Scientific Methods to Design Crushing and Screening Plants

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This article synopsizes the major conclusions of Allis-Chalmers research into crushing and screening plant design. The full text of the research findings, together with the supporting mathematical details, is expected to be made available to the industry within the next several months.

Crushing and screening, the common denominator of nearly all mineral beneficiation and processing circuits, has always been and still remains one of the most technologically neglected areas of our industry expertise. At Allis-Chalmers Corp., over a century of crushing involvement has led to an entirely new approach to crushing and screening plant design which relates to Bond's Third Theory of Comminution. For those used to designing plants or selecting equipment based upon existing criteria, Allis-Chalmers' approach will be easier to understand if one divorces his thoughts from past practice—this theory relies on the application of energy as a basis for machine selection and plant design.

Where comminution is concerned, the mineral industry has gone all out in the study of milling materials from 12.7 mm (½ in.) down to beneficiation sizes because this is normally where most of the power capital and operating costs are expended; another reason that research into crushing has been neglected in favor of grinding is that the physical properties of the milled product normally have a vital bearing on the recovery, concentrate grade, and other factors which might affect the end product's marketability. People have always tended to regard the crushing and screening section of a flowsheet involving grinding mills simply as a function of feed preparation for those mills. Consequently, in most operations, crushing plant operators produce mill feed as fast as possible. But the fastest feed rate produces the coarsest material, causing any subsequent milling operation to have the lowest output and maximum unit cost, both in terms of power as well as mill media and liner consumption.

It's a paradox that mine management generally acclaims the "gun operator" who produces a shift of mill feed faster—the same person who minimizes profitability by increasing overall plant production costs.

There is a size range between the product from a crushing plant and the feed to a grinding mill where crushers can utilize energy more efficiently than grinding mills. But with current machine application techniques, it isn't possible for an engineer to apply sufficient finesse in machine application to take advantage of the crusher's power efficiency.

Most application engineering which concerns crushing and screening has been based upon empirical data from manufacturers. The accuracy of such published information can be open to question and is not intended to fit the variables imposed by all applications. The fact that many of the largest crushing and screening plants—which are supposedly the best-engineered—perform very differently from design predictions leads to the conclusion that crushing and screening is a most fruitful area for achieving economies in overall mill performance.

In order to realize how gains can be made, it is necessary to look into the power relationships within a crushing plant.

Towards a Definition of "Crusher Power Rate"

To reduce a material's size, work has to be done on it. Bond's Third Theory of Comminution[1] calculates the amount of power required to reduce the material by the equation:

$$W = \frac{10W_i}{\sqrt{P_{80}}} - \frac{10W_i}{\sqrt{F_{80}}}$$

When adapted to the crushing process, power becomes a function of reduction ratio and work index:

$$W = f(R_r \times W_i)$$

Where W = power in kWh per st
W_i = Bond's crushing work index
P_{80} = size in μm, 80% product passing
F_{80} = size in μm, 80% feed passing
R_r = reduction ratio

This work is carried out in crushing machines of several types:

Hammermills and pure impact crushers have rotating impellers which lift the kinetic energy of the material to a level where, on sudden impingement against a stationary plate, breakage occurs.

In the more common jaw- or cone-type crushers, stone either breaks by impact or fails as a result of sufficient compressive or shear forces. Here, the geometry of the

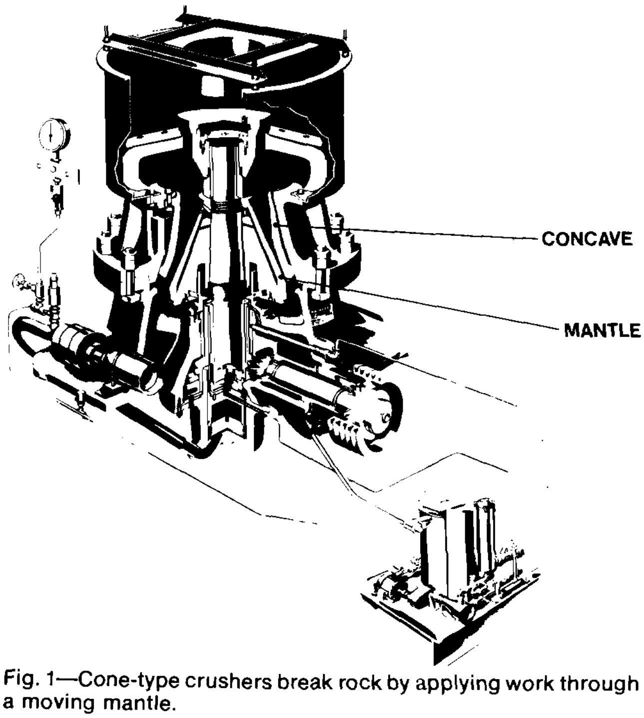


Fig. 1—Cone-type crushers break rock by applying work through a moving mantle.

