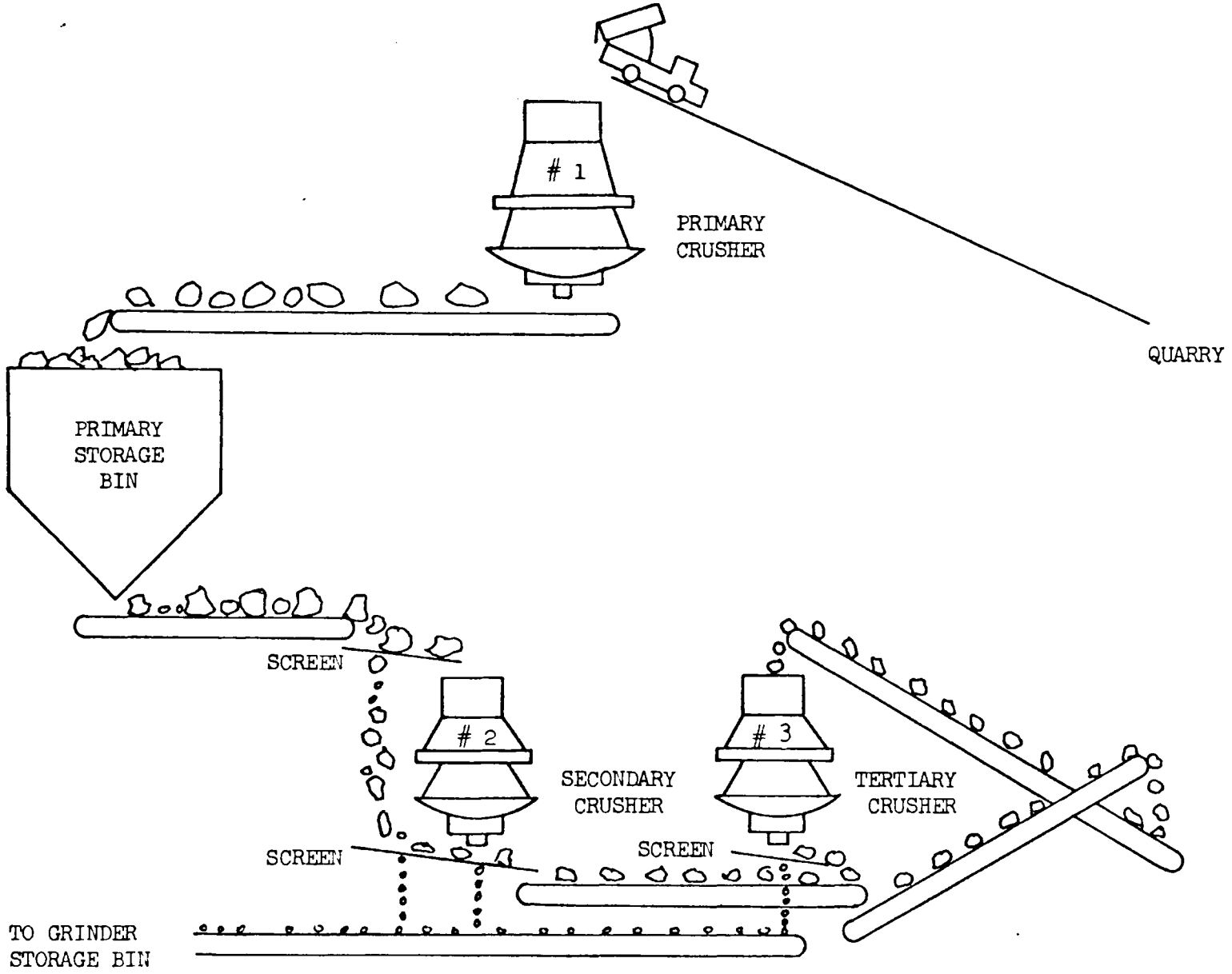

FIG. 1 GENERAL CRUSHING SYSTEM CONFIGURATION

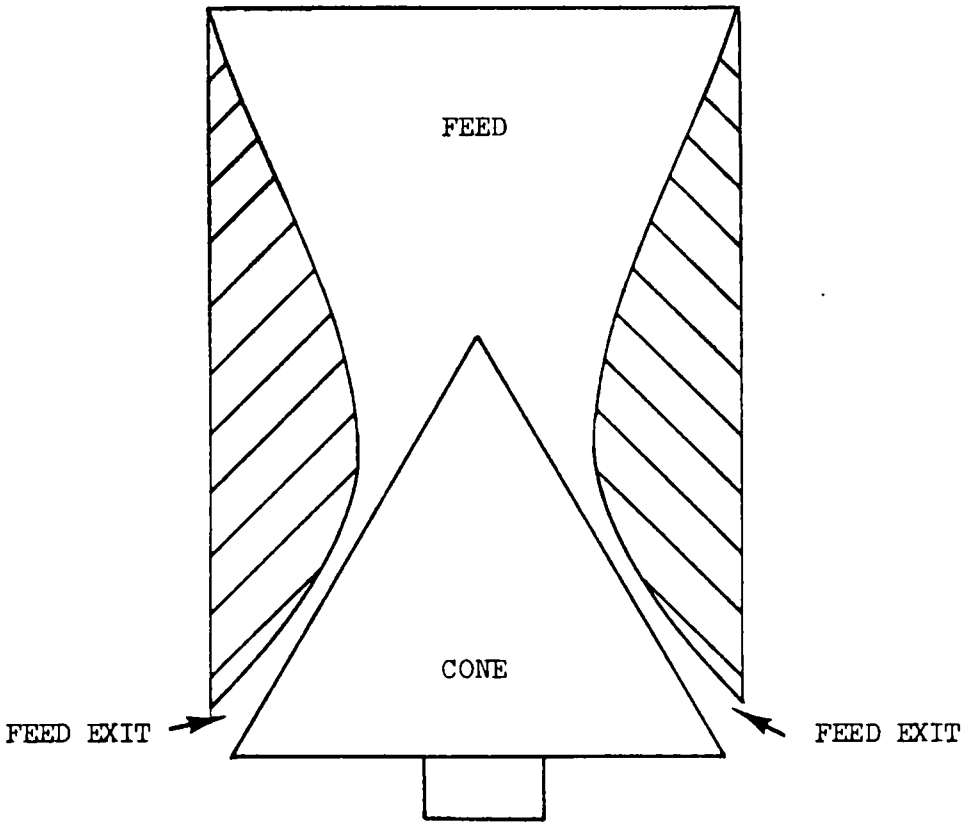

FIG. 2 A GYRATORY CRUSHER

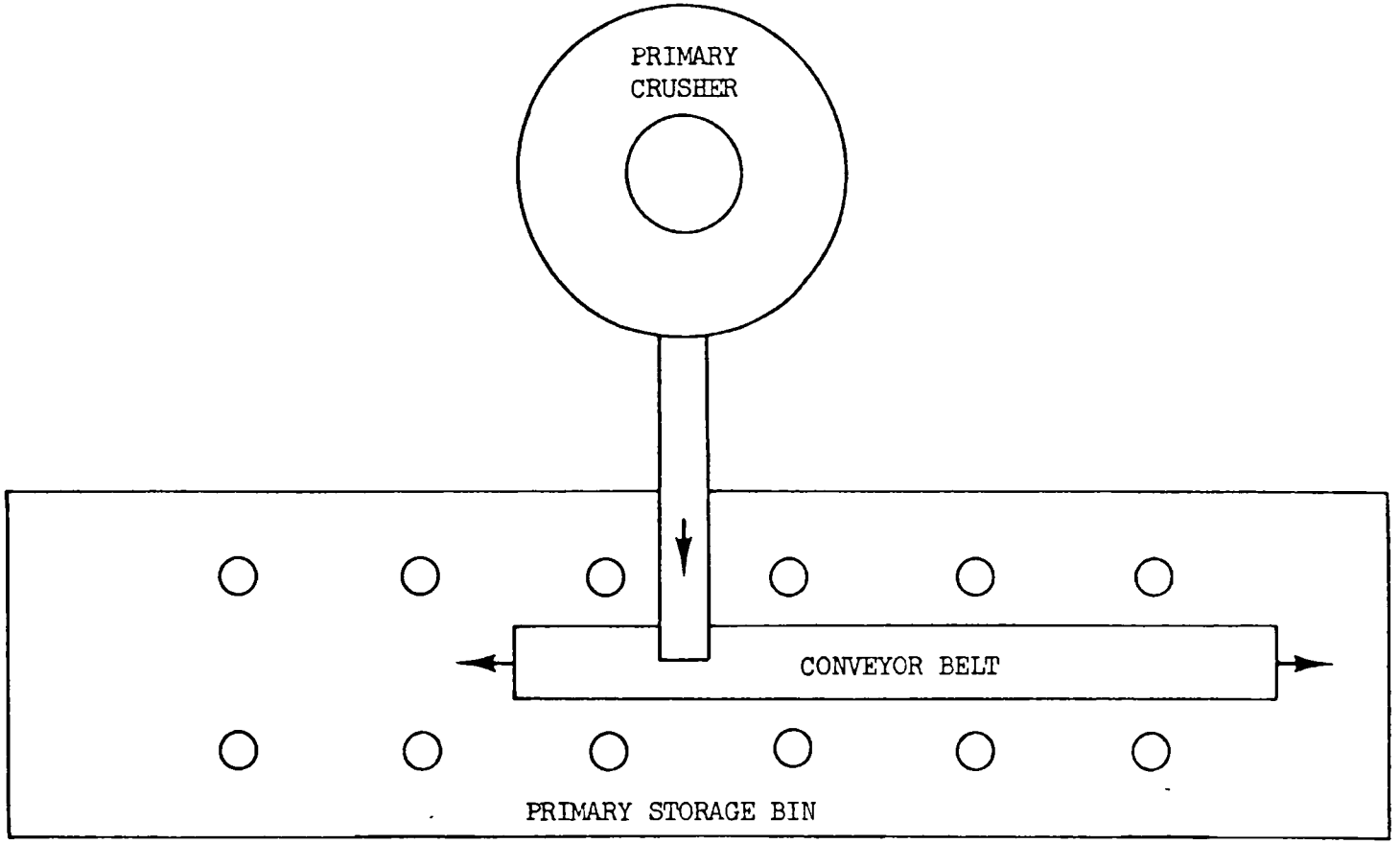

FIG. 3 THE CONTROL OF FEED POSITION IN PRIMARY STORAGE BIN

some pre-determined criteria. For example, this would allow the operator to store soft feed at one position in the bin and hard feed at another.

3. Feeder-Trays

Note that the storage bin in Fig. 3 has several openings through which feed may be withdrawn. Beneath each opening in this bin is a feeder tray as shown in Fig. 4. When a feeder-tray is activated by vibrating it, feed is caused to flow through the opening to a belt below. The rate of flow of this feed is controlled by the amplitude of vibration of the feeder-tray, flow rate being an increasing function of this amplitude. Most mining operations currently take advantage of this feature.

4. Screens

The feed which leaves the Primary Stockpile is then conveyed to the secondary crusher (crusher # 2) for further reduction. Prior to the crusher, however, it passes over screens, as shown in Fig. 5, which remove any undersize material from the feed which enters the crusher. This reduces the probability of the packing of fines in the crusher, a factor which reduces the crushing capacity. Generally, material smaller than the crusher product is removed. This undersized material is removed by vibrating the screens at constant amplitude in current operations.

Although not currently used in any known mining operation, another method of controlling the screens appears feasible. Let a

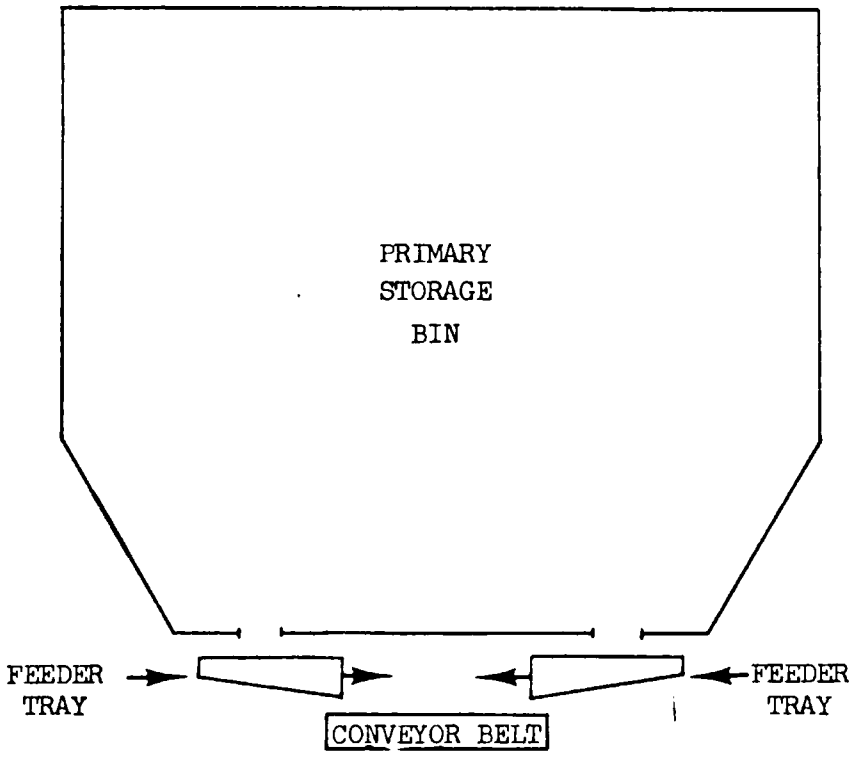

FIG. 4 FEEDER-TRAY OPERATION

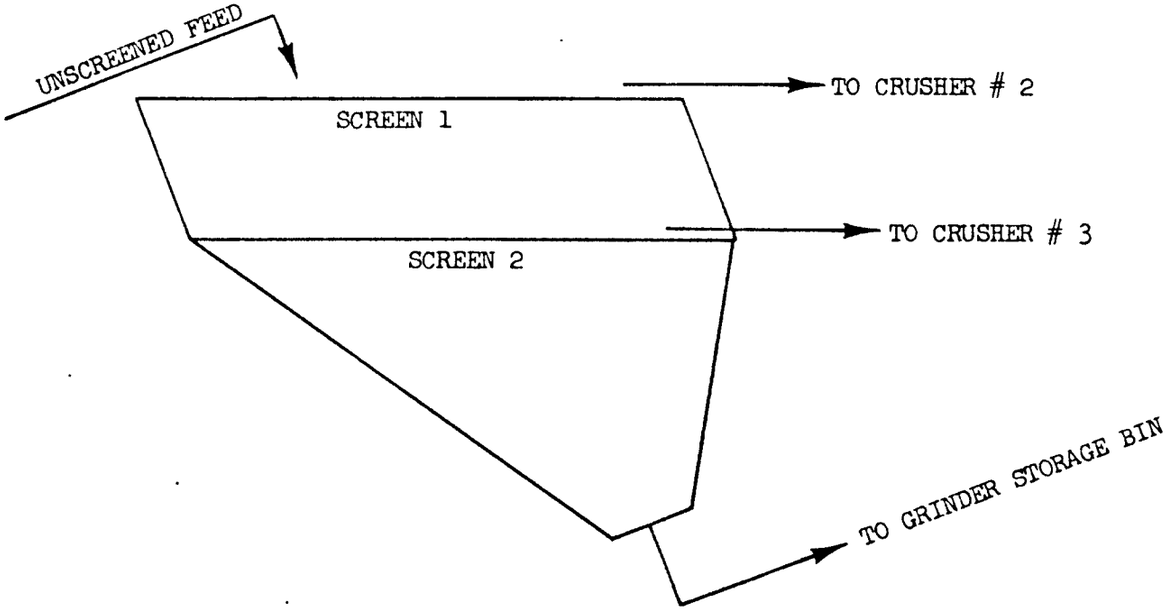

FIG. 5 CONTROL OF SCREENS

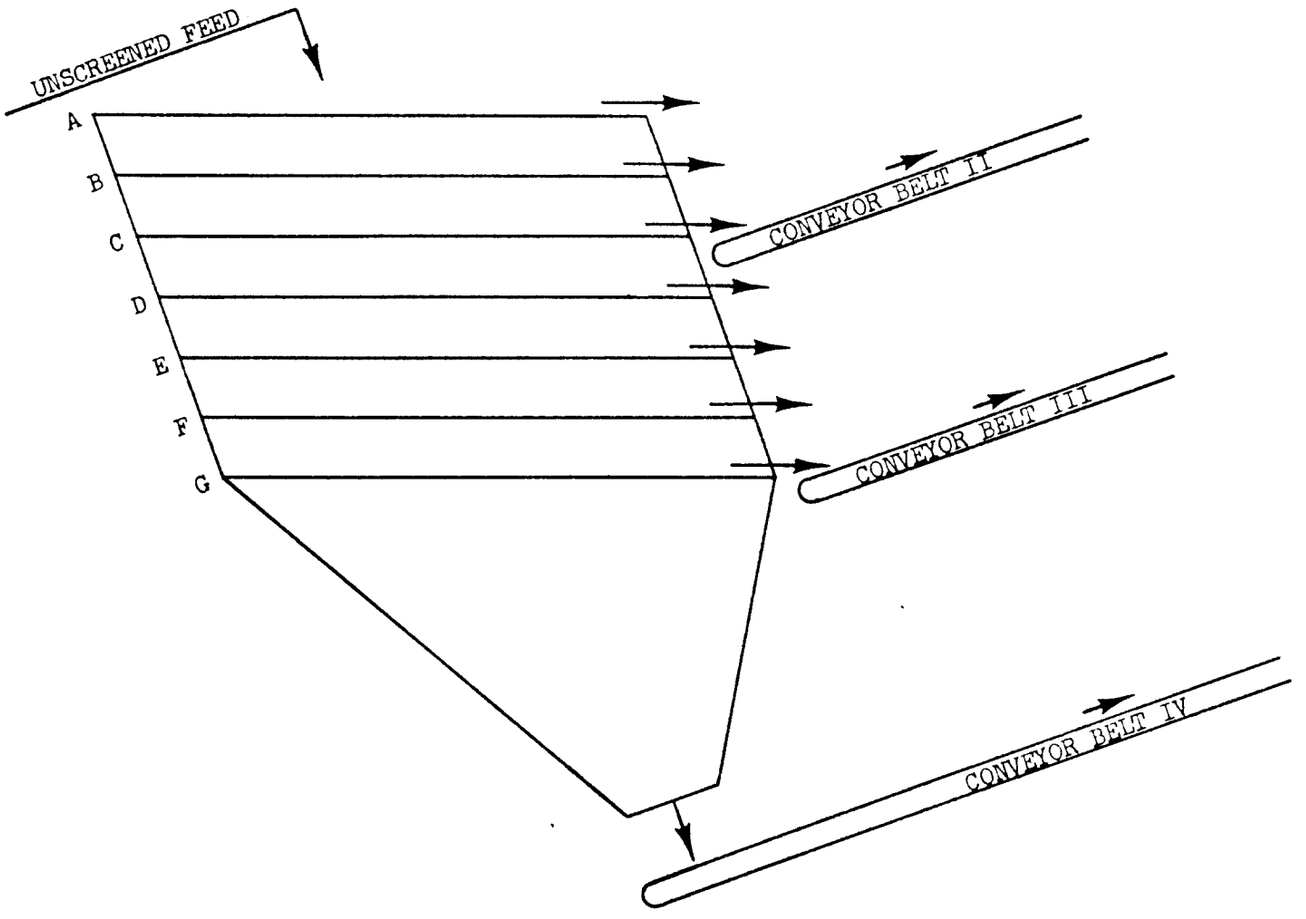

FIG. 6 USE OF MULTIPLE SCREENS TO CONTROL FEED FLOW

series of screens be as shown in Fig. 6 where the openings of each successive screen are smaller than those of the previous one. For example, under normal operation screens A, B and C may feed crusher # 2 by way of conveyor belt II while screens D, E, F and G feed crusher # 3 by way of conveyor belt III. Screen G would have openings the size of the desired product and thus conveyor belt IV would go to the bin which stores the final product. Let the levels of conveyor belts II and III be adjustable vertically at the screens. If crusher # 3 requires less feed conveyor belt II may be lowered to take the additional oversize resulting from screen D. Conversely, if more feed is required, belt I may be raised, allowing the oversize from screen C to bypass crusher # 2 and go directly to crusher # 3.

