Table 1. Improvements in Mill Performance Due to Decreased Ball Load

	NOW	BEFORE
Ball Load, tons	35	55
Ball Load, % volume	29%	45%
Tonnage	2250	2130
Horsepower Requirements	370	490
Ball Consumption, lb./ton	0.84	1.02
Grind: Sulphides—200 Mesh	65%	62%
Grind: Gangue—200 Mesh	35%	40%
Tails: Copper	0.068%	0.08%
Tails: Sulphur	2.5%	4.0%
Sod. Ethyl Xanthate, lb./ton	.28	.34

The Remarkable Case of the Copperhill Ball Mill

WHAT HAPPENED when the ball load in Tennessee Copper Co.'s huge Hardinge Tricone mill was reduced from 55 tons to 35 tons should give a lot of mill men food for thought. Not only did the reduced ball load make possible an increase in tonnage ground from 2130 to 2250, but power requirements dropped from 490 hp. to 370 hp. Nor was that all. As a result of the remarkable differential grind achieved (see table above), it has been possible to cut down on reagents.

Between August and October 1952 the amount of balls in the mill at Tennessee Copper's London plant was reduced from a load occupying 45% of the mill volume to a load occupying 29% of the mill volume. No other operating condition was changed. The mill turns over at 15 rpm (63% of critical speed), ball size is 1-in., average pulp density is 63% solids.

Results shown in Table I, were disclosed to a visiting *E&MJ* editor by Mr. F. M. Lewis, mill superintendent, who plans to experiment with further reduction in ball load in the near future. In addition to the lower ball consumption noted, it was possible to postpone an impending liner change because liner wear has been reduced.

Could the large classifying pool in this mill be contributing to these remarkable results? This pool has an area of about 70 sq. ft. and averages approximately 40-in. deep. The mill discharge is only 63% solids, but the material at the bottom of this pool, which must be the feed to the ball mass, is at least 75% solids. Also, this material is as clean as most conventional classifier sands. Thus only the coarse portion of the pulp in the mill, which has been thickened, ever enters the ball charge and in a very short time it is back in the mill pool for reclassifying.

Mr. Lewis doesn't know the answer at this time, but members of his staff are studying the conditions in their grinding circuit.

See *Engineering and Mining Journal*, June, 1953, pp. 86-89.

Copperhill

WE HAD INTENDED TO USE this space to record a majority opinion of the June and September contributors to the discussion, of Copperhill's improved ball mill practice as indicated at the left. The wide divergence of approaches to the problems, however, makes a tidy summation impossible. As a matter of fact, summing up isn't necessary. The real benefit of this discussion lies in the exploration of the problem. We feel that this kind of panel discussion is a step toward filling in the gaps in our knowledge of grinding. As Dr. Haultain puts it so aptly, "Groping may be an important engineering process."

H. R. BANKS
Consulting Engineer
Kimberley, B. C.

I WOULD LIKE TO GIVE YOU my reaction to the changes brought about by reducing the ball load in the Tricone Mill at the London plant.

1. Though not so marked as in this case, we have found an advantage in maintaining a ball load of say 47% instead of a higher percentage. We found it necessary to keep the load up to that approximate figure otherwise the grind would fall off.

2. I do not doubt that the classifying pool does play a prominent part in the amount of material finished in the mill.

When it comes to grinding I always refer back to the Muller and Bucking Board and the screen which removes the finished product. If we allow the full sample to remain on the Bucking Board too long between screenings we do tend to damp the action of the Muller.

The classifying pool with the current flowing down the gradient does remove the finished product and delivers the unground portion back to the ball charge in a similar way to the screen used for removing the finished material from the Bucking Board.

As the pulp flows out from the mill it is a mixture of the fines swept out on the classifying pool and the sands which are displaced

Story Stirs Thinking on Grinding

by new feed. The separation is made in the classifier.

If one could conceive of a stream of air being blown over the sample on the Bucking Board during the bucking action we would simulate the ball mill action since some of the finished product would be removed without waiting for the screening action.

3. The weight of the Muller is comparable to the ball load.

It would seem reasonable to assume that if the elimination of the fines could be improved, a lighter Muller might do just as much work as the heavier Muller damped by the inclusion of finished materials on the Bucking Board. The lighter [illegible]er would in turn yield a differe[illegible]al grind just as the lighter ball load has done.

H. E. T. HAULTAIN
Consulting Engineer
Toronto, Canada

AS AN OLDTIMER I much appreciate the opportunity of joining with the younger millmen on the common ground of some of our ignorance of what really happens in a ball mill. I *am* an oldtimer. I was a millman in the Erzgebirge more than sixty years ago. Milling was my first love and with some lapses I have been loyal to her ever since.

It appears that Lewis has two new achievements to his credit. He has the unquestioned result of materially reducing his fine grinding [illegible] and he has shown us that [illegible] is still much going on in a ball mill that we don't understand. This is a definite call for more experiment and more research and this, Mr. Editor, you have emphasized by encouraging us to confess our ignorance. Good work! I have not an answer to the problem, I have only some suggestions. But in such good company I venture to add a contribution based on work that Dyer and I did thirty years ago.