machine has a direct bearing on the rate of energy application. There is ample evidence available that plant designers and equipment manufacturers have not paid sufficient attention to mechanical design criteria and how this affects machine productivity.

In a cone-type crusher the work done on the stone is performed by the mantle and concave (Fig. 1). The amount of reduction that can be achieved is controlled by two major mechanical factors within the crushing chamber: first, the conical angle, shape, and length of the chamber; and second, the eccentricity and operating speed of the mantle.

The two cone configurations shown in Fig. 2 are commercially available and have entirely different concepts of the amount of ore being crushed as a proportion of the total feed. As a comparison, when the two machines are engaged in fine crushing with feed top size of 30 mm (1.2 in.) and the same close side setting, the smaller eccentric throw, long chamber machine can be expected to make a finer product than the larger throw, short chamber machine because the first is working on a greater proportion of the feed. For further discussion, I will define this ability to inject energy per unit of feed as the *power rate of the crusher*.

A number of field tests have been run verifying the effect of power. Figure 3 is one example which shows the product size distribution of three crushers, each with different eccentric throws being fed from the same bin. In each case, crushers two and three, with the smaller eccentric throws, made a higher percentage of finer products even though in the case of crusher three the close side setting was 40% more open.

Looking at the quantities of sized products from these tests (Fig. 4), it can be seen that the crushers drawing more power produced larger amounts of any given top-sized product.

Dividing the power consumed by the tons of size produced gave remarkably similar power-per-ton figures. Results from tests on other-sized crushers processing many different materials seem to confirm that cone-type crushers use the same energy to reduce similar quantities of material to the same size. *The efficiency in the application of energy converted to useful work by the crusher, therefore, appears independent of eccentric throw.*

If this were not a fact, it would invalidate Bond's Third Theory for relating power and size reduction achieved in a compression-type crusher.

Power Manipulation for Product Control

After the discussion above, it follows that there are two separate factors which the designer needs to control in order to tailor the quantity and fineness of production in a crushing and screening circuit:

- *Power consumed* by the crushers will directly affect productivity; and,
- The amount of energy applied per unit of feed (the *crusher power rate*) will affect product fineness.

The only variables in the process which the engineer can routinely control are feed rate and setting change to the crusher. These affect the power consumed at the drive motor and rate of energy input in the following manner.

At fixed settings (Fig. 5) near the point of economic operating capacity, feed rate vs. power drawn has a linear relationship. Power rate tends to remain a constant.

With variable settings, power changes in an exponential relationship (Fig. 6). This example shows that for a small change in setting there is a large change in power drawn. Since there is little volumetric change for a small change in setting, there will also be an exponential relationship in crusher setting vs. energy per ton of feed (power rate) which is a direct measure of reduction, as shown in Fig. 7.

If we can change the setting of the crusher while it is operating, we can affect both the productivity (consumed power) and, through the power rate, the amount of reduction within the constraints set by the eccentric throw, speed, and chamber configuration.

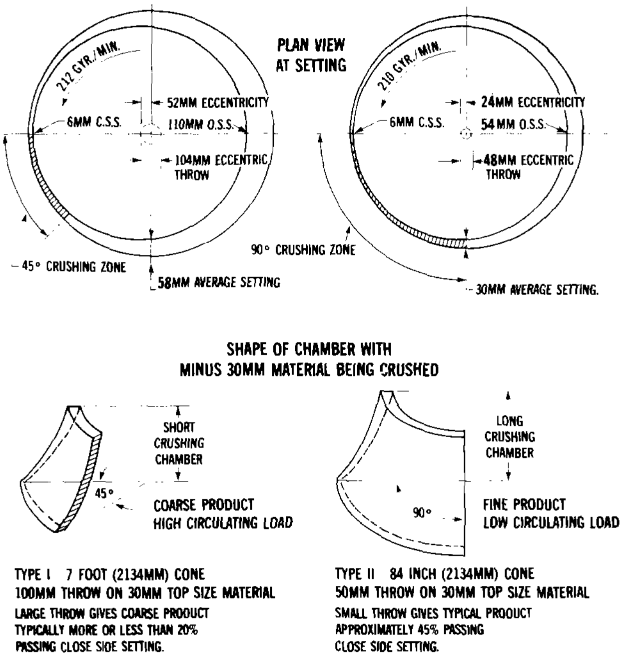


Fig. 2—The amount of work injected into a rock is dictated by the crusher's eccentric throw and chamber design.