An alternate approach to the above scheme which would accomplish the same goal would be either to vary the amplitude of vibration of the screens or the angle at which they are fixed. Either method would essentially control the efficiency (percent of possible feed which goes through the screen) of the screen but neither is known to be currently used.

5. Secondary and Tertiary Crushers

Crushers # 2 and # 3 are generally referred to as the secondary and tertiary crushers of a three-crusher system. Because of the smaller capacity of crusher # 3 it is not uncommon to have two such crushers in parallel, both of which accept feed from crusher # 2 and may be treated as a single crusher. Due to the control possibilities which

the gyratory crusher offers, it is assumed that all crushers discussed in this paper are of this type. Thus crushers # 2 and # 3 may also be represented as in Fig. 2.

In general, each of these crushers reduces the cross-section of the incoming feed by one-fourth. Thus, the 4"- 6" feed which comes from the Primary Crusher is reduced to less than 1/2" (-1/2") in size by these two crushers. Since the incoming feed is smaller and the combined weight of the feed and crusher cone are considerably less than in the case of the Primary crusher, it is possible to move the cone vertically while the crusher is crushing. This important feature thus allows control of the process without requiring shut-down of the operation. This feature is currently used in some mining operations, but the criteria which determine the adjustment to be made may vary significantly as shown in Chapters III and IV.

The desired -1/2" product results from the screening prior to crusher # 2 and from the crushing done by crusher # 2 and crusher # 3. It is conveyed to a bin referred to as the Grinder Storage Bin. When withdrawn from this bin it goes through a grinding process which reduces the feed to a powder sufficiently fine that the mineral content may be removed by flotation or some other process.

The work of this paper is restricted to controlling the operation from the Primary Stockpile to the Grinder Storage Bin. That is, no attention is given to control of the Primary Crusher, the positioning of feed in the Primary Stockpile or the withdrawal of feed for grinding. Before discussing the approach to optimal

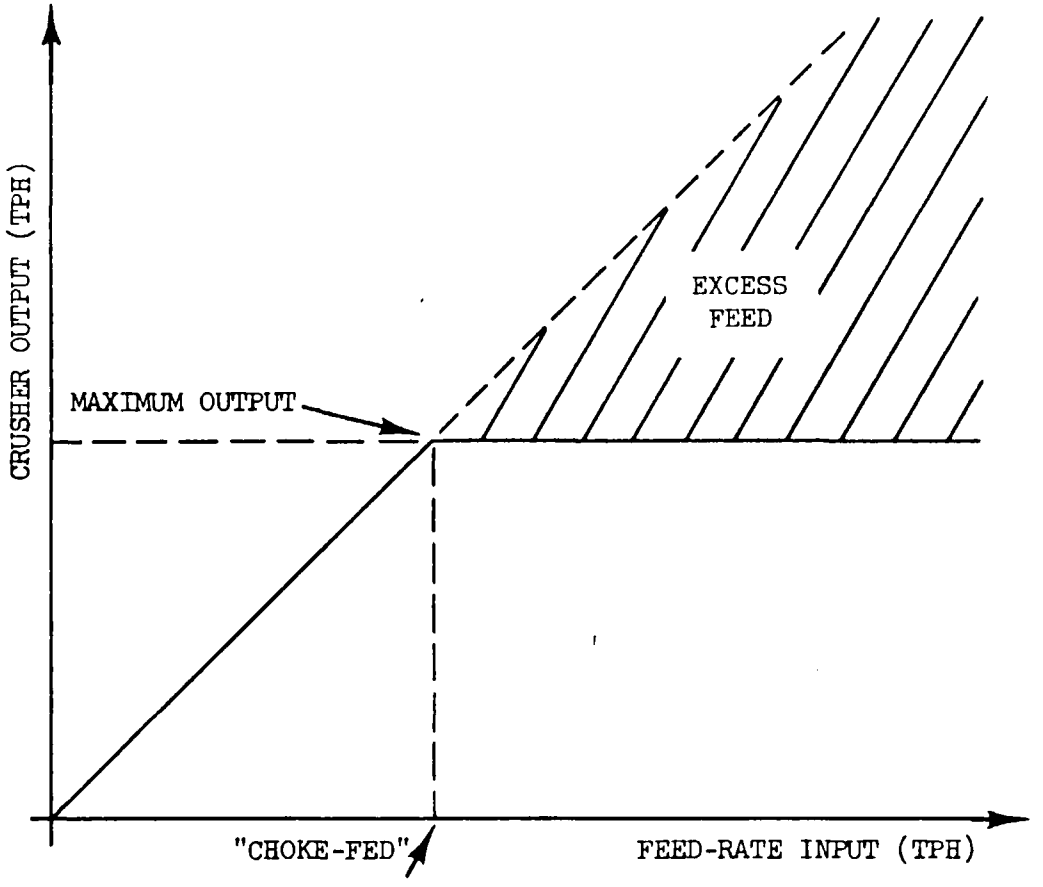

FIG. 7. CRUSHER OUTPUT AS A FUNCTION OF INPUT FOR A FIXED CRUSHER SETTING

control it is advantageous to consider the effect of a change in feed structure on the system.

B. Crushing Dynamics

The requirement that control be exercised in crushing is due to the changing composition of feed. This may be either a change in hardness, size or feed-rate. The paragraphs which follow show how the throughput varies as a function of hardness for a constant crusher setting, how the throughput varies as a function of crusher setting for feed of a constant hardness, and the relationship of crusher horsepower to these two variables. Closed-circuit and open-circuit operation of crushers is then discussed in terms of these factors. It should be noted that most information available on the subject is based on "average" data. The exact relationships between throughput, crusher setting, and feed hardness are not generally given in the literature. This is one of the difficulties which arise in the determination of optimal control methods as discussed in Chapter IV.

1. Change in Feed Rate

For belts running at constant speed, a change in feed-rate occurs when the quantity of feed on the belt changes. The effect of such a change on crusher output is shown in Fig. 7, where it is assumed that the crusher maintains a constant setting. The figure represents steady-state conditions in that a change in output does not respond immediately to a change in input. Note that the output is approximately equal to the input up to a certain point, beyond which

the output remains constant. The abscissa might also be labelled "level of feed in crusher" since the relationships are similar. Maintaining the input at which "Maximum Output" is obtained is referred to as keeping the crusher "choke-fed." As illustrated by the figure, a feed-rate below "choke-feed" results in a crusher which is not operating at capacity. Conversely, an input in excess of "choke-feed," when integrated over time will exceed the excess storage capacity of the crusher, resulting in the spillage of feed and the costly clean-up associated with it.

2. Work Index

The Work Index of a particular feed is the number associated with the energy required to achieve a standard reduction in size of that feed. In this paper, that feed which has a high Work Index is referred to as "hard" feed and that which has a low Work Index is referred to as "soft" feed.

Fig. 8 is useful in understanding intuitively the effect of a change in hardness on the energy required to achieve a given reduction. This figure is for a fixed crusher setting, and the throughput is in tons per hour (TPH) of feed at that setting. Horsepower is used here as a measure of the energy required. Note that, as in Fig. 7, only a finite output is possible and, in addition, some horsepower is required to run the crusher empty, with no output resulting. As the rock becomes harder, the motor load increases and the throughput decreases. The converse is true for softer feed.

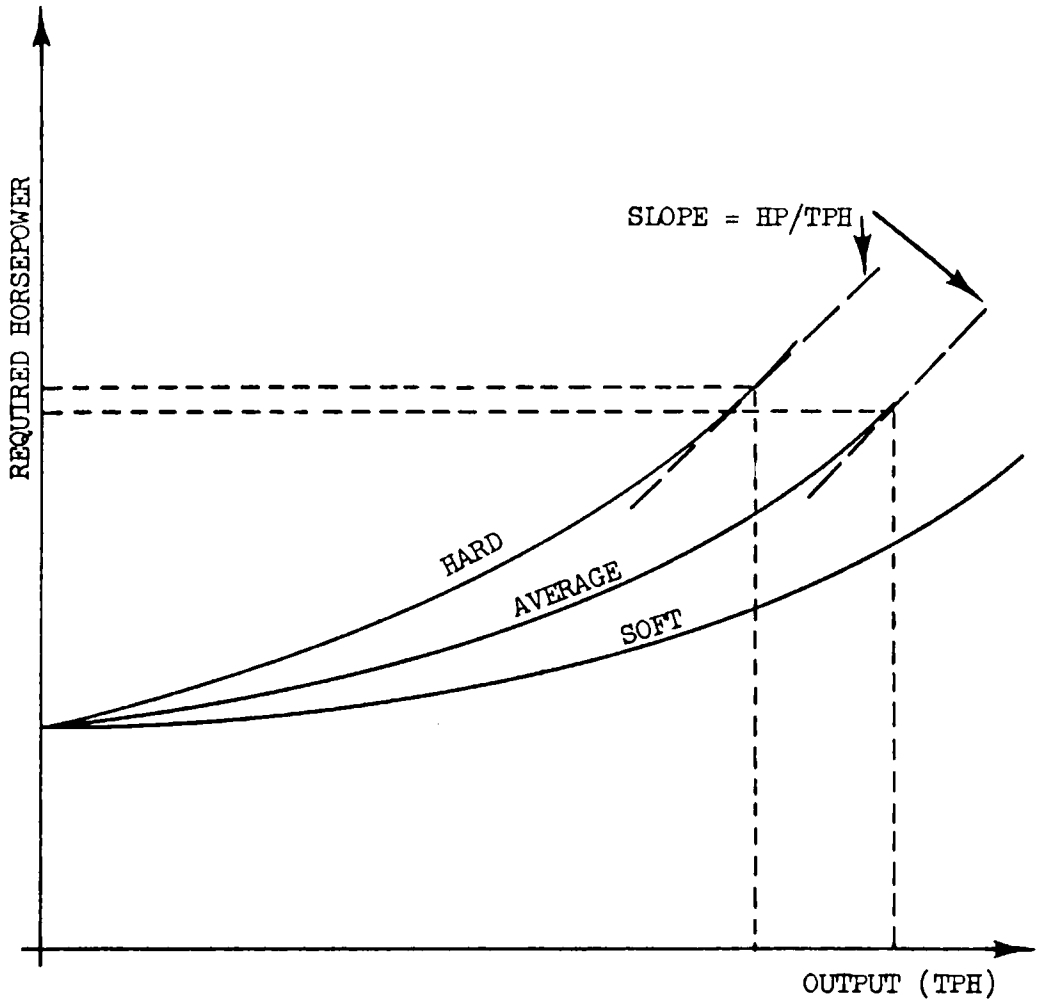

FIG. 8 REQUIRED HORSEPOWER AS A FUNCTION OF FEED HARDNESS FOR A FIXED CRUSHER SETTING

3. Fixed Crusher Setting and Variable Feed Hardness

Frequently mentioned in mining literature[1] are a "product table" (Table 1) and a "product curve" (Fig. 9) which give information relating product size to feed hardness and crusher setting. An example of the use of these tables would be as follows. If it is desired to determine the product to be expected from a crusher set at a particular discharge opening, reference is first made to Table 1 which shows the approximate percentage of the product that will pass through a screen whose openings are equal in size to the crusher setting. This gives a point on one of the product curves (interpolation may be necessary) which allows tabulation of the percentage of all sizes of interest.

Suppose, for example, that it is desired to examine the characteristics of granite for a crusher setting of 3/4". Referring to Table 1 it is seen that 70-75% of the crusher product will pass through a 3/4" screen. Selecting the lower value (70%), corresponds to the dotted curve shown in Fig. 9. This curve then indicates that 50% of the product can be expected to pass through a 1/2" screen, 70% through a 3/4" screen, and 85% through a 1" screen.

From Table 1 and Fig. 9 the following properties may be observed. A rock with a high Work Index such as Trap-Rock will have a larger mean size and a smaller throughput for a given crusher setting than a softer rock such as limestone. In summary, it may be

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1. McGrew, Brownell. "Crushing Practice and Theory." Reprinted from Rock Products for the Allis-Chalmers Co. Milwaukee: Maclean-Hunter Publishing Co., 1953, pp. 34-35.

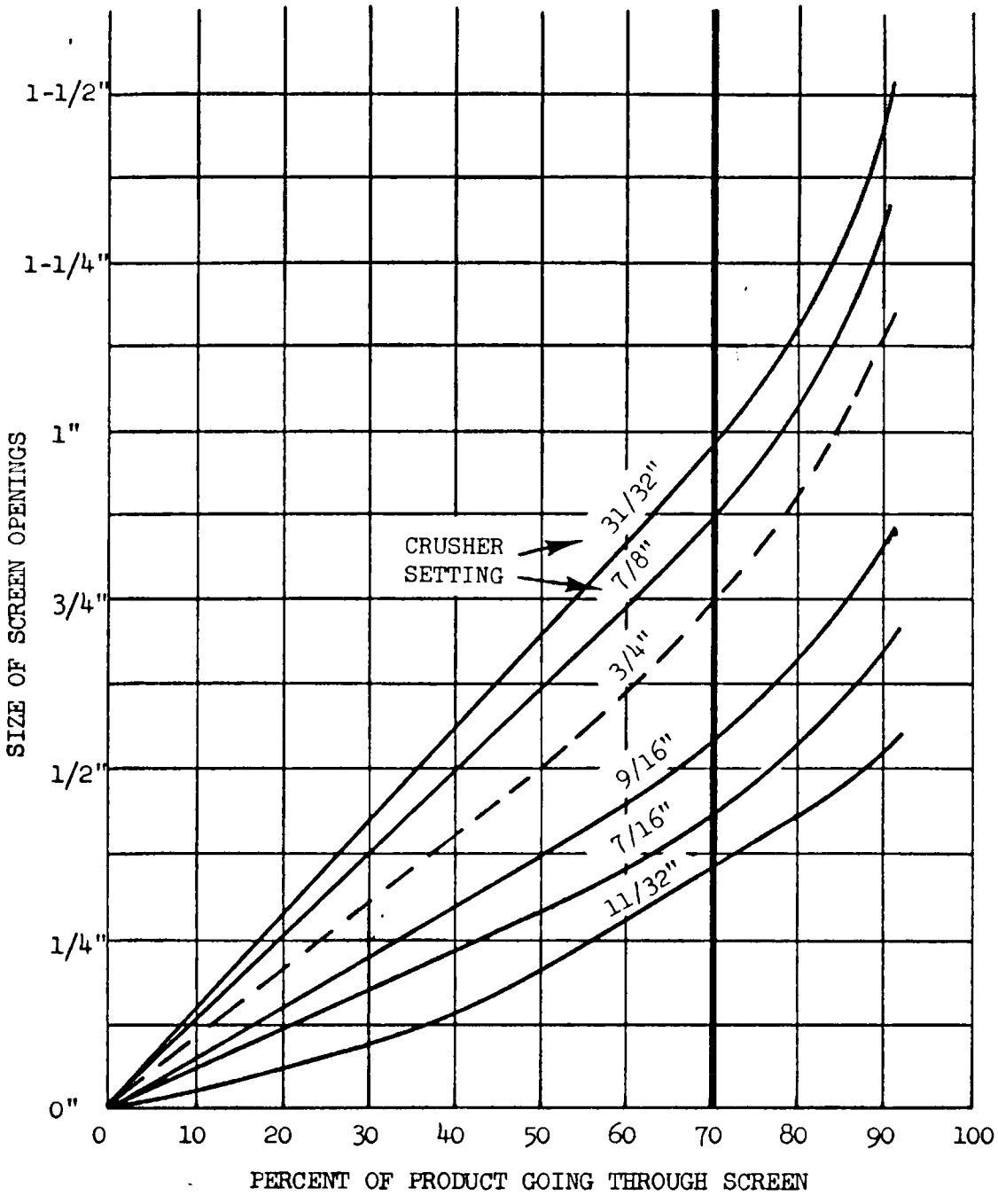

FIG. 9 CRUSHER PRODUCT CURVES

TABLE 1

PRODUCT TABLE

TYPE OF FEED	PERCENT OF PRODUCT PASSING A SCREEN WITH SQUARE OPENINGS EQUAL TO DISCHARGE SETTING OF CRUSHER
LIMESTONE	80-85
GRANITE	70-75
TRAP-ROCK	60-65
ORES	80-85

said that for harder feed, the throughput is decreased (Fig. 8), the percent throughput passing a given screen size is reduced (Table 1), and the horsepower required is increased (Fig. 8). The converse is true for softer feed.

4. Fixed Feed Hardness and Variable Crusher Setting

Consider now the effect of changing the crusher setting on the TPH of throughput and the size distribution of the throughput. Although this information is not usually presented in the literature, it may be derived from the product curves and crusher capacity ratings given by the manufacturer.[2] Such a method was used in tabulating the data which is given for average feed in Table 2 and illustrated in Fig. 10 and Fig. 11.

One may now use an intuitive approach in determining curves for soft or hard feed. For example, for a given crusher setting, the crusher capacity is expected to increase for softer feed and, in addition, a larger percentage of the product is expected to pass a screen of any given size. The converse is true for harder feed. The information for hard and soft feed are also given in Table 2 and Fig. 10 and 11. The data discussed to this point applies to crusher # 2 which is in open-circuit operation. That is, the feed leaving crusher # 2 never returns to it.

On the other hand crusher # 3 is operating in closed-circuit, which means that the oversize resulting from crusher # 3 is

2. "84 Inch Hydrocone Crusher." Allis-Chalmers Manufacturing Co. Technical Brochure No. 17B1647B. 1966.