First let me explain my use of certain words. In this discussion I prefer to use *cracking* and *crushing* in place of grinding. We grind tons but we crack or crush particles. (My bow to Myers. I can crack an egg and crush an eggshell but how do you grind an egg?) I would stress attention to the particle and the idea that the nipping of the particle is an essential, the essential, in all crushing and grinding. I suggest that in the final analysis what Lewis has done was to increase the number of nips per ball. There is another word *cascading* that I want to use but my interpretation of it differs from that given to it so far in this discussion. For example Dorenfield suggests that "the Copperhill mill does not cataract." Has he a word for what it does do? What does Crocker want us to understand when he uses the words "as suitable a cascading action (or ball mill action)." At Niagara we have cascades and falls. These words are used by engineers as well as by others. In the cascades above the falls the water rolls. In the falls the water falls in a free parabolic path. In my discussion of our slow motion films I stressed the idea that there were four different forms of ball paths in the ordinary practise of those days in ball mills. In the upward motion the path was circular. In the downward motion there were two separate and distinct types of paths. (I think E. W. Davis will remember this.) A free falling in parabolic paths and other paths in which the balls rolled on each other. I referred to the rolling as cascading and I am obstinate enough to still think I was right. Right or wrong please let me use this interpretation in the present discussion. I also stressed the turbulent motion in the "toe" where the downward motion was reversed into the upward path. This was the zone of hard knocks where I thought most of the energy in the balls was expended and that it was where the larger particles of the feed of those days were cracked. Forgive this digression but the words, cracking, crushing, particles, nips and cascading are the important ones in my contribution.

In the Copperhill Mill all the balls are rolling and to some extent slipping on other balls and on the liners. Let us grope about this phase. (I have long maintained that groping may be an important engineering process.) If particles are present they are nipped and cracked or crushed. Yes and no. If too many are present they resist or cushion the effect. We can imagine a pulp so thick that there would be no nipping, or so thin that there were too few particles to be nipped. Hence the importance of a suitable density of pulp. Let us try to tie in the idea of particles being cracked or crushed by nip with Hardinge's theory of ball cycles. He says, "... consider operating with a mill at 50% ball load, those balls on the outer rim make two cycles per mill revolution. A mill at 25% ball loading would cause the same balls in the same location to drop four times per revolution." Ignoring the fact that in the Copperhill Mill no balls drop (some cascade!) and without being quite satisfied about their being exactly two cycles per mill revolution for a 50% load it does seem probable that his general theory is sound. Perhaps it can be stated thus; the total number of ball cycles per revolution is the same with all ball loads, within limits of course. Does not that mean, also, ball nips per minute? And if the particles are small enough it means particles cracked or crushed per minute and that means tons per day. That looks like a perfect answer to our major problem but the older research man knows from painful experience that when a result fits into theory too soon or too perfectly that is the time to be on one's guard and check and double check. Inside a ball mill there are so many variables that theories by themselves are well nigh useless but they are a spur and a guide to further experiment. This theory of the ball cycles and nips lends itself to experimenting with smaller mills, laboratory work where variables such as speed can be readily altered and controlled. It should be noted that the smaller the load the greater the speed that can be used without departing from the cascading (rolling) action. How I regret that age and circumstances prevent my tackling the laboratory phase of the problem.

D. H. FAIRCHILD
Mining & Metallurgical Engineer
Tucson, Arizona

FIRSTLY, I THINK it should be recognized that, usually, there are so many variables and uncontrolled or not-understood factors involved in many milling practices that the engineer may run afoul by the slip-stick or by drawing conclusions

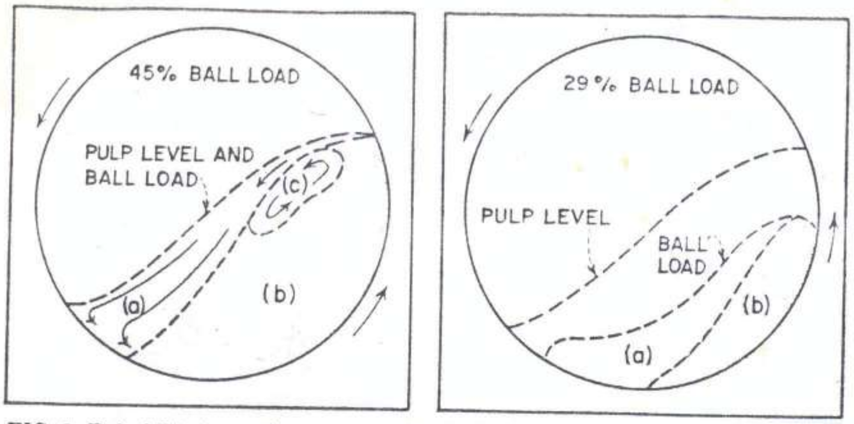

FIG. 1. Fairchild shows three zones when ball charge is large (left): (a) where most of the work is done; (b) less active; (c) kidney or "loblolly" where no work is done. At low ball charge (right), with dilute pulp, zone (c) disappears.

too hastily. Of the comments published in the June issue of *E&MJ* I feel that Mr. J. F. Myers has used good judgment in his reasoning, but possibly this is only a natural personal reaction since his and my theories roughly parallel each other.