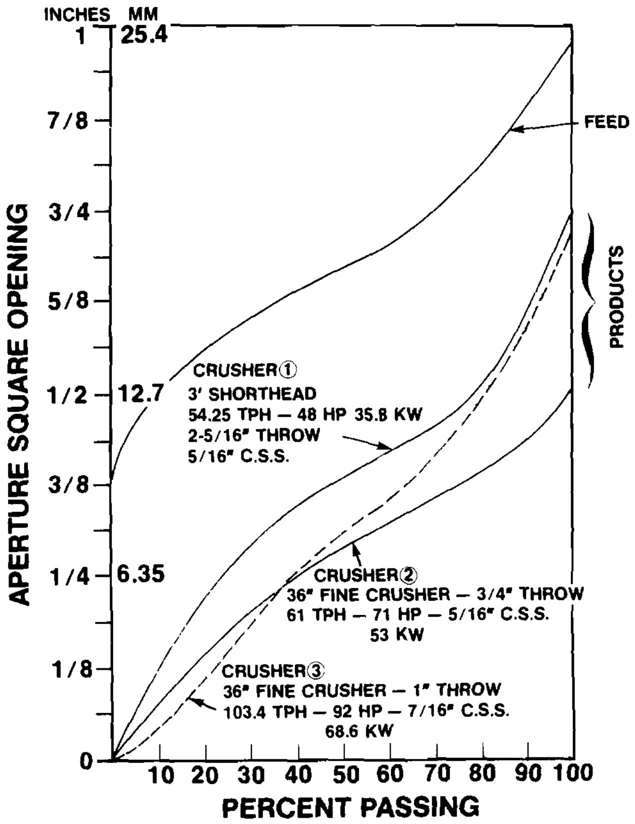


Fig. 3—Screen analyses of products from three different crushers, each with a different eccentric throw.

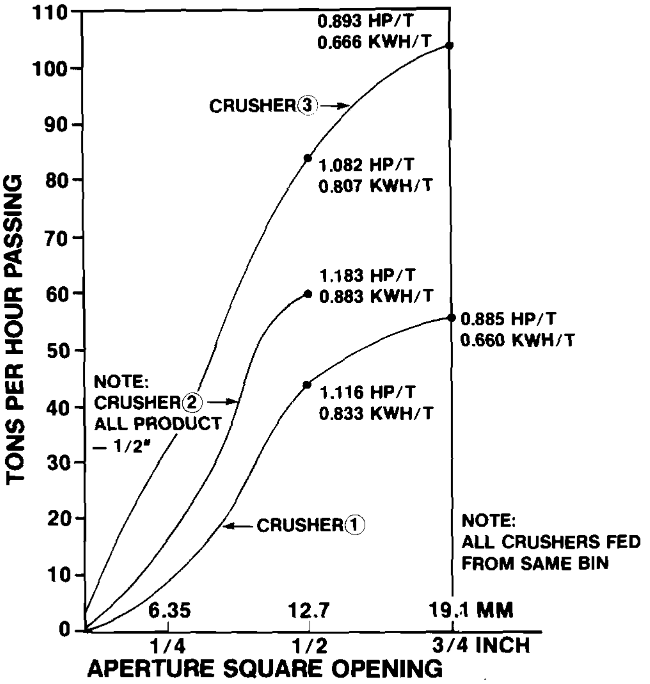
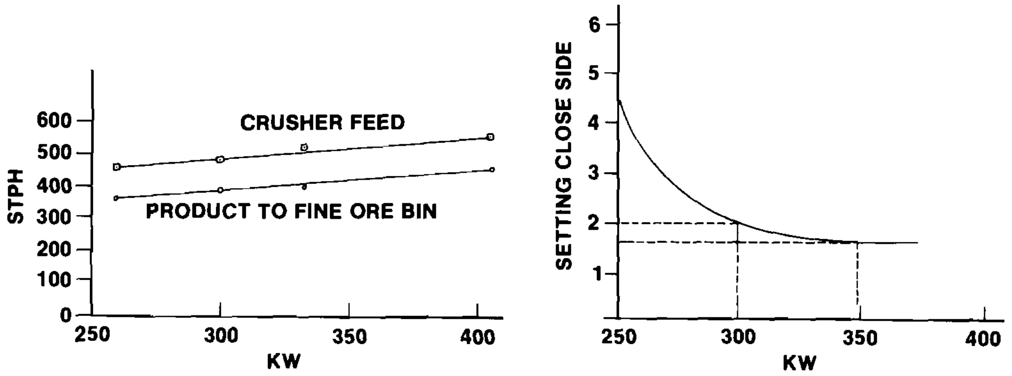