TABLE 2

PRODUCT RESULTING FROM CRUSHER # 2 (CHOKE-FED, OPEN-CIRCUIT OPERATION)

AS A FUNCTION OF HARDNESS AND CRUSHER SETTING

CRUSHER SETTING	RATED CAPACITY (TPH)			PERCENT ≤ 1/2"			TPH ≤ 1/2"			TPH ≥ 1/2"		
	SOFT	AVE	HARD	SOFT	AVE	HARD	SOFT	AVE	HARD	SOFT	AVE	HARD
3/4"	300	295	290	60	50	43	180	147	125	120	148	165
7/8"	310	305	300	52	43	37	161	131	111	139	174	189
1"	320	315	310	46	38	32	147	120	99	173	195	211
1 1/8"	330	305	320	42	35	28	139	114	90	191	211	230
1 1/4"	340	335	330	38	31	25	129	104	82	211	231	248
1 3/8"	350	345	340	34	28	23	119	96	78	231	249	262
1 1/2"	360	355	350	31	25	21	111	89	74	249	266	276
1 5/8"	370	365	360	28	23	20	104	84	72	266	281	288
1 3/4"	320	375	370	25	21	19	95	79	70	285	296	300
1 7/8"	390	385	380	23	20	18	90	77	68	300	308	312
2"	400	395	390	22	19	17	88	75	66	312	320	324

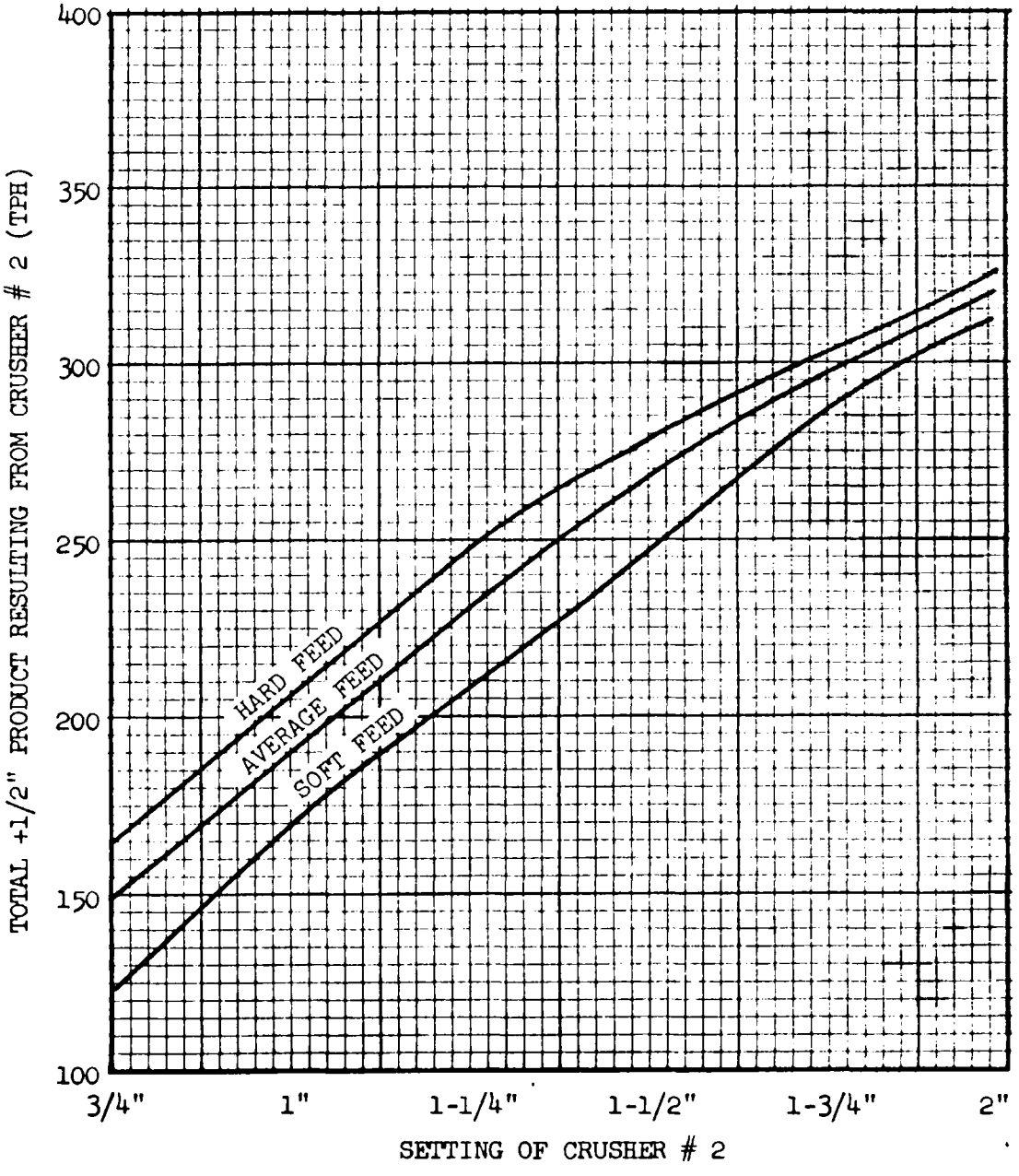

FIG. 10 TPH OF + 1/2" PRODUCT RESULTING FROM CRUSHER # 2 (CHOKE-FED, OPEN-CIRCUIT OPERATION)

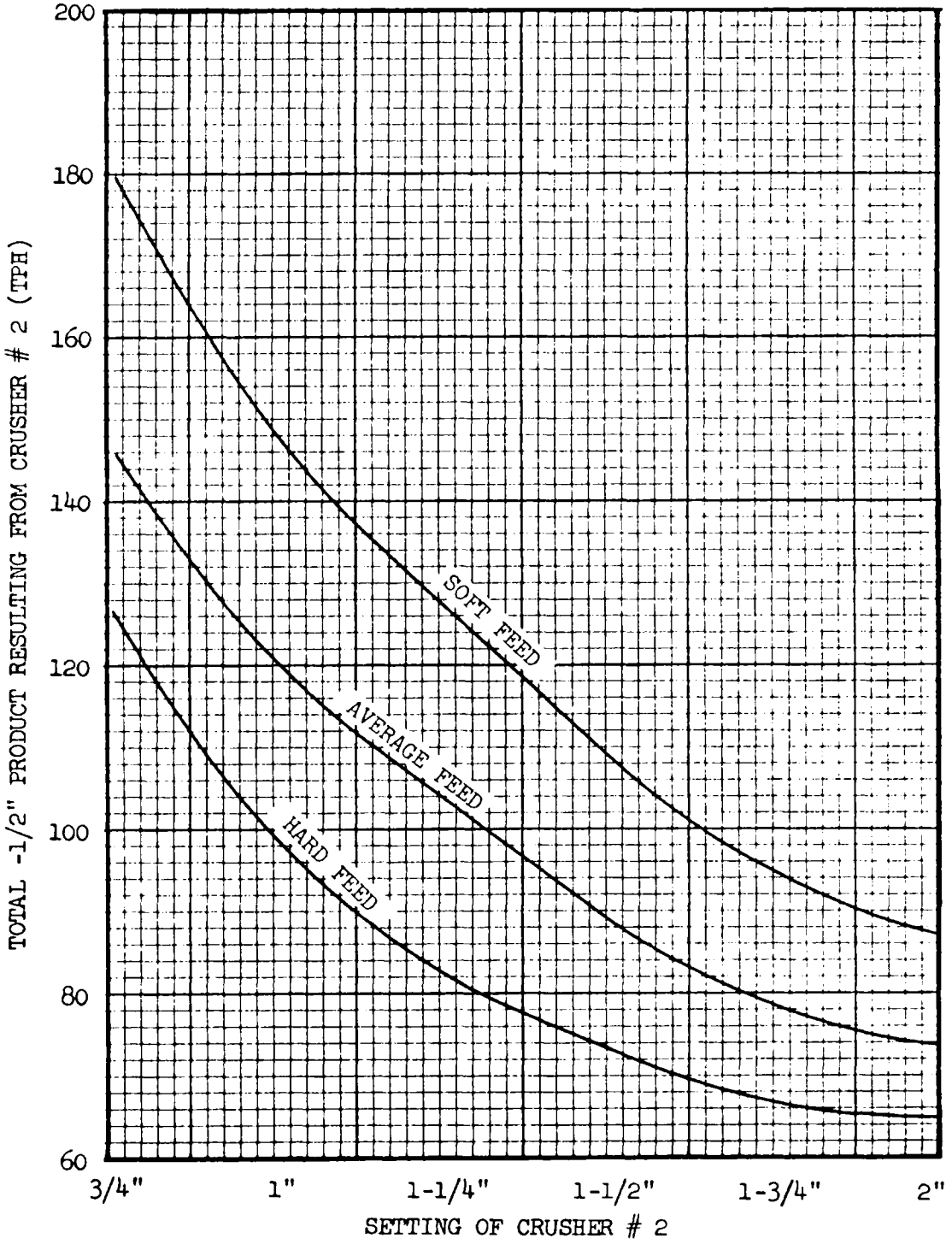

FIG. 11 TPH OF - 1/2" PRODUCT RESULTING FROM CRUSHER # 2
(CHOKE-FED, OPEN-CIRCUIT OPERATION)

returned to it to be re-crushed. It has been shown that the capacity of a crusher operating in closed-circuit may be approximated by:[3]

$$\text{crusher capacity} = \frac{\text{open-circuit capacity}}{1 + (\text{percent circulating load expressed as a decimal})}$$

The percent circulating load is given in the literature[3] and Table 3 for reference. Using this information and assuming 100% screen efficiency, Table 4 was compiled from which Fig. 12 was constructed. It should be noted that the fixed setting of the Primary Crusher assures a constant relationship between hardness and size of the feed going to crusher # 2. The setting of crusher # 2 may vary during the operation, however, and thus the data given in Table 4 and Fig. 12 are only valid for one setting of crusher # 2.

An interesting point illustrated in Fig. 12 and to which frequent reference is made throughout this paper is that the maximum tonnage passing a screen of specified size varies as a function of hardness. More important, however, is the fact that this maximum tonnage is obtained at <u>different</u> crusher settings, depending on the hardness of the rock.

This concludes the discussion of basic relationships between feed composition and the elements of the system. Reference is made in future sections to these factors both in analysis and in providing recommended control procedures.

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3. McGrew. <u>op. cit.</u>, p. 50.

TABLE 3

CIRCULATING LOAD (PERCENT)

PERCENT OVERSIZE IN CRUSHER PRODUCT	SCREEN EFFICIENCY (PERCENT)						
	100	95	90	85	80	75	70
5	5.3	5.7	5.9	6.3	6.7	7.1	7.7
10	11.2	11.8	12.6	13.3	14.2	15.4	16.8
15	17.7	18.8	20.0	21.5	23.1	25.0	27.3
20	25.0	26.7	28.4	30.7	33.4	38.3	40.0
25	33.4	35.8	38.7	42.0	45.4	50.0	55.5
30	42.9	46.3	50.3	54.7	60.0	66.7	74.5
35	53.9	58.5	63.8	70.0	77.8	87.7	100.0
40	66.7	73.0	80.0	89.0	100.0	114.3	133.5
45	81.8	90.5	100.0	112.5	128.5	150.0	181.0
50	100.0	111.4	125.0	143.0	166.7	203.0	250.0
55	122.2	137.5	158.0	183.5	219.5	276.0	365.0
60	150.0	172.0	200.0	240.0	300.0	400.0	600.0
65	186.0	216.0	261.0	326.0	435.0	652.0	1290.0
70	233	280	351	568	700	1416	
75	300	374	498	747			
80	400	537	802				
85	567	852					

TABLE 4

PRODUCT RESULTING FROM CRUSHER # 3 (CHOKE-FED, CLOSED-CIRCUIT OPERATION)

AS A FUNCTION OF HARDNESS AND CRUSHER SETTING

CRUSHER SETTING	RATED OPEN-CIRCUIT CAPACITY (TPH)			PERCENT OPEN-CIRCUIT ≤ 1/2"			PERCENT CIRCULATING LOAD			CLOSED-CIRCUIT CAPACITY (TPH ≤ 1/2")		
	SOFT	AVE	HARD	SOFT	AVE	HARD	SOFT	AVE	HARD	SOFT	AVE	HARD
1/8"	298	290	282	100	100	100	0	0	0	298	290	282
3/16"	306	298	290	100	100	100	0	0	0	306	298	290
1/4"	314	306	298	100	100	98	0	0	2	314	306	292
5/16"	322	314	306	100	98	90	0	2	11.2	322	308	280
3/8"	330	322	314	98	90	80	2	11.2	25	324	295	254
7/16"	338	330	322	92	84	73	8	19	35	315	277	238
1/2"	346	338	330	85	75	65	18	33.4	54	294	253	214
5/8"	362	354	346	74	65	55	34	53.9	82	270	230	190
3/4"	378	370	362	65	55	47	54	81.8	114	246	203	169
7/8"	394	386	378	56	49	41	80	105	145	219	189	154
1"	410	402	394	50	43	36	100	135	206	205	171	129

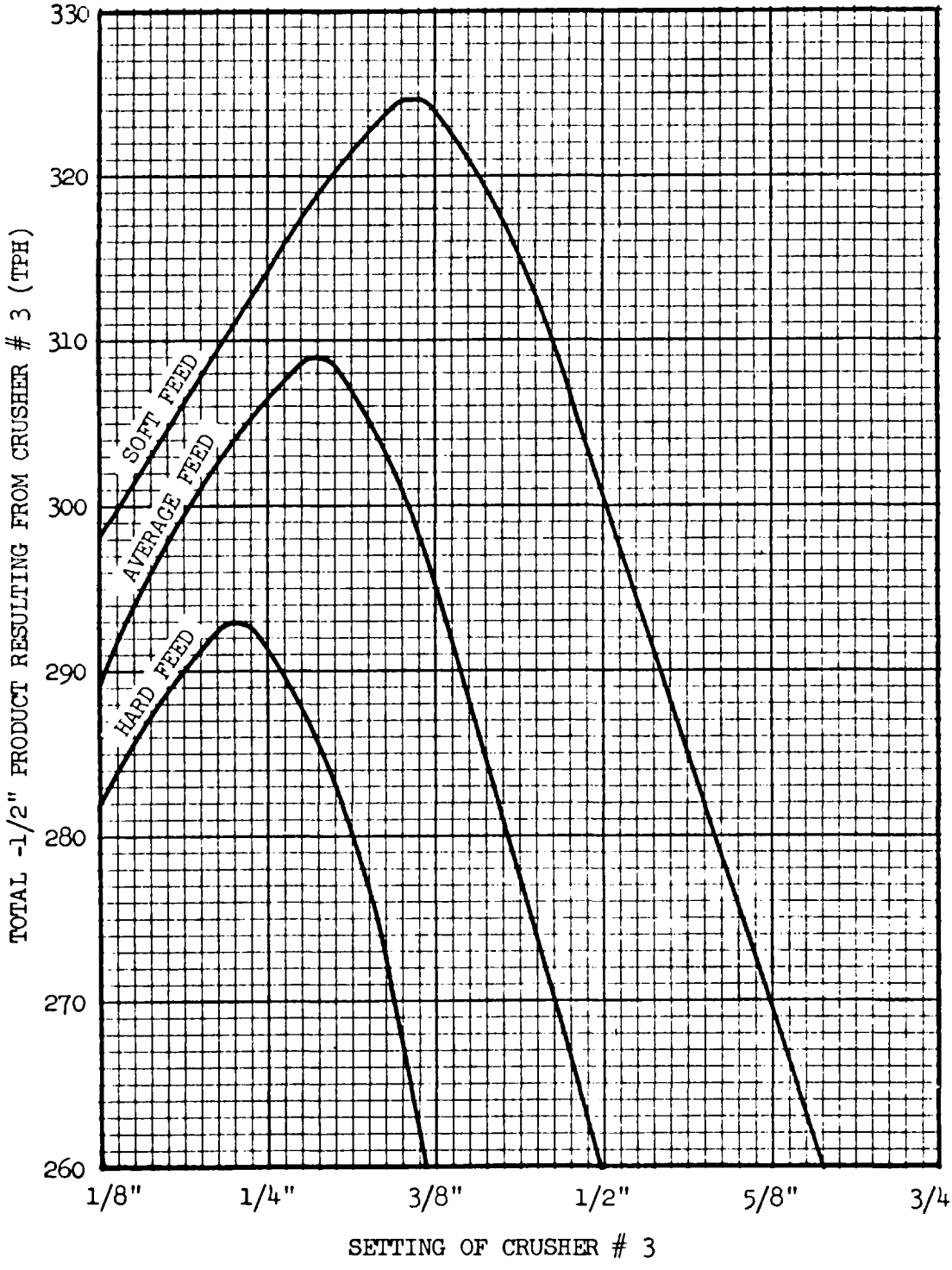


FIG. 12 TPH OF - 1/2" PRODUCT RESULTING FROM CRUSHER # 3 (CHOKE-FED, CLOSED-CIRCUIT OPERATION)

C. Theory of Optimal Control

The terminology of optimal control theory is frequently employed in the subsequent chapters of this paper. To clarify the discussion these terms are presented below. The exact application of these terms to the problem of crushing is also detailed to facilitate the understanding of material presented in the remaining chapters. In general, optimal control is distinguished from the usual control theory in that it demands not only acceptable performance but optimal performance.[4]

1. Performance Index

In order to talk of optimal performance it is necessary to specify some method for determining the quality of performance of the system. This is most frequently done by means of an integral Performance Index of the following general form.

$$\text{Performance Index} = \int_{t_i}^{t_f} f(x_1, x_2, \ldots x_n)dt$$

The system is said to be optimal over the time interval t_i to t_f if the value of the Performance Index is maximum (minimum).[5] In this equation $f(x_1, x_2, \ldots, x_n)$ is the function to be optimized. In Chapters III and IV this function is just the TPH of desired product at any instant. Thus the Performance Index is the total tonnage of

4. Schultz, D. G., and J. L. Melsa. State Functions and Linear Control Systems, McGraw-Hill Book Company, New York, 1967, p. 198.

5. Ibid., p. 198.

desired product over a given interval. It is desired to maximize this Performance Index.

2. Constraints

Quite often the maximizing of a Performance Index is limited by the physical considerations. These limitations are called constraints. For example, the achievement of maximum output may require a crusher setting that draws excessive horsepower. A constraint is placed on the operation which allows the crusher setting to approach the optimal position until the peak allowable horsepower is reached. At that point the constraint takes precedence over the optimal control which would have been exercised otherwise.

The Performance Indexes and constraints which might be used in a crushing system are presented in Table 5.

3. State Variables

Knowledge of "what is going on" in certain parts of the system as well as the control to be exercised provides sufficient information to determine the future behavior of the system. Those aspects of the system which provide this information are called state variables. The future behavior of the system is related to the present value of the state variables and the control law by some functional relationship usually referred to as the state transformation equations. In systems where the state variables are electrical quantities the state transformation equations are generally differential equations.

TABLE 5

PERFORMANCE INDEXES

SOME TYPICAL PERFORMANCE INDEXES	*CONSTRAINTS
1. Minimize cost of product	Total tonnage produced over a specified interval of time must exceed some minimum value.
2. Maximize tonnage	None
3. Minimize variation of pressure on crusher surfaces from some predetermined value. (This is a hypothetical criteria which recognizes that control may be based on something other than output.)	Total tonnage produced over a specified interval of time must exceed some minimum value.
4. Minimize variation of crusher setting from a desired setting which is a function of hardness. It may be desirable that hard feed be crushed smaller than soft feed to best accomodate the grinding process which follows. A particular size of desired product might be specified for each feed hardness prior to operation.	None
5. Minimize size of product	Total tonnage produced over a specified interval of time must exceed some minimum value.

*Three constraints which are present for all Performance Indexes are:

1. The horsepower rating of the motor must not be exceeded.
2. No spillage can result from overfilling of hoppers or crushers.
3. The crusher surfaces must not come in contact with each other.

In a crushing system, however, the state variables might be chosen from the following:

a. Level of feed in crusher

b. Feed-rate from belts to screen

c. Crusher setting

d. Feed-rate through each screen

e. Pressure on crusher surfaces

f. Horsepower requirements of crusher motors

g. Feed hardness

It is possible that these quantities may be related by difference equations but, at the current time, the functional relationships do not appear to be known, even empirically. It is important to measure as many of these state variables as possible since a lack of information may not correctly specify the system performance. An example of misinterpretation of a state measurement due to monitoring an insufficient number of states is given in the next chapter.

4. Sampling

If the state variables were changing rapidly as a function of time, it would perhaps be necessary to make continuous measurements. Practical consideration of crushing dynamics, however, shows that changes in feed composition are relatively slow. Thus, it is only necessary to measure the states at intervals of time. Nevertheless, these intervals must be sufficiently frequent to detect changes before they become too great for the system control to compensate

adequately. These periodic measurements are referred to as sampling since the state is "sampled" at these intervals.

5. Transportation Lag

A transportation lag exists in a system when a period of time lapses between the exercise of a command or control and the time at which the resulting change is noted in the system. For example, the level of feed in a crusher may be too low and, as a result, the storage bin which supplies this crusher is then controlled to increase the rate at which feed is put on the conveyor belt. A certain amount of time is then required before this increased quantity of feed on the belt arrives at the crusher in question. This time lag between control (increased feed-rate from storage bins) and measured response (level of feed in crusher chamber) is the transportation lag.

The sampling time of a system is related to the transportation lag. Redundant information is obtained, for example, if the sampling of feed level in a crusher occurs over a shorter interval than the transportation lag associated with a change in feed-rate.

6. Stability

In control terminology a system is defined as being stable if the output response to any bounded input disturbance is finite. In the context of this paper a crusher control system is defined to be "unstable" if spillage of feed occurs due to overfilling of hoppers or crushers, or if the hoppers and crushers become empty. A system

will be referred to as "marginally stable" if oscillations in feed level occur in the crushers, but they neither overflow nor become empty.

In the strict sense then, a crusher system is considered "stable" only if the crushers are choke-fed at all times and the hoppers do not overflow.

7. Optimal Control

An Optimal Control system is one which maximizes the given Performance Index. For example, classical control system would give satisfactory performance in crushing, such as achieving a minimal daily tonnage of desired product, whereas the optimal system would maximize the total tonnage of desired product.

D. Summary

In summary, this chapter has provided the theoretical groundwork for later chapters. The function of each of the elements used in a crushing system has been discussed as well as the associated control which is currently used and that which might be available. The effect of a changing feed structure on the dynamics of the system has been presented as well as the effect of crusher changes on the feed structure. The theory of control is outlined in the areas which are applicable to the problem at hand. The next chapter employs this theory to perform an analysis of the varying degrees of control which have been used on crushing systems.

CHAPTER III

ANALYSIS OF CURRENT PRACTICE IN CRUSHING CONTROL

This section contains an analysis of the varying degrees of control that may be exercised in a crushing system. The first system discussed is one which has no control and is essentially an open-loop system. The second controls the rate of feed to the secondary crusher. The third system provides the greatest flexibility in that, in addition to feed-rate control, the crusher settings are controlled during operation. Also, more of the states of the system are measured than in the first two cases, thus providing more information for controlling the system. A search of the literature showed this approach to come nearest to optimizing performance for a given Performance Index among those systems described.

Each of the three systems mentioned above is analyzed below in terms of one particular Performance Index. It is desired to maximize the total output in tons per hour (TPH) of rock less than a certain size. This Performance Index is selected for comparison because it is the stated goal of the third system discussed. The accomplishments and deficiencies of each system are discussed to lay the groundwork for a meaningful evaluation of the proposed system described in Chapter IV.

A. The Control-Less System

It is possible to design a crusher system that crushes rock without requiring any control. Such a system cannot be the optimum one in terms of the Performance Index specified above, however. The reasons for this are presented below.

Consider the general crusher configuration which is repeated for reference in Fig. 13. Since no control is exercised, all of the following possible variable elements must be fixed prior to operation.

1. Amplitude of vibration of feeder tray at Primary Stockpile
2. Amplitude of vibration of screens
3. Belt speed
4. Crusher settings

Since the above factors do not change during operation, they must be fixed in such a way that all constraints on the problem are satisfied. One such constraint which is always present is that of avoiding spillage due to excess feed going to crushers. This requires that the crusher be large enough to absorb surges (increases) in feed which may extend over some period of time. This is a most common occurrence for the # 2 crusher since the flow of feed from the Primary Stockpile experiences such variations. If the crusher is sufficiently large to absorb such increases, however, subsequent decreases in feed-rate will result in insufficient feed to meet the total crushing capabilities of the crusher. Thus the crusher does not always operate on a constraint boundary and the system is marginally stable. This means that the crusher is not maximizing its

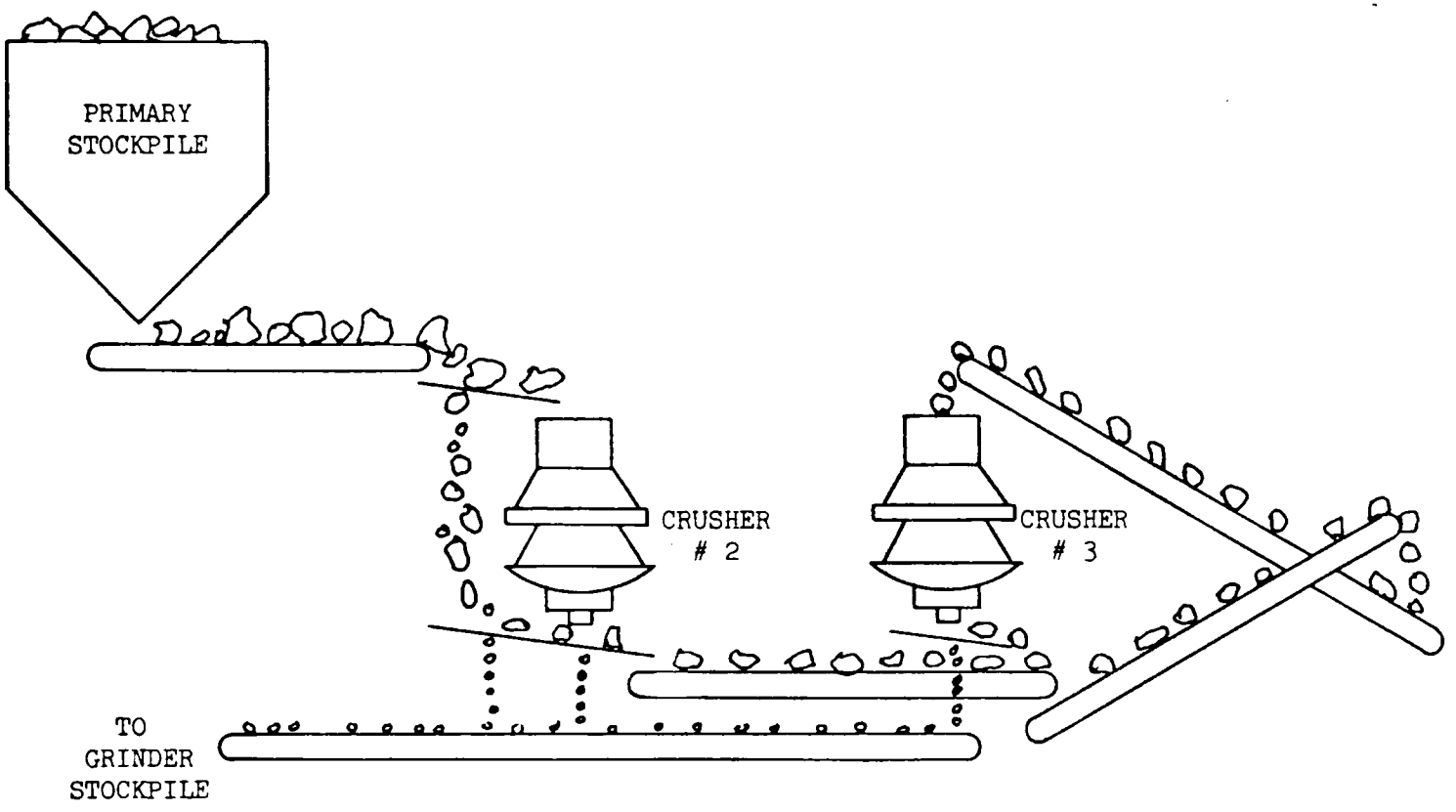


FIG. 13 TYPICAL CRUSHING PLANT CONFIGURATION

output; i.e. crushing as much as its capacity allows. The advantages and disadvantages may be summarized below.

Advantages

1. The system is not unstable, provided the crushers are large enough.
2. No control is needed, resulting in no cost of control.

Disadvantages

1. Crushers larger than necessary result in greater expense than should be required.
2. The crushers run below capacity when they have insufficient feed, thus not maximizing Performance Index.
3. All those which exist in the next system discussed.

B. A System in Which the Input is Controlled

Suppose now that the level of feed in crusher # 2 is monitored and that this level is used to control the input coming from the Primary Stockpile. The possible variables which remain unchanged during operation are now:

1. Amplitude of vibration of screens
2. Belt speed
3. Crusher settings

It is immediately apparent that if the feed composition fluctuated rapidly and/or the transportation time from Primary Stockpile to secondary crusher were long, spillage could occur.

For example, if the level were to rise rapidly, a signal would be sent to decrease the feed coming from the Primary Stockpile. The stockpile-to-crusher time must then elapse, however, before the change is realized at the crusher. During this time the level may continue to increase to the point of spillage. In general, however, if it is assumed that fluctuations in feed are relatively slow and the stockpile is not far in time from the crusher, there remain other problems which result in sub-optimal performance.

For example, there is no control which maintains a constant level of feed in crusher # 3. Thus, as in the previous system discussed, this crusher must be sufficiently large to absorb surges in feed and avoid the associated problem of spillage. Once again, however, this means that the # 2 crusher is operating below capacity much of the time.

In addition, the fact that the crusher setting remains constant automatically prevents optimal performance in terms of the specified Performance Index which requires maximization of total TPH of product less than a given size. It is obvious from Fig. 12 that, in order to achieve maximum tonnage of the desired product (in this case, less than 1/2") the crusher setting must vary as a function of hardness. As the rock becomes softer an increased crusher setting is desired and the converse is true for harder feed. The principal advantages and disadvantages of this system may now be stated.

Advantages

1. The probability of feed spillage is small.

2(a). Crusher # 2 need not have as much excess capacity. Thus the crusher cost is less.

2(b). If the size of crusher # 2 is the same as in the previous system the output will be increased by

$$\frac{(\text{maximum feed-rate expected} - \text{minimum feed-rate expected})}{\text{average feed rate}} \text{ 100 percent}$$

3. The output of crusher # 2 (and thus that of the whole system) is increased due to the maintenance of constant feed level in crusher # 2.

Disadvantages

1. The system is marginally stable in that the feed level in crusher # 2 may be expected to oscillate due to the transportation lag between control and response.
2. Crusher # 2 and crusher # 3 are still larger than necessary resulting in greater crusher cost.
3. The fixed crusher settings do not allow optimal settings for variations in hardness.
4. All those which exist in the next system discussed.

C. Current Practice in Crushing Control

The method of control presented below was developed for a rock-crushing plant whose product was to undergo no further reduction.[6,7]

6. Patterson, W. R. and D. E. King. "Magnetic Logic Maximizes Crusher Output," Control Engineering, January, 1963, pp. 97-99.

7. "Packaged Crushing Plants-Automated." Allis-Chalmers Manufacturing Co., Technical Sheet No. 17S1266A, October, 1963.

This product was to be used as aggregate for roadbeds, concrete, etc. In a sense then, it is not, strictly speaking, identical to the crushing in a mining operation which prepares rock for further reduction by grinding. Nevertheless, the selected Performance Index (maximizing TPH of a given size) is used in many mining operations.

The analysis of this system is given in considerable detail relative to the previous two systems. This is done to establish a basis of comparison with the system suggested in Chapter IV. A description of the system and the method of control is presented first. The literature does not describe in completeness the philosophy of this method. For this reason, the explanation of the reasoning behind some aspects of this method are presented as this author's interpretation only. Next, the deficiencies of the system are analyzed. It should be noted that the specific problems arising in this system may be related to general control theory. A general problem which is present is that of measuring the wrong states of the system. That is, the wrong information is used to determine the proper control to be exercised. This will become clear in the discussion below. An additional problem is that the system is marginally stable, oscillating about a desired point of operation rather than settling on it.

1. Method of Operation

The plant layout is shown in Fig. 14. Note that the plant is somewhat different from that in Fig. 13 and that it contains a transweigh unit at point A which measures the total tonnage out of

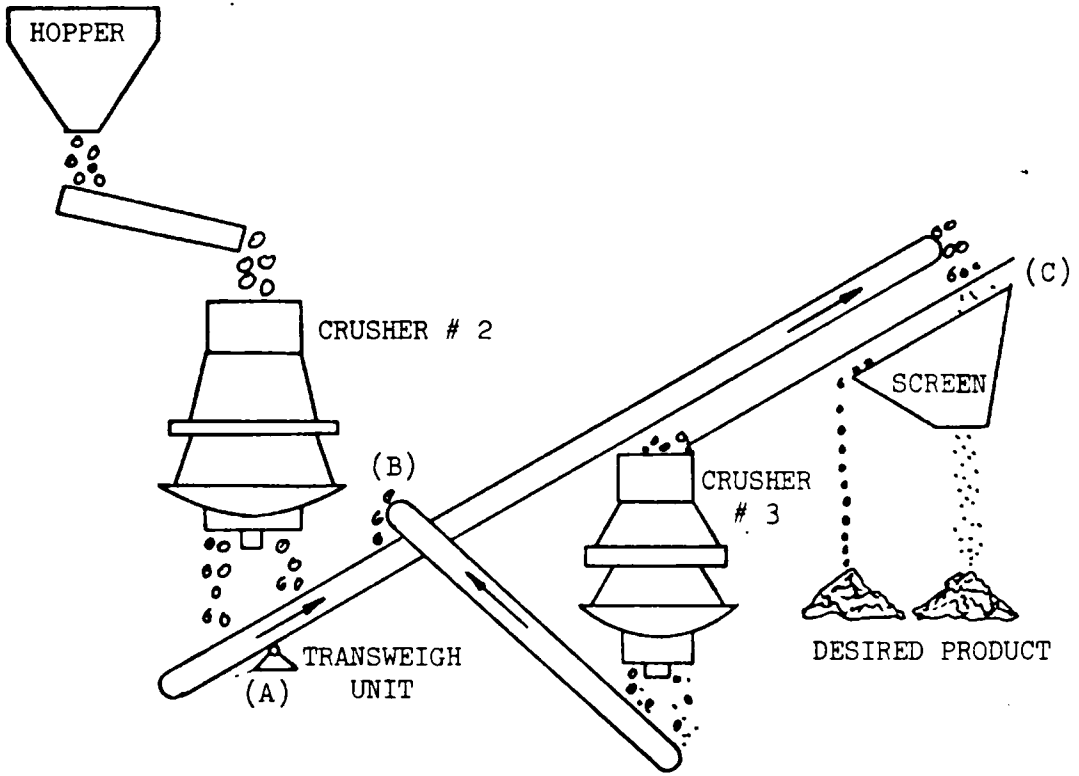


FIG. 14 PLANT CONFIGURATION OF EXISTING CONTROL SYSTEM

crusher # 2. The belt speed remains constant, allowing this measurement to be converted to TPH. Note that this is not TPH of desired product, but rather of the total product from crusher # 2. The product from crusher # 2 is joined by the product from crusher # 3 at point B. This feed then goes to a screen at C where the size, S, is divided into three categories:

1. $S \leq 3/16"$ - a usable undersized product
2. $3/16" \leq S \leq 1/2"$ - the desired product
3. $1/2" \leq S$ - the oversize which must pass through crusher # 3 again.

This system provides a greater degree of flexibility than either of the two systems discussed above in that the crusher settings are adjusted during operation. The possible variables which remain constant are:

1. Amplitude of screen vibration
2. Belt speed.
3. Setting of crusher # 3.

The states of the system which are measured are:

1. Horsepower drain on motors for each crusher
2. TPH output of crusher # 2
3. Level of feed in both crushers
4. Level of feed in hopper above crusher # 1.

Intuitively then, the additional control possibilities as well as the increased information from the state measurements would appear to offer a more optimal solution. Improvements over the previous systems are

made although weakness in control theory is apparent and prevents achievement of the optimal solution.

The system is once again constrained to avoid the spillage of feed. In addition, however, additional constraints are imposed to aid in determining the control to be exercised. These constraints are referred to as "set-points" and they limit the range in which some of the state variables are allowed to vary. These variables and their limits are presented in Table 6.

The purpose of set-points in this system appears to be as follows. Reference is made to Table 6.

Set-points (1) and (2): These are specified as aids in determining feed-rate to crusher # 2 and the setting of crusher # 2. For example, if the Hp/TPH set point is exceeded, the feed-rate is decreased incrementally in an attempt to bring operation back within the desired range. If this is not successful by the time the feed-rate has dropped to the TPH set-point, the feed-rate decreases no more and the setting of crusher # 2 is increased incrementally until operation is once again within the Hp/TPH set-points. Note that first the feed-rate is changed and then the crusher setting.

Similarly, if the TPH drops below the set-point, the feed-rate is increased until the Hp/TPH set-point is reached. Then the crusher opens up once again.

TABLE 6

SET-POINTS USED IN A CURRENT ROCK-CRUSHING OPERATION

(1) HORSEPOWER/TON/HOUR - BOTH UPPER AND LOWER LIMITS ARE SPECIFIED ON THE ALLOWABLE CONSUMPTION OF POWER PER TPH TON PASSING THROUGH CRUSHER # 2.

(2) TONS PER HOUR (TPH) - A LOWER LIMIT IS ESTABLISHED ON THE TOTAL TPH RESULTING FROM CRUSHER # 2.

(3) MAXIMUM HORSEPOWER - AN OPERATING POINT AT WHICH THE MOTOR FOR CRUSHER # 3 IS TO OPERATE IS SPECIFIED. THIS IS GENERALLY THE HORSEPOWER RATING OF THE MOTOR.