Fig. 4—Productivity comparisons of the crushers from Fig. 3. Crushers drawing more power break larger amounts of rock.



At fixed settings, feed rate vs. power drawn has a linear relationship (Fig. 5, left). Variable settings change this to an exponential relationship (Fig. 6, right).

An important point often overlooked by plant design and application people is that the crusher must have an adequate amount of evenly distributed feed. Figure 8 shows the effect of poor and good feed distribution. If the feed is correct, the crusher will have maximum productivity (highest average crushing force) for minimum mechanical stress.

A crusher normally cannot be properly fed from a vibrating screen discharge—properly designed surge bins with pan or belt feeders have been proven to give the best feeding arrangements to crushers. The commonly adopted practice of feeding the crusher directly from a vibrating screen discharge, while reducing plant construction costs, builds-in operating problems and increased operating costs.

Let's look at the other essential element in all fine crushing installations—the size classifier or screen.

How Screening Controls Power Rate

If the cone crusher could operate at zero eccentric throw (which it can't), and if it were set at the same discharge setting as the classification size, then all products would be to the classifier size, the appropriate amount of energy would have been expended, and no external sizing screen would be required.

Unfortunately, this state of affairs cannot exist, hence classifying screens are necessary to ensure that oversize material produced in crushers is recycled until sufficient work has been done on it.

Because the efficiency of recovery of product-sized material in a device such as a vibrating screen is affected by the size distribution and depth of bed caused by the screen feed material, the power rate of the crusher will have a direct effect on the screen area required and, therefore, relates to the screen efficiency for a given size of classifier. This is demonstrated in Fig. 9. The screen efficiency affects the reduction ratio and, as a result, it also affects the feed size graduation to the crusher. Consequently, screen and crusher performance are interrelated: *The lower the power rate for the crusher, the greater the screen area required to remove product from the process circuit.*

Because performance variables demonstrated in Fig. 10 are not considered, present-day screen application formulae have proven very inaccurate, particularly in fine crushing closed circuit computations. This is due mainly to the lack of formally published data relating power rate to screen performance.

Understanding what has just been stated is so important to appreciate this new theory that I will repeat it in a different way:

Because the crusher power is controlled by the reduction ratio, at fixed setting a change in the feed size causes the power rate for the crushing chamber to also change since fixed setting tends to hold the discharged product-size constant. The lower the screen efficiency, the lower the power rate because the screen oversize graduation, which is crusher feed, would become smaller. In a closed circuit this effect will tend to increase the circulating load until a balance is achieved.

The efficiency of the classifier has a direct effect on the operation of the crusher and its selection is critical to the performance of the overall circuit.

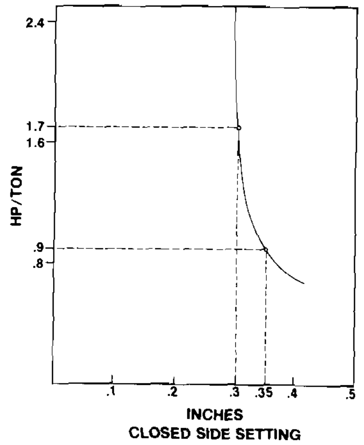


Fig. 7—A small change in setting induces a large change in power drawn. Crusher setting vs. power rate is an exponential relationship.