(4) CRUSHER SETTING - BOTH UPPER AND LOWER LIMITS ESTABLISH THE RANGE IN WHICH THE SETTING OF CRUSHER # 2 MAY VARY.

(5) FEED LEVEL - AN UPPER LIMIT IS SPECIFIED ON THE LEVEL OF FEED IN BOTH CRUSHERS.

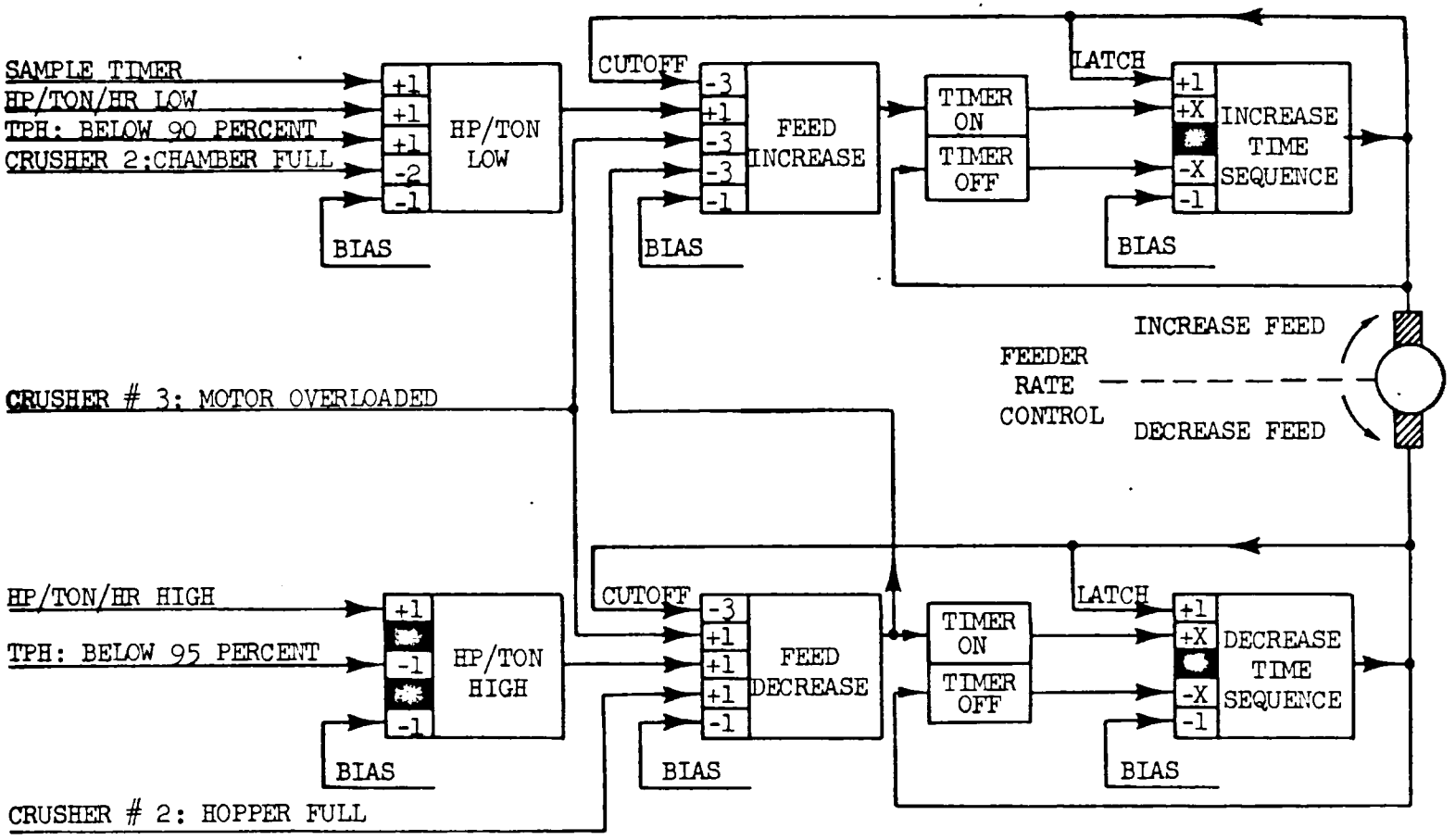
Set-point (3): This seems to insure maximum motor efficiency without overloading, as well as maximum power put into crushing. Although this is true, it is shown that the setting of the # 3 crusher plays an important role in achieving the desired Performance Index and that (3) is not necessarily a valid criteria.

Set-point (4): The maximum setting of crusher # 2 must not exceed the maximum size particle # 3 can accept. The minimum setting of both crushers must be such as to prevent contact of surfaces.

Set-point (5): This is obviously necessary to prevent spillage of feed.

For a two-crusher system such as shown in Fig. 14, three elements are controlled.

1. Setting of crusher # 3: This is adjusted at the start of operation so that crusher # 3 draws maximum allowable horsepower. Once operating, however, this setting remains fixed.
2. Control of feed-rate to crusher # 2: Fig. 15 shows the logic circuit which is used to control the rate of feed to crusher # 2. In words, the factors indicated below cause the system to change the feed-rate as shown.



NOTE: THE BLOCKS REPRESENT MAGNETIC AMPLIFIERS WHICH ARE OFF IF THE NET CONTROL SIGNAL IS NEGATIVE OR ON IF THE NET CONTROL SIGNAL IS ZERO OR POSITIVE. THE OUTPUT DRIVES A SMALL DC MOTOR WHICH VARIES THE FEED RATE OR SIZE SETTING.

FIG. 15 LOGIC DIAGRAM FOR FEED RATE CONTROL

Command to decrease feed-rate

(a) Crusher # 3: motor overloaded

(b) Crusher # 2: hopper full

(c) Hp/ton/hr consumption of crusher # 2 exceeds set-point and TPH out of # 2 above minimum established by set-point (here, 95% rated capacity).

Command to increase feed-rate

*(a) Crusher # 2: Chamber not full - TPH out of # 2 below set-point (here, TPH 90% rated capacity)

*(b) Crusher # 2: Chamber not full - Hp/ton/hr consumption of crusher # 2 below established set-point.

(c) Crusher # 2: Chamber not full - A sample timer which goes on every 12 minutes is on.

(d) Crusher # 2: Chamber full - Sample timer on and Hp/ton/hr consumption of # 2 below set-point and TPH of # 2 below 90% of rated capacity.

*Note that (a) and (b) constantly monitor the need for increased feed whereas (c) and (d) may increase feed only at intervals of twelve minutes.

3. Setting of # 2 crusher: This crusher setting is varied during operation to maintain the # 3 crusher

(which is operating at a fixed setting) at maximum allowable power. If this power decreases, the # 2 crusher setting is increased allowing more and larger feed to go to crusher # 3. The converse is true for excessive power drain by crusher # 3.

As seen above in the discussion of the set-points given in Table 6, however, there is another criteria which controls the setting of crusher # 2. This occurs when the control of feed-rate to crusher # 2 cannot establish or maintain operation within the desired set-points. In such a case, the setting of crusher # 2 must then be adjusted to achieve operation within the allowable set-points.

Note that these controls on the setting of crusher # 2 are essentially independent. In fact, it is quite likely that they be conflicting. Consider, for example, the situation below which occurs when hard feed in introduced into the system. This results in a hp/TPH for crusher # 2 above the set-point. The feed-rate is decreased to the TPH-set-point in an attempt to bring hp/TPH back within the desired region of operation. At this point the setting of crusher # 2 would be increased until hp/TPH is acceptable. If crusher # 3 is operating at its rated horsepower, the harder feed will cause the

set-point on the horsepower of crusher # 3 to be exceeded, thus calling for a decrease in the setting of crusher # 2!

Such a situation is not discussed in the literature, although a similar one is presented.[8] This situation supposedly occurs when the power draft on crusher # 3 is below peak hp and if hp/TPH of crusher # 2 is too high because set-point is below normal operating conditions. The control is to increase the setting of crusher # 2 thus increasing tonnage and product going to crusher # 3. A low power draft on crusher # 3 could occur when soft feed is introduced into the system. Such a case would result in a low hp/TPH, however, which would call for a decrease in the setting of crusher # 2. No explanation is given to show how the stated situation could physically occur.

Due to this seeming inconsistency, the analysis presented below considers the cases separately. The first case maintains peak power on crusher # 3. The second case maintains operation within the desired set-points on crusher # 2.

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8. "Packaged Crushing Plants-Automated." Allis-Chalmers Manufacturing Co., Technical Sheet No. 17S1266A, October, 1963, p. 3.

2. Analysis of System Operation

Recall that the Performance Index to be maximized is the total TPH of desired product (-1/2"). Note also that the major portion of this product is a result of the work done by crusher # 3.

a. Consider the operation of crusher # 3 which has a fixed setting but which operates constantly at peak horsepower. It has already been shown for the previous system that operation at a constant crusher setting does not necessarily maximize output. In fact, the data for each of the curves in Fig. 10, 11, and 12 are for a relatively constant horsepower drain on the crusher motor. Consider, for example, Table 7 which shows the data used for feed that is average in hardness. The corresponding curve shown in Fig. 12 makes it evident that for a given horsepower drain on the motor (it is assumed that horsepower is more a function of hardness than crusher setting), the actual product of desired size may vary significantly.

For example, the same horsepower may produce 308 TPH of desired product (-1/2") at a 5/16" setting and only 276 TPH at a 7/16" setting. The reason for this is easily explained. At small crusher settings much of the work done is in over-reduction; i.e., the production of fines considerably smaller than the maximum desired size. At large crusher settings the crusher handles a larger volume of material and the energy input is spread "thinner" resulting in less product reduced to the desired size.

Thus, although it appears logical that having maximum power input would maximize the output, this is clearly not the case.

TABLE 7

TYPICAL CAPACITY OF CRUSHER # 3 (CLOSED-CIRCUIT OPERATION)

FOR VARIOUS CRUSHER SETTINGS AT RATED HORSEPOWER

CRUSHER SETTING	THROUGHPUT (TPH)
1/4"	306
5/16"	308
3/8"	295
7/16"	277
1/2"	253
5/8"	230
3/4"	203
7/8"	189
1"	171

This is a good example of misuse of state information. A better measurement would be that of total output.

b. If the setting of crusher # 2 is adjusted in correspondence with the horsepower drawn by crusher # 3, the following stability problem arises due to the transportation lag problem which results. This lag is the time which must lapse between the change of setting of crusher # 2 and the arrival of feed affected by this change at crusher # 3. If the crusher # 2 setting is decreased in increments, the time between these increments is critical. If each successive change awaits the results of the previous one at crusher # 3, the system will constantly lag the change in feed. If the changes occur more frequently the system will overcorrect, the magnitude of overcorrection increasing with the frequency of correction. In both cases crusher # 3 cannot be operating optimally at all times. This illustrates the transportation lag problem typical of all crushing systems. The system is unstable because there may be sufficient feed on the belts going to crusher # 3 to overload. In any case, the system is no better than marginally stable because the feed level may be expected to constantly fluctuate due to the transportation lag. Marginal stability is bad because it prevents the system from operating on a constraint boundary, that of maintaining choke feed in crusher # 3.

c. The following statement is made in the literature: "Maximum tonnage to the screen and a maximum power draft on crusher # 2 (# 3 in this case) are the conditions for maximum production."[9]

9. "Packaged Crushing Plants-Automated." Allis-Chalmers Manufacturing Co., Technical Sheet No. 17S1266A, October, 1963, p. 3.

It has been shown in 2-a above that the second part of this statement is not necessarily true. The first part of the statement must be interpreted to mean maximum tonnage out of crusher # 2 since the system provides no way of measuring the maximum tonnage to the screen (see Fig. 14). This, in turn, must mean the TPH out of crusher # 2 which exceeds the set-point.

Consider Fig. 16 which shows the total TPH out of crusher # 2 vs. the TPH that will not pass through a 1/2" screen and actually reaches crusher # 3. Indicated on this figure are various settings for crusher # 2. If, for example, the minimum allowable TPH out of crusher # 2 is 375 TPH, the following may be noted. Assume the crusher has a 1 3/4" setting. For average feed this results in 295 TPH arriving at crusher # 3. If the feed becomes hard, the output of crusher # 2 drops to 370 TPH, but results in 300 TPH arriving at crusher # 3 which will greatly exceed the capacity of crusher # 3. Nevertheless, the TPH out of crusher # 2 is below the set-point and therefore the setting of crusher # 2 would be increased, thus compounding the problem!!

The above is another example of measurement of the wrong state. A better measurement would be of that portion of the output of crusher # 2 that actually arrives at crusher # 3.

d. Consider now the control of the setting of crusher # 2 which maintains operation within the set-points. The situation already discussed in detail serves to illustrate the difficulty here. It has been shown in 2-c that the introduction of hard feed into the system

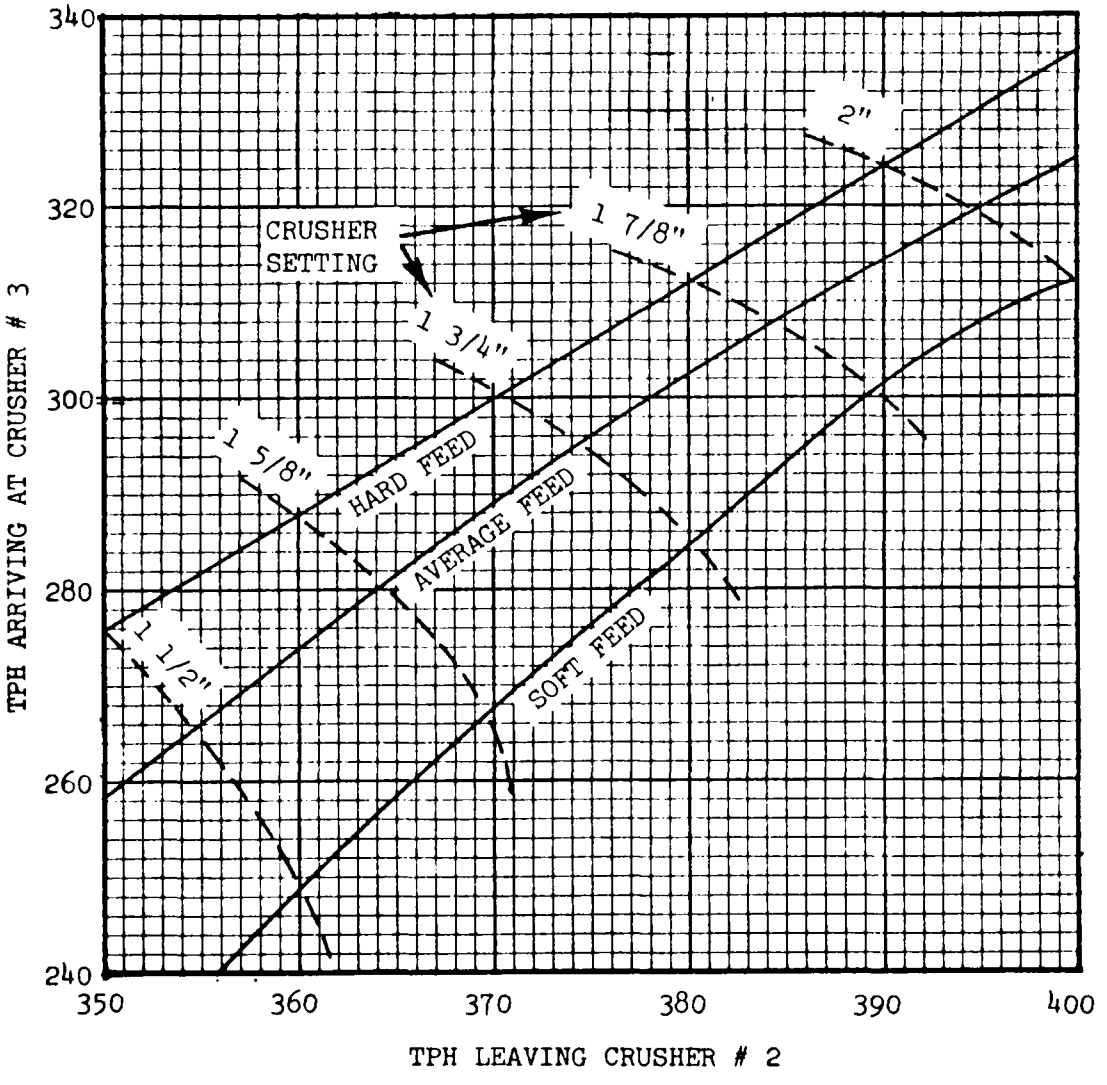


FIG. 16 TPH ARRIVING AT CRUSHER # 3 AS A FUNCTION OF TPH LEAVING CRUSHER # 2

may eventually result in an increase of the setting of crusher # 2. Since the setting of crusher # 3 is fixed, however, its capacity decreases for harder feed. Thus it is more desirable that the setting of crusher # 2 initially decrease for harder feed, the exact opposite of the actual control presently used. Once the hard feed reaches crusher # 3 it will force crusher # 2 to decrease its setting to avoid spillage, but the transportation lag problems are introduced.

It is not surprising that the above problem results. Consider the set-points which are used to determine the setting of crusher # 2. It has been shown in 2-c above that total TPH out of crusher # 2 is not a good criterion. In addition, a hp/TPH criterion is somewhat artificial in that it is only an estimate of what the rock-crushing efficiency should be and is even less powerful than operating at peak horsepower. The results of this system may now be summarized.

Advantages

1. The system should operate without spilling feed. (The belts stop if there is danger of spillage!)
2. The crushers need no longer have excess capacity. Thus the crusher cost is reduced.
3. The output of both crushers is increased due to the maintenance of a more constant feed level in the crushers.
4. The total output should be increased due to the fact that crusher # 2 may be adjusted to send

smaller feed to crusher # 3 when the feed is harder rather than decreasing the feed-rate to crusher # 2.

Disadvantages

1. The fixed setting of crusher # 3 removes all possibility of operating optimally for variations in hardness. See Fig. 12.
2. Transportation lag results in feed level in crusher # 3 not being at capacity. Therefore, the system is marginally stable, preventing crusher # 3 from operating on the constraint boundary of choke-feed.
3. Transportation lag results in less-than-optimum size feed* arriving at crusher # 3.
4. Use of TPH and hp/TPH set-points may result in opposite control from that desired, creating time lag problems.

In Chapter IV it is shown that, for a feed of given hardness, there is an "optimum size" feed which should arrive at crusher # 3. This is a size for which the crusher # 3 setting may be adjusted to achieve a true maximum output. At the same time, the feed-rate to crusher # 3 must maintain a constant feed level. Thus a smaller feed to crusher # 3 will be crushed faster, but the feed level will drop. A larger feed would exceed the feed level and be crushed more slowly.

*The importance of the size feed resulting from crusher # 2 is detailed in Chapter IV.

It is interesting to note that the oscillations in the setting of crusher # 2 are interpreted in the literature to be a constant "search" for the optimum setting. As explained above, however, these "oscillations" are a consequence of compensation for incorrect control methods.

In conclusion, the following observations may be made about this final system.

1. Incorrect state measurements were made; for example, that of the total TPH out of crusher # 2).
2. Incorrect assumptions were made from the states measured (e.g. that peak horsepower operation assured maximum output).
3. More control could be exercised by controlling the setting of crusher # 3.
4. The use of set-points introduced some new constraints. These have been shown to be artificial ones that are in conflict with physical reality.

The following chapter now develops a control system which is felt to profit from the above analysis and incorporate some techniques which lead to an optimal solution.

CHAPTER IV

SYNTHESIS OF OPTIMAL CRUSHING CONTROL SYSTEM

Control procedures are developed in this section which are thought to maximize the Performance Index discussed in this paper, that being the TPH of desired product of a given size. It is shown by example that there is a unique combination of crusher settings which achieve this for each hardness of feed. An interesting result of this examination is the fact that there are many combinations of crusher settings which maintain all crushers at choke-feed. This is not, therefore, a sufficient criterion for optimal performance.

The two basic goals of optimal crushing operation are: (1) The proper crusher setting for both crushers, and (2) The maintenance of choke feed in both crushers.

A. Demonstration that Optimal Crusher Settings are Unique

Prior to discussing the overall control system, the following fact should be established.

> Fact: For a feed of given hardness there is a unique combination of crusher settings in a two crusher system that maximizes the TPH of product of a specified size.

To demonstrate this fact, consider the crushing system shown in Fig. 13. The crushing characteristics of crusher # 2, which is in open-circuit operation, are given in Table 8 and shown graphically in

TABLE 8

PRODUCT CHARACTERISTICS OF CRUSHER # 2

CRUSHER SETTING	RATED CAPACITY (TPH)			PERCENT ≤ 1/2"			TPH ≤ 1/2"			TPH ≥ 1/2"		
	SOFT	AVE	HARD	SOFT	AVE	HARD	SOFT	AVE	HARD	SOFT	AVE	HARD
3/4"	300	295	290	60	50	43	180	147	125	120	148	165
7/8"	310	305	300	52	43	37	161	131	111	139	174	189
1"	320	315	310	46	38	32	147	120	99	173	195	211
1 1/8"	330	305	320	42	35	28	139	114	90	191	211	230
1 1/4"	340	335	330	38	31	25	129	104	82	211	231	248
1 3/8"	350	345	340	34	28	23	119	96	78	231	249	262
1 1/2"	360	355	350	31	25	21	111	89	74	249	266	276
1 5/8"	370	365	360	28	23	20	104	84	72	266	281	288
1 3/4"	320	375	370	25	21	19	95	79	70	285	296	300
1 7/8"	390	385	380	23	20	18	90	77	68	300	308	312
2"	400	395	390	22	19	17	88	75	66	312	320	324

Fig. 17, 18 and 19. The characteristics of crusher # 3 are given in Table 9 and shown in Fig. 20. It should be understood that the ratings of crusher # 3 actually vary as a function of the size of feed as well as hardness and that the figures given are for feed resulting from the "average" setting of crusher # 2. The ratings of crusher # 2 need not consider the size of its input, however, since it may be assumed that feed of a given hardness always has the same size distribution due to the constant setting of the Primary Crusher (crusher # 1).

The logical argument for demonstration of the fact stated above now goes along the following lines. Assume some "optimum" point of operation is achieved which means that crusher # 3 is operating at a maxima of one of the curves in Fig. 20 and both crushers are choke-fed. The possible alternatives are now as follows.

1. Crusher # 2 unchanged
    a. Increase setting of crusher # 3 - this action decreases the capacity of # 3 and thus # 2 must decrease setting to avoid spillage.
    b. Decrease setting of crusher # 3 - this action decreases the capacity of # 3 and thus # 2 must decrease setting to avoid spillage.
2. Crusher # 2 decreases setting - The TPH of original feed must be decreased, resulting in decreased output.
3. Crusher # 2 increases setting - Less -1/2" product results from crusher # 2 (see Fig. 18). Less product

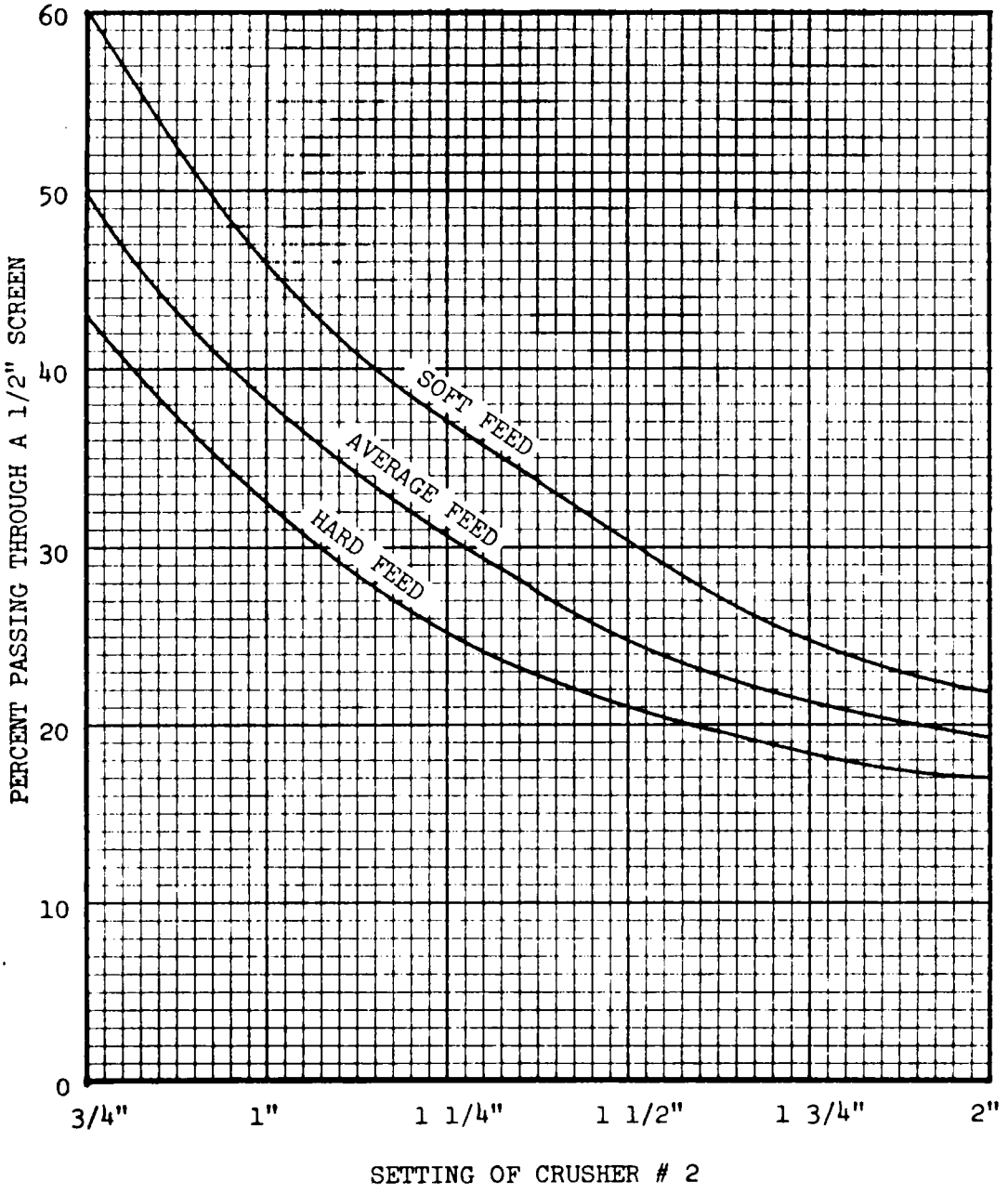


FIG. 17 PRODUCT DISTRIBUTION AS A FUNCTION OF HARDNESS AND THE SETTING OF CRUSHER # 2

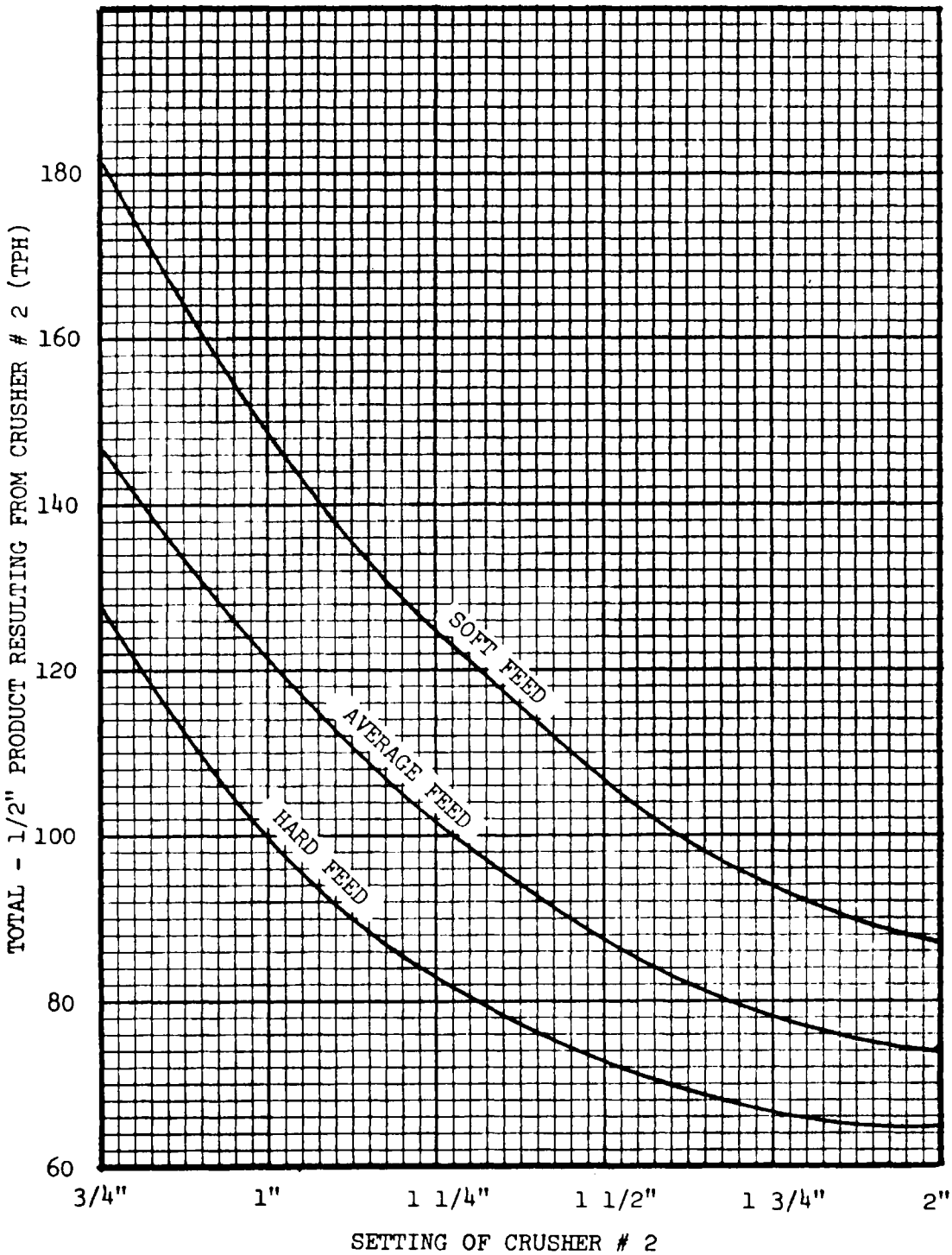


FIG. 18 TPH OF - 1/2" PRODUCT RESULTING FROM CRUSHER # 2 (CHOKE-FED, OPEN-CIRCUIT OPERATION)

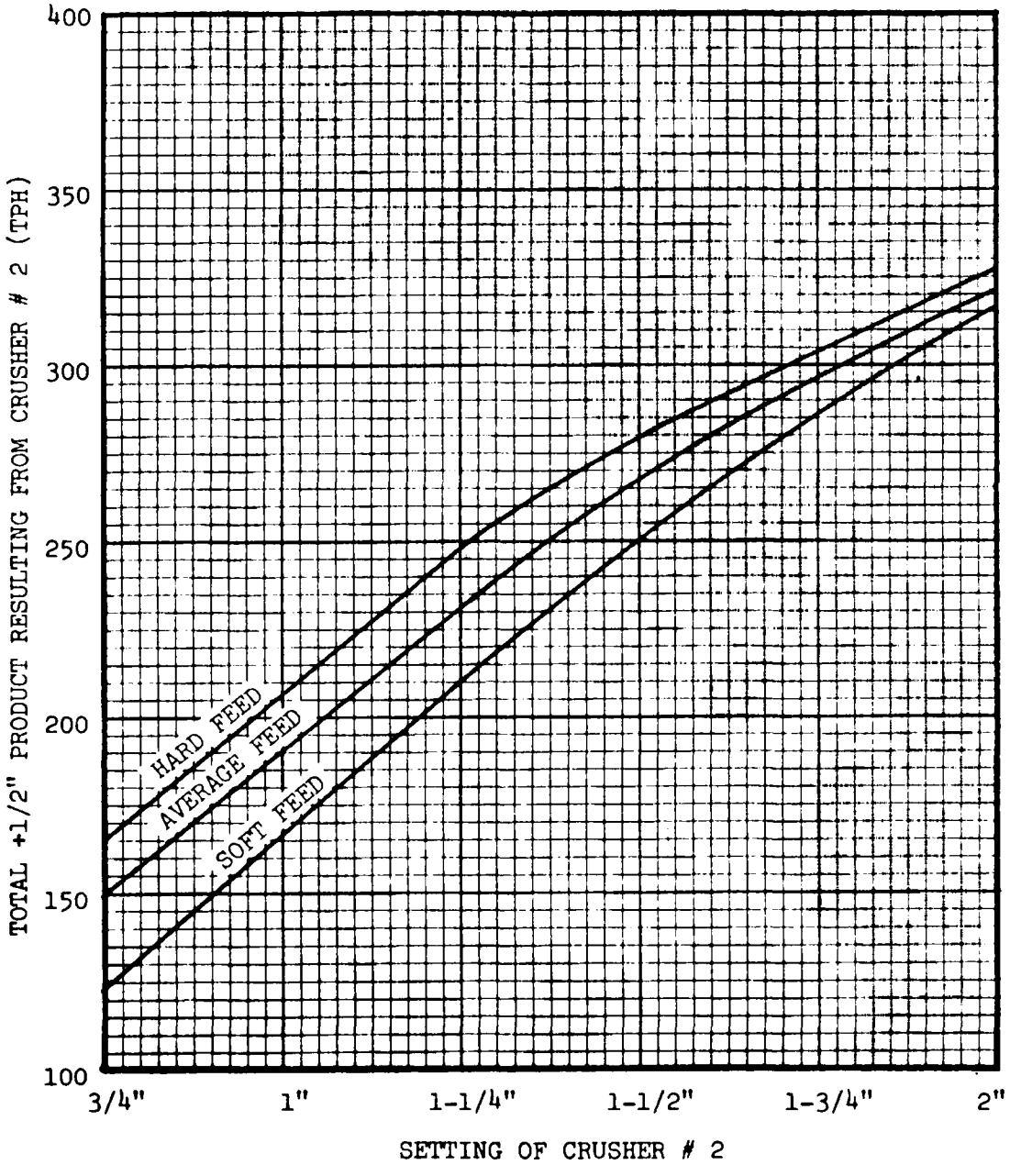


FIG. 19 TPH OF + 1/2" PRODUCT RESULTING FROM CRUSHER # 2 (CHOKE-FED, OPEN-CIRCUIT OPERATION)

TABLE 9

PRODUCT CHARACTERISTICS OF CRUSHER # 3

CRUSHER SETTING	RATED OPEN-CIRCUIT CAPACITY (TPH)			PERCENT OPEN-CIRCUIT ≤ 1/2"			PERCENT CIRCULATING LOAD			CLOSED-CIRCUIT CAPACITY (TPH ≤ 1/2")		
	SOFT	AVE	HARD	SOFT	AVE	HARD	SOFT	AVE	HARD	SOFT	AVE	HARD
1/8"	298	290	282	100	100	100	0	0	0	298	290	282
3/16"	306	298	290	100	100	100	0	0	0	306	298	290
1/4"	314	306	298	100	100	98	0	0	0	314	306	292
5/16"	322	314	306	100	98	90	0	2	11.2	322	308	280
3/8"	330	322	314	98	90	80	2	11.2	25	324	295	254
7/16"	338	330	322	92	84	73	8	19	35	315	277	238
1/2"	346	338	330	85	75	65	18	33.4	54	294	253	214
5/8"	362	354	346	74	65	55	34	53.9	82	270	230	190
3/4"	378	370	362	65	55	47	54	81.8	114	246	203	169
7/8"	394	386	378	56	49	41	80	105	145	219	189	154
1"	410	402	394	50	43	36	100	135	206	205	171	129

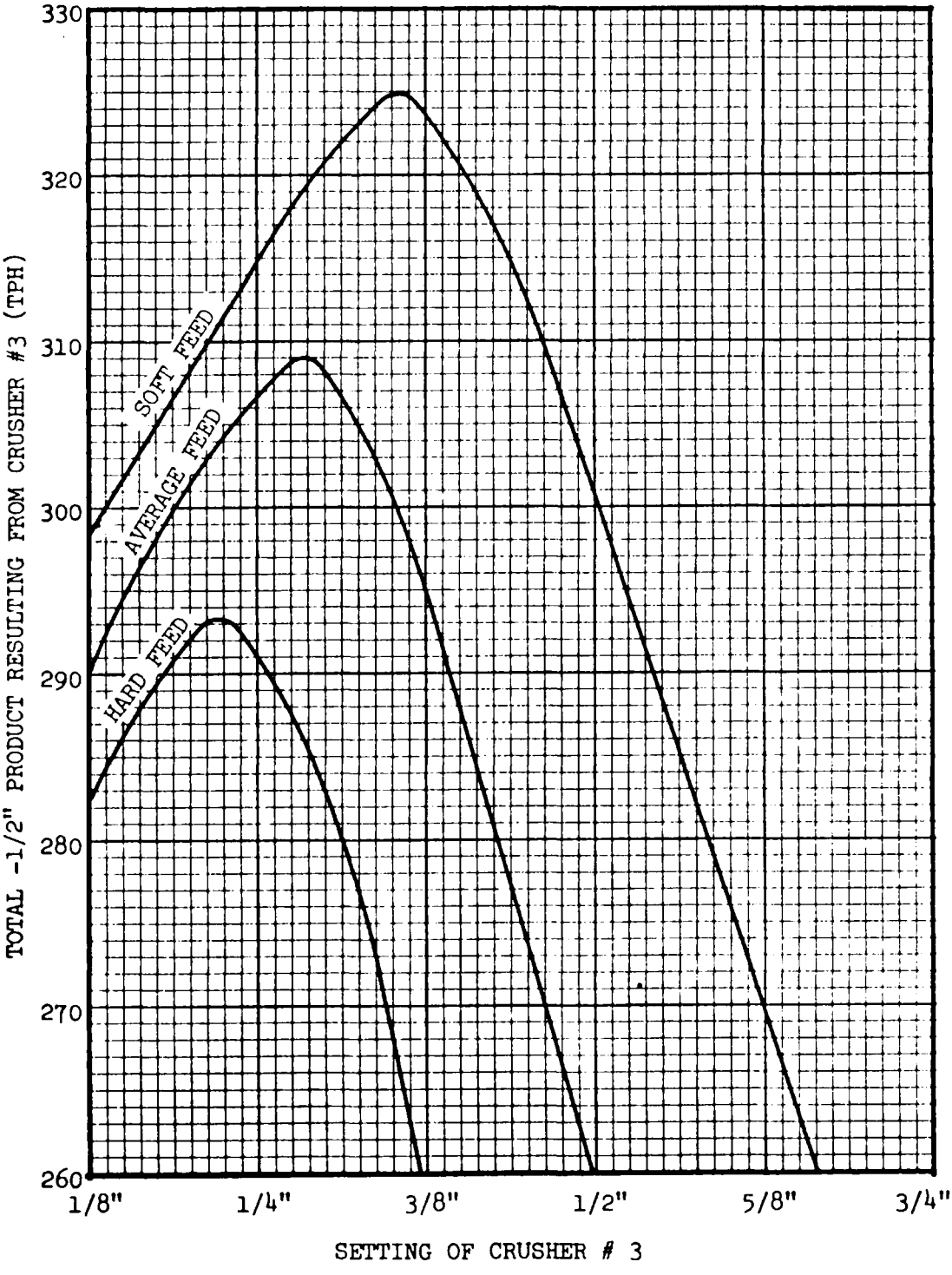


FIG. 20 TPH OF - 1/2" PRODUCT RESULTING FROM CRUSHER # 3
(CHOKE-FED, CLOSED-CIRCUIT OPERATION)

results from crusher # 3 since it must take longer to crush larger feed.