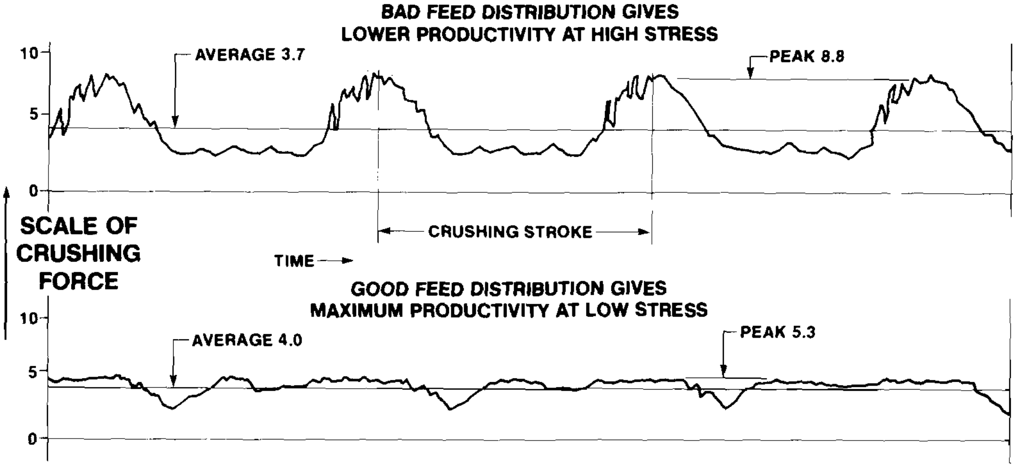


Fig. 8—Effects of good and bad feed distribution on crusher stress and productivity.

There has been a tendency in plant design to undersize screens, with a result that during plant operation screen apertures have had to be selected on the basis of size that gives sufficient open area necessary to meet production requirements. When this occurs, the classifier cannot perform its intended function of recycling oversize material until sufficient reduction work has been performed on it.

The most common crushing and screening plant as we apply it today in mining is a three-stage crushing facility as shown in Fig. 11.

There is a rational way of applying our energy theory to a crushing plant. Consider the following example:

We can ascertain the amount of power to reduce the material according to Bond's equation.

Within the crushing plant in Fig. 12 we have to apply 1.5 kWh to every ton of feed to get the material to pass through the 12.5-mm aperture screens that control the top size of the plant output. In this fictitious example which only portrays energy balance, if we could apply 0.34 kWh equivalent energy per ton of plant feed at the primary crusher, 0.58 kWh equivalent energy per ton of plant feed in the secondary crusher, and 0.58 kWh equivalent energy per ton of plant feed in the tertiary crusher, all of the product from the three crushers would pass through the screens and there would be zero circulating load caused by oversize from the tertiary crusher product. With the circuit under stable operating conditions, each crusher might be drawing 200 kW and 350 kW, as shown.

If the mechanical arrangement and chamber design of the crusher were such that the energy per ton of crusher feed (power rate) was less than for the first example, but the crushers still draw 900 kW total, the product from the plant would still have the same fineness, but there would be a change in the energy relationships within the circuit because a different rate of feed would have to be handled by the secondary and tertiary crushers to draw their 350 kW. Therefore, a circulating load would build up in the closed circuit. This circulating load is a function of the energy injecting capability of the crusher, or the power rate as we have defined it. The more energy applied per ton of feed at each stage of crushing in open circuit, the less work, and, consequently, higher power rate that will be achievable in the last closed circuit stage of crushing. This will minimize circulating loads, equipment sizes, and capital and operating costs.

Should physical conditions allow, the plant might be capable of applying energy at a rate greater than 1.5 kWh per ton of plant feed. As shown by experiment, if the power

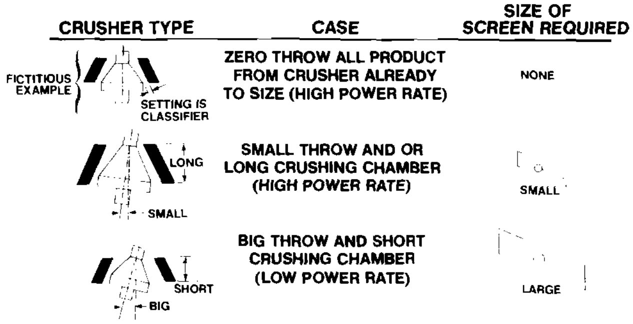


Fig. 9—Crusher power rate affects the screen area required.