Thus it has been shown by exhaustion (of all possible changes) that there is a unique combination of crusher settings which maximize the TPH of product of a specified size.

If the desired product size is -1/2" then the optimal setting of crusher # 3 would be 9/16" for average feed. The optimal setting of crusher # 2 would be that which maintains choke feed in crusher # 3 or, in this case, supplying crusher # 3 with 308 TPH of feed. From Fig. 19 this is seen to be 1 7/8". It should be noted at this point that the primary role of crusher # 2 is to maintain crusher # 3 at choke-feed with the smallest feed possible. As may be seen from Fig. 18, variations in the setting of crusher # 2 do not change the TPH of -1/2" product from crusher # 2 significantly, neither does the size distribution of the output of crusher # 2 change greatly.

A corollary to the fact demonstrated above is that both crushers may be operating at choke-feed yet not have optimal operation. This may easily be demonstrated by the combinations shown in Table 10 which use the information in Tables 8 and 9 and which maintain both crushers at choke feed.

Note that the 1/2" setting of crusher # 3 corresponds to an output which is 38 TPH below or 10 percent less than that which is possible, even though both crushers are choke-fed! Thus, choke-feed may be considered a necessary, but not sufficient condition for optimal operation.

TABLE 10

VARIATION IN TOTAL DESIRED PRODUCT TONNAGE

AS A FUNCTION OF CRUSHER SETTINGS: BOTH CRUSHERS CHOKE-FED

SETTING OF CRUSHER # 3	CAPACITY OF CRUSHER # 3 (EQUALS TPH $\geq$ 1/2" OUT OF # 2)	SETTING OF CRUSHER # 2	CRUSHER # 2 TPH $\leq$ 1/2"	TOTAL DESIRED PRODUCT (TPH $\leq$ 1/2")
1/4"	306	1 55/64"	78	384
5/16"	308	1 7/8"	77	385
3/8"	295	1 47/64"	80	375
7/16"	277	1 9/16"	88	365
1/2"	253	1 7/16"	94	347

Systems which are unable to maintain choke-feed in both crushers may be expected to be even farther removed from optimal operation.

B. The Ideal Optimal Control System

The two basic goals to be achieved in an optimal crushing control system are: (1) The maintenance of choke feed in both crushers, and (2) The achievement of proper crusher settings for each hardness as the feed varies.

One of the principal causes of both difficulties is the transportation lag from the time feed leaves crusher # 2 until it arrives at the chamber of crusher # 3. For example, the setting of crusher # 2 should be that which keeps crusher # 3 choke-fed. If the feed hardness changes, however, crusher # 2 does not normally compensate until the effect of this change is realized at crusher # 3.

The ideal solution to this problem would be to position crusher # 2 directly above and to the side (to allow screening) of crusher # 3 as shown in Fig. 21. This has the obvious benefit of eliminating any significant time delay and can easily maintain choke feed in crusher # 3. The positioning of a small surge hopper directly above crusher # 2 provides the capability of maintaining crusher # 2 choke-fed when fluctuations in the feed-rate from the Primary Stockpile may occur or the demand from crusher # 3 may vary. Thus the first problem mentioned above may be resolved by the proper positioning of equipment.

The optimal setting of the crushers may be achieved by realizing the following facts. First, the function of crusher # 2 is

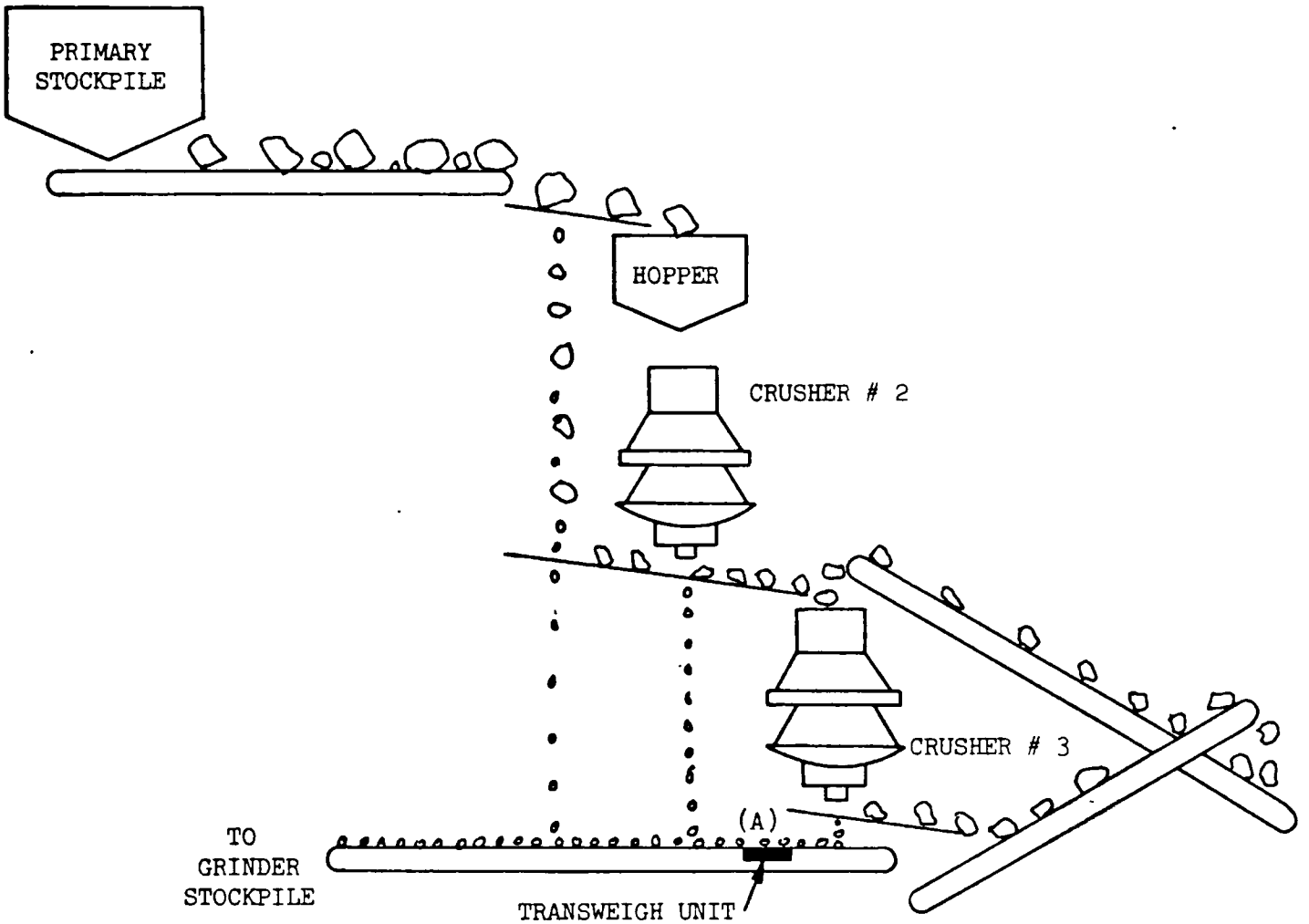


FIG. 21 OPTIMAL PLANT CONFIGURATION

primarily that of feeding crusher # 3, and not of contributing significantly to the output. The second fact may not appear obvious, but it is important that it be understood. If crusher # 2 is at the wrong setting for a feed of some hardness and if crusher # 3 is adjusted to maximize the output of a given size, crusher # 2 will be then forced to re-adjust in the direction of the optimal setting simply by the requirement that crusher # 2 be choke-fed.

Since the change in feed structure may be expected to vary continuously, yet not significantly over a short period of time, the optimal crusher settings may now be easily achieved. The optimal crushing plant is shown in Fig. 21 and operates as described below.

1. Control of setting of crusher # 3

The setting of crusher # 3 is varied automatically at increments of T seconds. The interval T must be sufficiently small that no large changes in feed hardness may occur during T thus avoiding the danger of instability. This may be determined empirically.

The desired output at (A) is weighed shortly after each such change in the crusher setting, also at intervals of T seconds. This time delay must be sufficiently long to allow the effect of the crusher setting change to affect the output. Nevertheless, it should be short to avoid the problem of instability. This would normally be not much longer than the time required for the feed to go from the crusher output to (A).

The value of this output is compared with the previous value. If the output has increased or remained the same, the crusher setting is changed an additional increment in the same direction. If the output has decreased, the opposite control is exercised, returning the system to its previous state, starting incremental changes in the opposite direction.

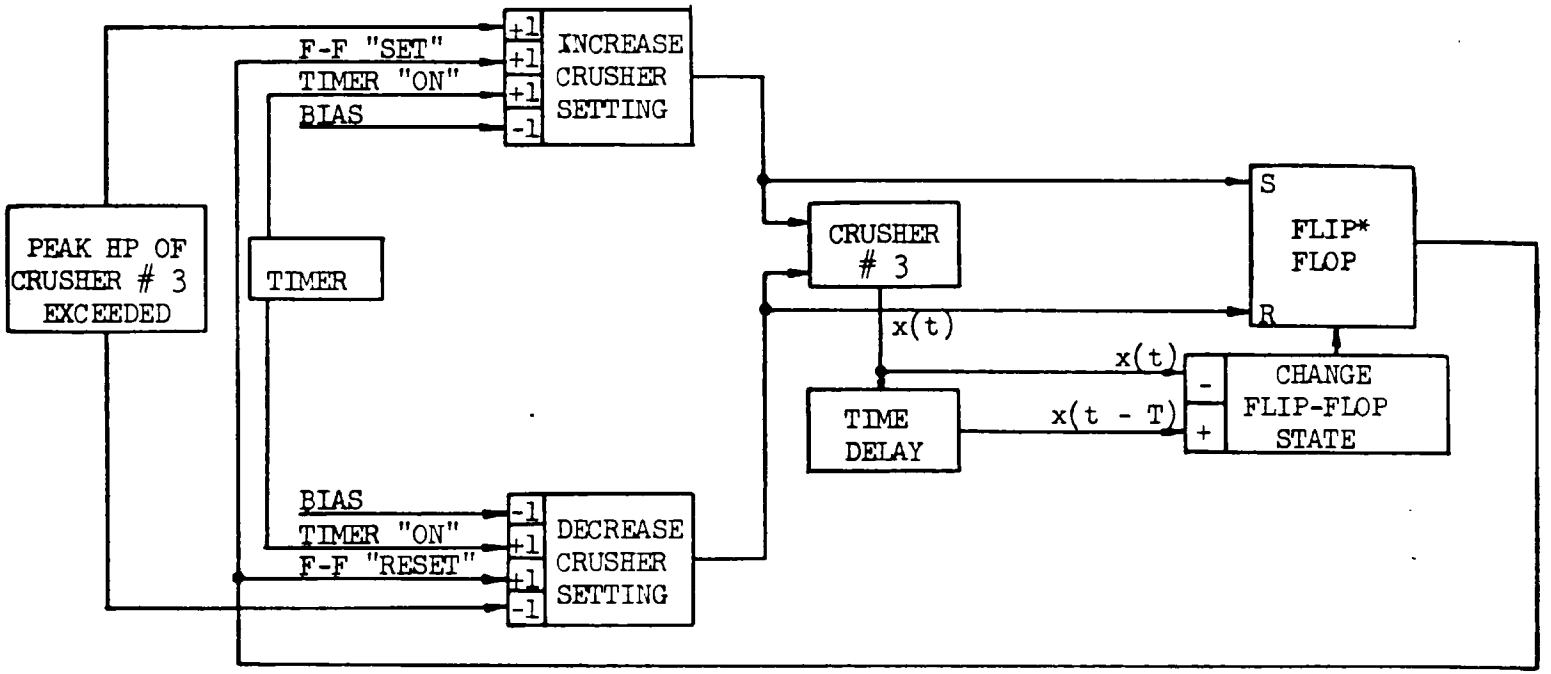
To avoid excessive power drain on the motor of crusher # 3, the above sequence of control applies only until peak horsepower is exceeded. At this point, an over-ride control controls the crusher setting until peak horsepower is no longer exceeded. The logic circuit for the control of crusher # 3 is shown in Fig. 22.

2. Control of setting of crusher # 2

The setting of crusher # 2 is varied to maintain crusher # 3 choke-fed. The level of feed in crusher # 3 is monitored constantly, and as this level drops, the setting of crusher # 2 is increased to allow more feed to flow. The converse is true when the feed level rises.

3. Control of feeder-trays of hopper above crusher # 2

The amplitude of vibration of the feeder-trays is increased as the feed level in crusher # 2 drops and the converse is true when the feed level rises. When the feed level exceeds a certain level the trays are stopped. When the peak horsepower of crusher # 2 is exceeded, the trays are stopped.



NOTE: EACH OF THE THREE SUMMING AMPLIFIERS ABOVE IS "ON" IF THE SUM OF THE INPUTS IS POSITIVE.
$x(t)$ = THE TPH MEASUREMENT OF THE DESIRED PRODUCT
*THE "SET" OR "RESET" INPUTS ARRIVE BEFORE THE "CHANGE FLIP-FLOP STATE" PULSE ARRIVES

FIG. 22 LOGIC DIAGRAM FOR CONTROL OF CRUSHER # 3

4. Control of feeder-trays from Primary Stockpile

The amplitude of vibration of the feeder-trays is controlled by the feed level in the hopper above crusher # 2. The hopper should be large enough to absorb any surges in feed. When the level in the hopper exceeds a certain point the feeder-trays are stopped. This point is to be far enough below the top to absorb the remaining feed in the belt.

Note that this system maintains both crushers at choke feed. In addition, the constant search by crusher # 3 assures the optimal setting for that crusher which, in turn, forces the optimal setting of crusher # 2 as discussed above.

A final point, and one which is not discussed in detail above, is the fact that the system does not contain any inner loops. A block diagram of the system is shown in Fig. 23. The fact that each element in the process is controlled by the immediately following element reduces the transportation lag problem until it is essentially non-existent. This means that the resulting system is stable.

C. Optimal Approach to Existing Systems

In many existing systems, the plant is fixed and the repositioning of machinery is uneconomical. Such a system is shown in Fig. 24. Within the limitations of this configuration, an optimal control approach is presented below. Note that a hopper is positioned above crusher # 3.