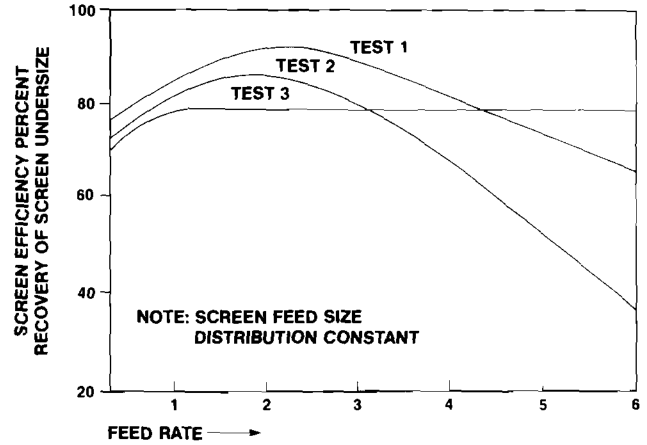


Fig. 10—Screen recovery efficiency for similar apertures and different modes of operation.

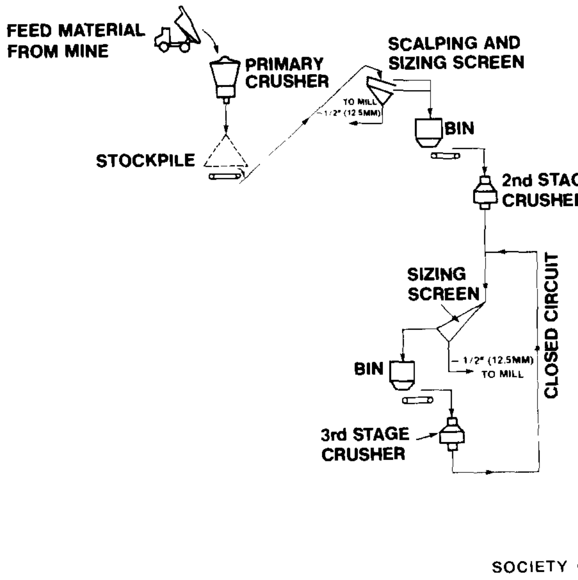


Fig. 11—Typical three-stage crushing plant used in the mining industry.

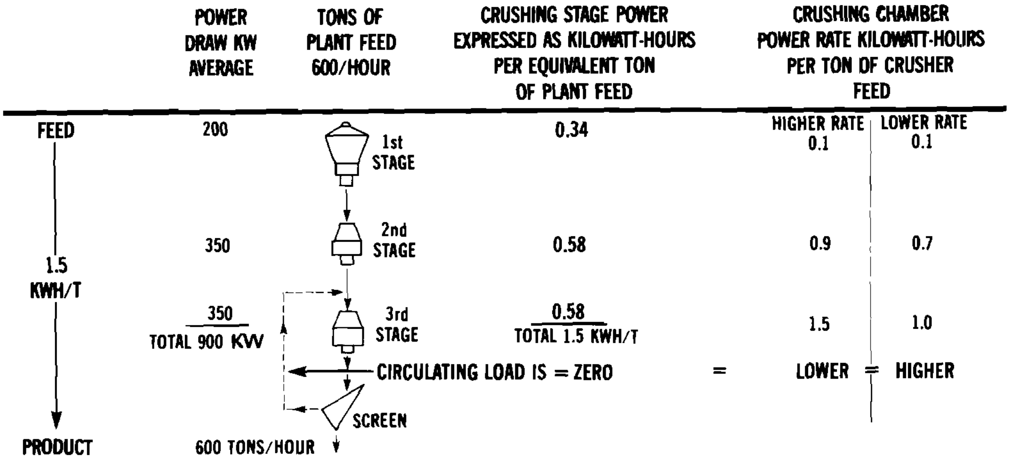


Fig. 12—Chart differentiates between productivity (which is proportional to plant power) and power rate (which influences circulating load).

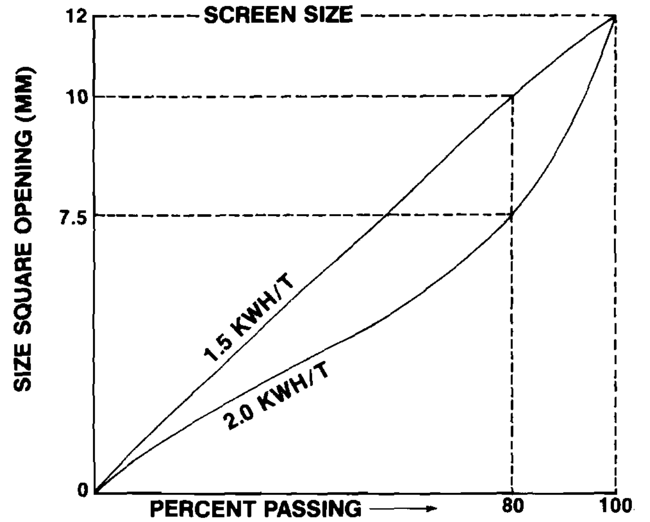


Fig. 13—Screen undersize becomes finer as more crusher power is applied per unit of feed.

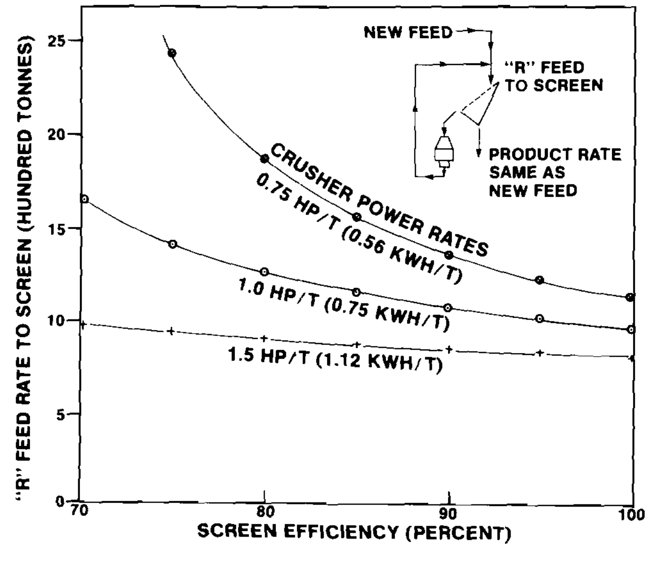


Fig. 14—Theoretical relationship between screen feed rate (*R*) at various screen efficiencies and three power rates.

rate was set at 2.0 kW per ton, and if the same 12.5-mm screens are used, then plant product in the screen undersize will become recognizably finer—an 80% passing size might change from 10 000 μm to 7500 μm as shown on Fig. 13.

Product Size Affects Mill Performance

There has been considerable study on how feed size affects mill performance. Chester A. Rowland, in the paper "The Tools of Power Power,"[2] describes milling efficiency as it relates to oversize feed. The efficiency factor EF_4 should be calculated when a rod or ball mill is fed a coarser-than-optimum feed. This milling efficiency factor is directly related to the work index:

$$EF_4 = \frac{[R_r + W_i - 7]\left[\frac{F - F_o}{F_o}\right]}{R_r}$$

Where F = feed size in μm, 80% passes

P = product size in μm, 80% passes

R_r (reduction ratio) = $\frac{F}{P}$

F_o = optimum feed size

for rod milling: $16{,}000\sqrt{\frac{13}{W_i}}$

for ball milling: $4000\sqrt{\frac{13}{W_i}}$

W_i = Work index

There are mills operating today with oversize feed power efficiencies greater than 30%. The mill power can be reduced and the overall combined plant crushing and milling power will fall if we could reduce plant produce size (mill feed size). Media and liner costs per ton would also fall and mill tonnage could increase.

Controlling the Plant for Maximum Productivity

From the discussion thus far, it can be appreciated that there are many variables involved within the crushers and screens as well as those imposed by the flowsheet design.

It is possible to set up formulae relating all performance variables in an energy balance—details of this are covered elsewhere (see box, p. 65).