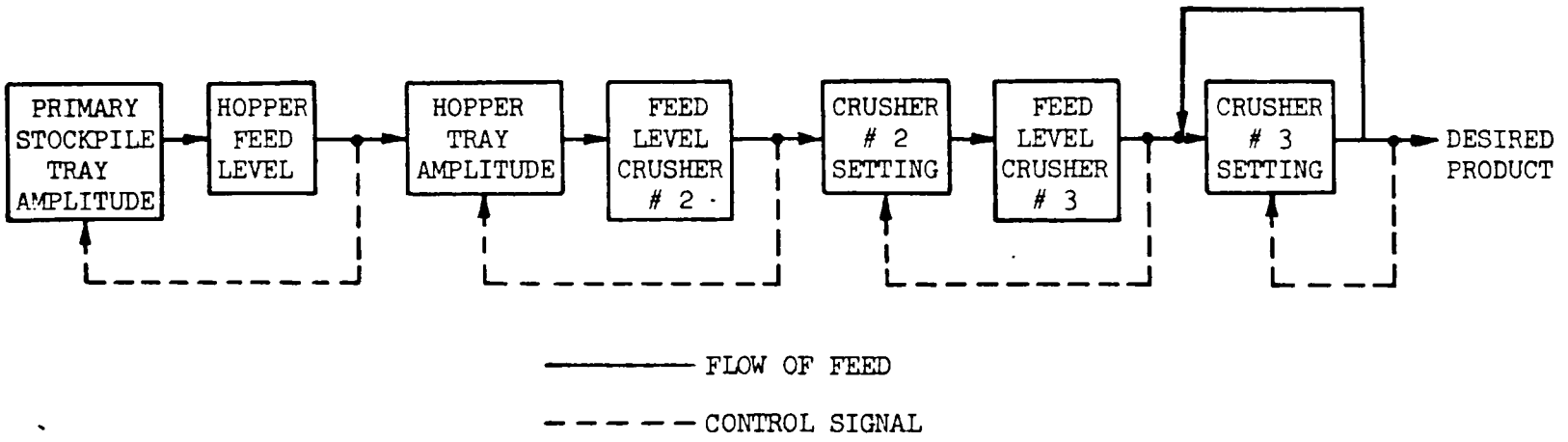


FIG. 23 BLOCK DIAGRAM OF IDEAL CRUSHING CONTROL SYSTEM

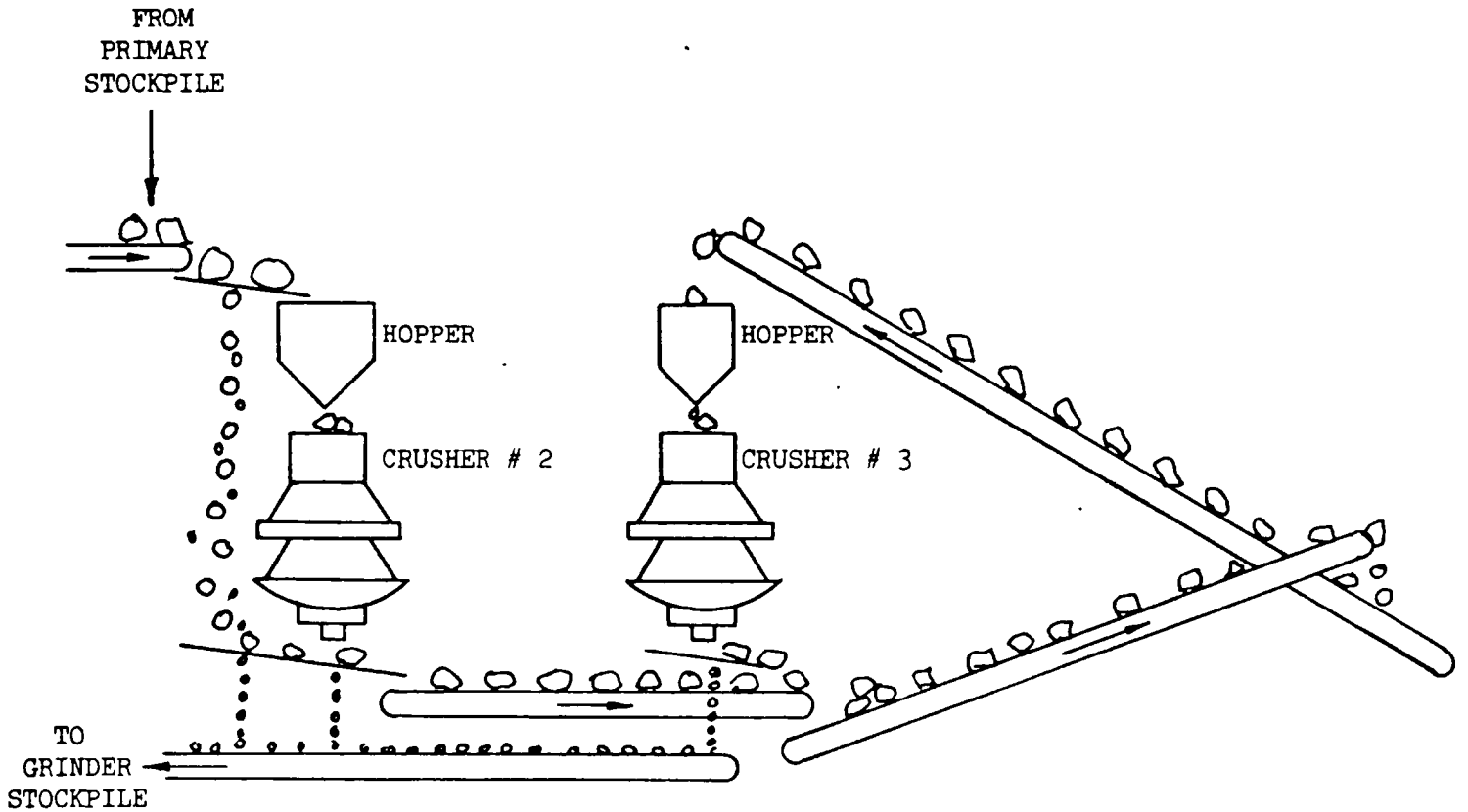


FIG. 24 ADAPTATION OF EXISTING PLANT TO OPTIMAL TECHNIQUES

1. Control of crusher # 3

This is the same as in the previous system.

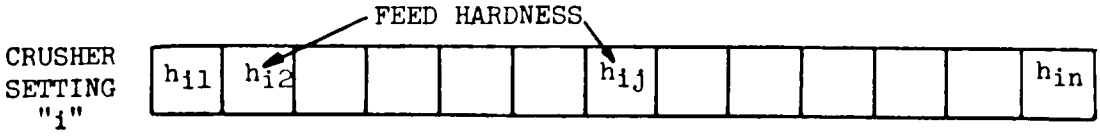
2. Control of feeder-trays above crushers # 2 and # 3

These are controlled by the level in the crushers fed by these trays as in the ideal case above.

3. Control of setting of crusher # 2

The setting of crusher # 2 is varied automatically as a function of the hardness of feed. This function may be determined as explained below.

A possible method of determining feed hardness is the following. Assume that the crusher setting is calibrated in some manner such that the operator may know at all times the value of the setting at which the crusher is operating. For a given setting of crusher # 2, then, the measurement of the TPH out of crusher # 2 that goes to crusher # 3 is a measure of feed hardness. This information may be determined empirically and tabulated as in Fig. 25(a). It is assumed of course, that crusher # 2 is choke-fed. Similar data may then be compiled for different crusher settings. The total information may then be stored in a matrix H, (Fig. 25 (b)) where the h_{ij} elements correspond to feed hardness for a crusher setting i and TPH j. Thus during operation, the crusher setting and TPH may be sampled at intervals of T seconds. These values are inputs to the matrix and the output is the feed hardness. This information is then fed into an array which has pre-stored the optimal settings for crusher # 2 for each possible value of feed hardness as shown in Fig. 25 (c).



THE SECOND SUBSCRIPT CORRESPONDS TO TPH GOING TO CRUSHER # 3

FIG. 25(A) DETERMINATION OF FEED HARNESS FOR A FIXED CRUSHER SETTING

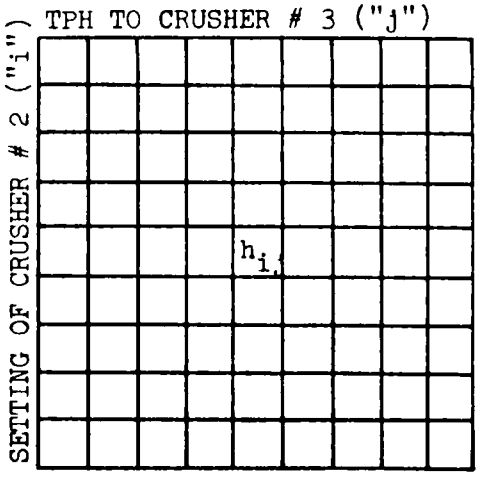


FIG. 25(B) MATRIX FOR FEED HARDNESS AS A FUNCTION OF SETTING OF CRUSHER # 2 AND TPH OF OVERSIZE GOING TO CRUSHER # 3

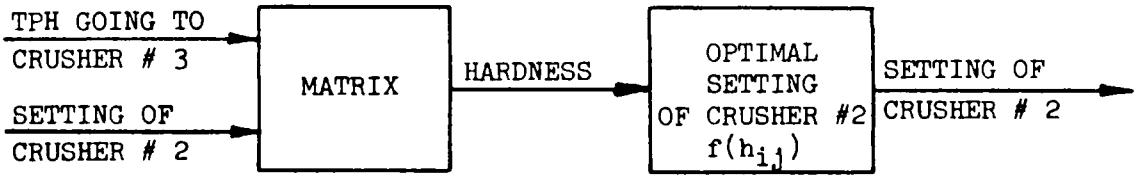


FIG. 25(C) BLOCK DIAGRAM FOR DETERMINATION OF OPTIMAL SETTING OF CRUSHER # 2

FIG. 25 DETERMINATION OF OPTIMAL SETTING OF CRUSHER # 2

Because of wear on the crushing surfaces, the calibration procedure mentioned above may become inaccurate. This generally results in excess or insufficient feed going to the hopper above crusher # 3.

If spillage or empty hoppers ever result from this factor, the setting of crusher # 2 should be re-calibrated, a relatively easy task. In the ideal system, wear on crusher surfaces is compensated by the constant optimizing of the setting of crusher # 3 as a function of the output.

Although the introduction of this matrix-type control may appear unwieldy, it serves to eliminate the transportation lag problem prevalent in existing systems. Ideally, it would adjust the setting of crusher # 2 as soon as a change in feed occurs at that point as opposed to waiting for the feed change to arrive at crusher # 3.

4. Control of feeder-trays from Primary Stockpile

This control is the same as in the ideal system.

5. Example of System Operation

To illustrate the system operation, the following example is given.

Let the system be operating optimally for feed of some constant hardness. When the feed becomes harder, the TPH going to crusher # 3 changes accordingly. This TPH measurement as well as the setting of crusher # 2 is fed to the hardness matrix. The crusher setting is then immediately changed to the new optimum setting. Some time later

this feed arrives at crusher # 3. Because it is constantly optimizing for its input, crusher # 3 changes its setting for the feed of new hardness.

If the data which determined the optimum setting of crusher # 2 were exact, the feed-level in crusher # 3 would remain at choke-feed throughout the operation. If the setting of crusher # 2 were not optimum, however, the feed level in crusher # 3 would not be at choke-feed and would cause crusher # 3 to adjust to a more near optimum setting. This obviously introduces some transportation lag problems into the system, but they are of considerably smaller magnitude than in present systems.

In summary then, for a Performance Index which requires maximization of output, the variables which are controlled and the states which are measured are given below:

Variables Controlled

1. Setting of each crusher.
2. Amplitude of vibration of feeder-trays at Primary Stockpile.
3. Output of hoppers above each crusher.

States Measured

1. Level of feed in each crusher.
2. Level of feed in each hopper.
3. Horsepower drain of each crusher.
4. TPH out of crusher # 2 which goes to crusher # 3.

5. TPH of desired product resulting from crusher # 3.

6. Setting of crusher # 2.

If it were possible to have an exact calibration procedure as is postulated, this system performance would be identical to that of the ideal system. Because of the open-loop nature of this type of control, however, slight errors in such a calibration would require constant use of the over-ride control. In addition, the presence of the hopper above crusher # 3 introduces a transportation lag. This results in sub-optimal size feed going to crusher # 3, and hence, sub-optimal performance.

The next chapter introduces a new Performance Index and its application to a mining operation.

CHAPTER V

SUMMARY AND RESULTS

The previous chapters contain a detailed analysis of the application of optimal control techniques to crushing. The discussion is limited to only one Performance Index, that of the total tonnage of -1/2" product. As demonstrated in Chapter II, there are numerous Performance Indexes which might appropriately be applied to a mining operation. There are two principal justifications for the selection of and restriction to the Performance Index discussed.

First, it is the desire of the author to demonstrate in meaningful and quantitative terms the benefits derived by applying optimal control techniques to crushing systems. To do so, it is necessary to find a comparable system which is adequately described in the literature for purposes of comparison. The system described in Chapter III met these qualifications and thus it was decided to use the Performance Index of this system in developing the optimal control system. The application of optimal control techniques achieves two basic improvements over the other system. First, the problem of instability due to transportation lag is eliminated. Second, the correct crusher settings are obtained for varying feed hardness.

It has been shown that, although the ideal system requires a different relative positioning of crushers, the techniques discussed

may also be applied to existing systems. It is shown that application of these methods should result in at least a ten percent increase in output. Improvements of similar magnitude are to be expected if optimal control techniques are applied to systems with a different Performance Index.

The second reason for discussing a single Performance Index is that the results of the analysis may be easily extended to other Performance Indexes. In addition, the system may be easily modified to optimize on a new Performance Index. This is demonstrated in subsequent paragraphs of this chapter. It should be noted that improvements of a similar magnitude (better than ten percent) are also to be expected in these other optimal systems.

In fact, it appears that the Performance Index used in this paper is not really the best one for a mining operation. For this reason, two alternate Performance Indexes are suggested below, as well as a brief outline of the manner in which the optimal system described in Chapter IV might be modified to optimize on these Indexes.

A. Maximize TPH of Desired Product: Desired Product Size Varies as a Function of Hardness

In a mining operation, the crushing plant is followed by a grinding process which reduces the feed to powder. Although untried in any such operation today, it may be desirable to control the size of the output as a function of hardness. For example, it may be possible to increase the capacity of the grinders by crushing hard feed smaller

than soft feed. Let a Performance Index be specified which maximizes the TPH of desired product, but where the desired product size is a specified function of the hardness of feed.

Such a Performance Index may be maximized by some minor changes in the system discussed in detail above. The screens which separate desired product from the rest of the feed would be similar to the one shown in Fig. 26. Note the addition of a diverter whose position is controlled as follows. If the desired product is less than size C all feed which does not pass through screens A, B, or C is diverted to a belt which returns it to the crusher since it is oversize. The remaining feed drops to the product belt. The control is as follows:

1. Control of feed-rate to crusher # 2: same as in Chapter IV.
2. Control of setting of crusher # 2: same as in Chapter IV.
3. Control of setting of crusher # 3: same as in Chapter IV.
4. Control of diverter: The position of the diverter is changed as a function of hardness. The hardness is determined as in Chapter IV and the corresponding desired product size is pre-specified. The diverter position is changed T_1 seconds after the change in hardness is sensed where T_1 is the time required for the feed to get from crusher # 2 to the diverter.

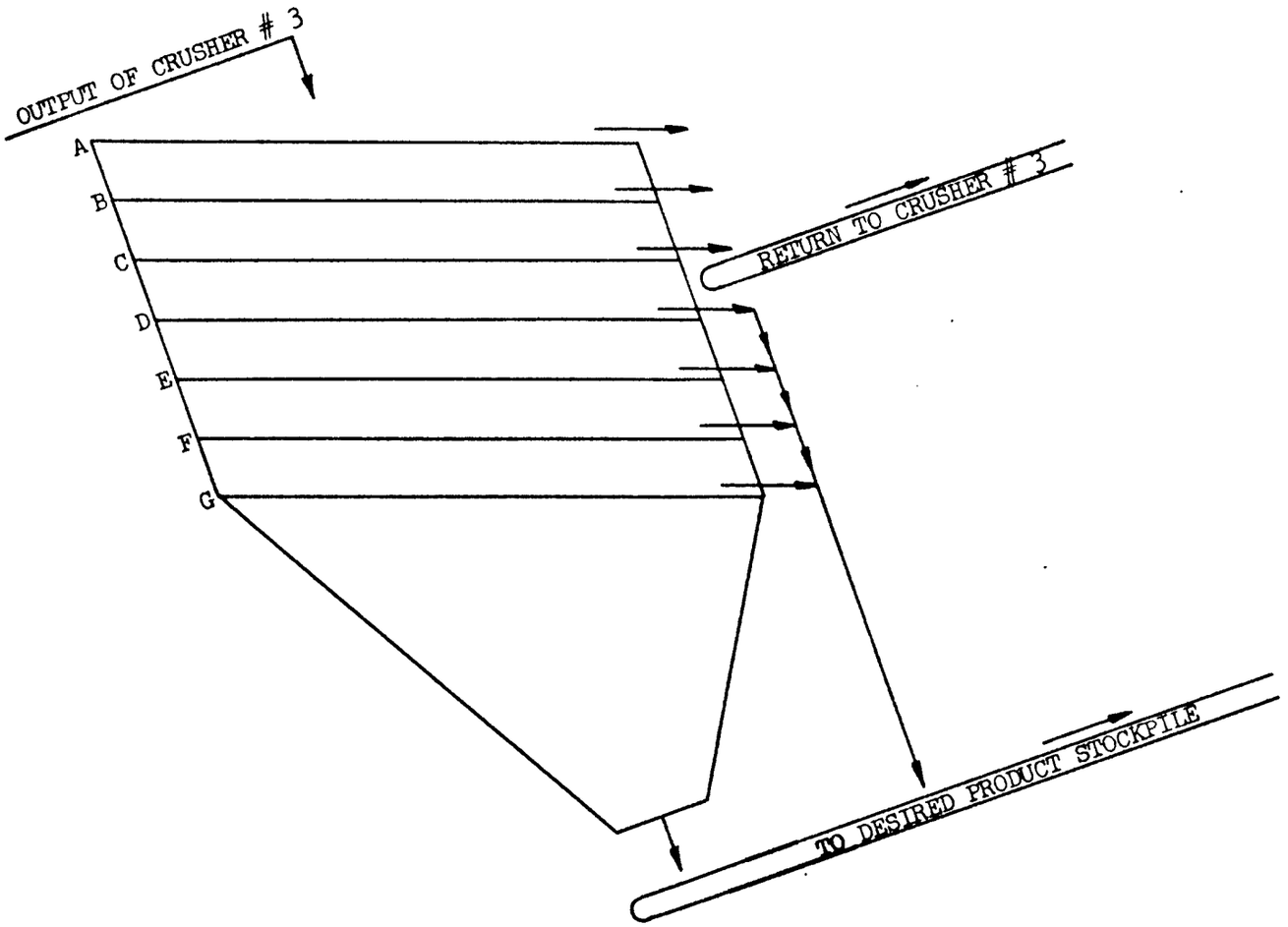


FIG. 26 CONTROL OF FLOW OF CRUSHER PRODUCT THROUGH USE OF MULTIPLE SCREENS

B. Minimize Size of Product: Maintain Constant Flow Rate

It may be desirable to obtain as high a reduction in the feed as possible, operating within certain time constraints. For example, the system described in the preceding paragraph could conceivably fulfil the grinder requirements in less time than is allowed for crusher operation. The Performance Index under discussion here would have the crushers operating 100 percent of the allowed time. The method of control would be as follows.

1. Control of feed-rate to crusher # 2: The feeder-trays below the Primary Stockpile would be controlled to maintain a constant feed-rate to crusher # 2. This feed-rate would be determined prior to operation.
2. Control of setting of crusher # 2: Adjust setting to maintain crusher # 2 at choke-feed.
3. Control of setting of crusher # 3: Adjust setting to maintain crusher # 3 at choke-feed.
4. Control of diverter: Position diverter of Fig. 26 such that the product in TPH on belt IV equals the constant TPH feed-rate going to crusher # 2.

Some argument may be justified both for and against each of the above Performance Indexes, but such a discussion is not within the realm of this paper. It should suffice to show the facility with which the basic optimal control techniques may be adapted to a system for different Performance Indexes. In each case the resultant performance is

significantly improved over that of the classical approach. These are the distinct features of the approach provided in this paper.

CHAPTER VI

RECOMMENDED FURTHER AREAS OF STUDY

Although significant improvements in the theory of crushing control are included in this paper, there remain additional factors to be studied.

The commitment of large funds to existing machinery configurations warrants further research into the problem which is limited by these factors. In the majority of these plants significant transportation lags exist. The improvement offered in Chapter IV seems to justify the limited time and expense involved in calibrating and determining more exact relationships between the crusher settings, hardness and TPH throughput. Not only does this allow the introduction of optimal control methods, but it also provides information relating to feed hardness which appears to be heretofore unknown.

Associated with the acquisition of this data should be a study of the statistical properties of the feed hardness and size distribution. At best, the crushing process is not completely deterministic in nature and proper control may only be defined in terms of "average" hardness and similar terms at any specific time.

Once this information is known, it is possible to simulate an entire crushing process on a computer. Even if these relationships are unknown, approximate functions of hardness and crusher setting may be postulated. The effect of varying transportation lags on the output

of a system may be demonstrated as well as the effect of various crusher settings. Thus, a really meaningful comparison may be made between existing systems and postulated ones.

One very critical area of additional study is in determining the proper Performance Index. To do so, the entire operation must be considered, including crushing, grinding and flotation. In effect, the problem is really a system problem and crushing may not be considered to be really isolated from the rest of the system, although the author had thought otherwise when selecting this topic for study.

In conclusion it may be said that little pertinent information appears to be known in this area. Application of the methods described in this paper combined with the additional research discussed in this chapter promise significant increases in the output of mining operations at little additional cost.

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