I will point out here, however, that there is a crushing

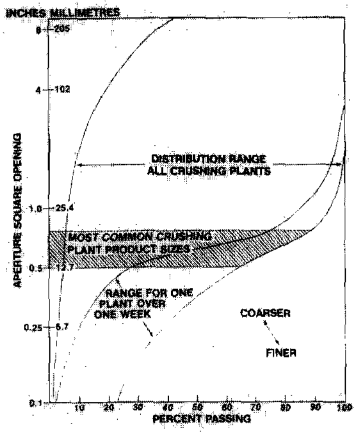
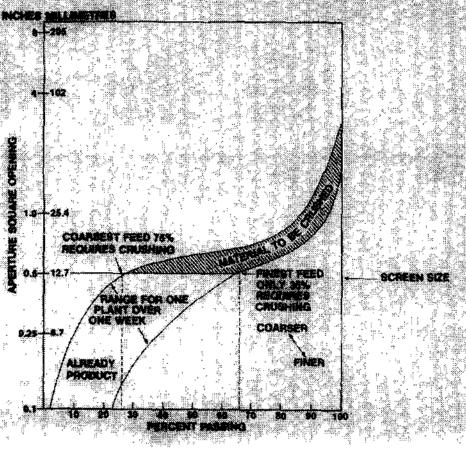


Fig. 15—Range of feed size distribution to crushing plants.

Fig. 16—Variations in feed size distribution to one plant under study



limiting size beyond which a particular number of crushing stages cannot further reduce material. This point is where the screen has too low an efficiency to remove the undersize produced by the crusher and the power rate is too low. By referring to the following circulating load formula, one of several used by Allis-Chalmers, it is seen that the circulating load becomes infinite when the screen efficiency is 50% and there is 50% oversize in the crusher product. Both these factors relate to the power rate of the crusher.

$$R = \frac{100}{e/r - 1}$$

Where R = percent circulating load to the crusher
e = percent screen efficiency
r = percent oversize in crusher product

The graph shown in Fig. 14 gives the theoretical relationship between the screen feed rate (R) at various screen efficiencies and three power rates for a closed circuit operation involving an ore with specific feed size and work index. The higher the crusher power rate, the less effect that a change in screen efficiency has on circulating load.

If a particular configuration cannot reduce the material to the required size, then it would be necessary to increase the power rate of the crushers or increase the number of crushing stages, at the same time taking into account the effects of the classifier efficiency.

In addition to the variables in crushing plant performance mentioned so far, there are others relating to variations of feed size distribution, as shown in Fig. 15. And along with this, there are usually variations to feed rates and the material work index that may or may not relate to feed size distribution.

Figure 16 graphs data collected on feed size distribution for one plant which we have studied. Due to the variable crushing requirements, it is obvious from the previous discussion that the best way to control the level of circulating load is to maximize the power rate of the crusher, as demonstrated in Fig. 14.

Essentially, the best crushing plant operator will be the one who gets the crushing plant to draw the most kilowatt hours in a shift since he will produce the finest feed for the grinding mills.

Summarizing the New Theory

From the discussion we can draw the following conclusions:

- It is dangerous to use existing crusher and screen application data for proper design of crushing and screening plants, since this does not make specific allowances for material work index, feed size, and precise specifications for products.
- Crusher and screen performance are interrelated and are affected by the quantity and rate of energy applied (the *power rate of the crusher*).
- To properly apply a crusher, we need to know its properties of power draw and power rate for a specific feed and product condition.
- To properly apply a classifier such as a vibrating screen, we need to know specific properties for feed rate vs. recovery efficiencies for the separating surface.
- Crushers from various manufacturers have different geometrical arrangements within the crushing chamber. Because of this, all will make different products at different close-side settings. It is also probable that all will differ with respect to the total power each crusher will draw, its productivity, and its power rate.
- For better application engineering, crushers that are presently described by physical size of the crushing mantle, such as "84-in., 7-ft, 2100-mm," would better be described by power application. Such a new size specification might take the form "350-2100-1.0" to describe the connected power in kilowatts, the mantle diameter in millimeters, and the crusher power rate for a specific crushing duty.
- By using variable setting control on the crusher, we can optimize both power consumption and power rate.
- The number of crushing stages, equipment sizes, circulating loads, and operating costs for both the crushing and milling operations will be minimized if the power rate at each crushing stage is maximized.

For average materials, capital and operating cost gains of 30% might not be unrealistic by using this new technology as a basis for design and operation. ☐

References

[1] Bond, F. C., "Crushing and Grinding Calculations," *British Chemical Engineering*, June 1960, pp. 378–385 and 543–548. (Revised January 1961, *Allis-Chalmers Publication 07R9235B*)

[2] Rowland, C. A., Jr., "The Tools of Power," SME Preprint No. 76-B-311, 1976 SME Fall Meeting, Denver, Colo.

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