Many years ago, a short time prior to the studies by Mr. H. E. T. Haultain and associates in Canada on what went on within operating ball mills, I had done considerable similar work. Our findings were closely parallel but, inasmuch as I was working on a private problem, I could not and did not publish my results. Motion pictures of glass-ended ball mills (taken by Pathe) disclosed a pattern that indicated two things quite clearly. The first that there are, roughly, three main zones or gradations of activity within ball mills. These "zones" are (Fig. 1) that region of cascading, falling or rolling action of the ball charge and ore across some substantial portion of the diameter as indicated by (a); The great mass of balls and ore that must be lifted by the rotation of the mill so they may cascade or roll or fall (b), and that zone so aptly referred to as the "kidney" or "loblolly" (c) where the balls seemed to eddy in a pattern that was kidney-shaped in cross-section, occasional balls escaping from this zone into one of the others. The value of these zones in terms of work done were felt to be in the order mentioned.

The second thing that was quite apparent was that, in the cylindrical (cross section) type of ball mill the maximum action possible for any given ball was $1\frac{1}{2}$ actions per revolution of the mill. This was based, of course, upon what we felt to be the optimum condition at that time, namely a load of probably 45% volume so that the above-referred to zone (a) would be the greatest. Naturally, as one reduces the ball load (without ore or other "passing"), the activity of the remaining balls tends to rise as they are carried upward a shorter portion of the revolution before they cascade or roll. I feel that this would tend to be the situation in the Copperhill ball mill as it was operating on a "relatively dilute" pulp. Mr. Hardinge hit one of the nails on the head, in my opinion, when he commented that due to this dilution, the small charge of balls was permitted or caused to expend their work upon the unfinished material, which may be assumed as collecting low in that type of mill, with a high dilution of the pulp where the balls could act upon it. Mr. Lewis also mentions this.

Many years ago, in a large-scale test, I saw a ball load of from 11 to 14 tons occasionally do even more work in terms of finished product than 24 tons of balls were doing in the other mills. There were uncontrolled variables in this case that made results erratic and incomplete but there was no question about the results being comparable. Although ball mills, as they now stand, have been well developed and have given a good account of themselves, it is time for further basic developments in that art and those developments are, in my opinion, possible of fruition.

With possibly the single exception of the so-called "balanced" types of mills, there are fields for all of the main successful designs. The improvement must come from making better use of known factors. I feel that there are too many loose ends and unknown factors and variables in the Copperhill operation to draw definite conclusions. Certainly the indications are interesting and Mr. Lewis is to be commended for his attitude and his reluctance to jump to conclusions.

F. C. LENDRUM and G. PARE
Ascot Metals Corp., Ltd.
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WE ARE EXTREMELY INTERESTED in the reported increase in efficiency of the Tennessee Copper Corp.'s Tricone Mill when the ball load was reduced. Mr. Lewis is to be congratulated on his original work and for the speed with which he has spread the good news. You of the *Engineering and Mining Journal* are to be congratulated for gathering the opinions of so many mill operators.

We feel that your article will go a long way to free the ball mill from its present "convicts' status" of making little ones out of big ones, and put it in its true position as a conditioning agent for the process or processes that follow. We hope that other operators of small tonnage mills, who have not had the time or facilities to compute such things as "kilowatthourballs" in their grinding circuits, will contribute their ideas and experiences to this open discussion.

One of the writers had the opportunity to see this ball mill in operation in May of this year, and he was particularly impressed with the cascade action of the ball load. We believe that the increased performance as put forward by Mr. Lewis comes from two separate, though related, causes.

There is improved grinding of the sulphides with a coarser grinding of the gangue material because of this cascading action. This is an actual physical and mechanical process. In grinding a sulphide ore prior to flotation, we try to produce a product where the minerals are freed at the coarsest size. If a piece of ore is struck a sharp blow it will break along a plane or line of weakness, and crystal faces; or the interface between two minerals, which is a weaker plane than through the solid mineral. The cascading effect of the balls gives this sharp impact grinding.

In the work on grinding done at Ascot Metals, we found that if the ore was ground in an overflow type ball mill with conventional wave type liners, it was necessary to grind to 90% minus 200 mesh to liberate the minerals. In a low discharge, grate mill, using a liner with a heavy lifter bar, liberation was complete at 65% minus 200 mesh. Gotte records similar experiences in his paper on the early work on the Tsumeb ore in South Africa.

The improved metallurgy is probably due in part to the low density of the mill, and the decrease in horsepower necessary to effect the grind. There is not enough data available to determine how much of the difference in horsepower formerly entered the picture as heat energy. It would be interesting to know if Mr. Lewis noted whether or not there was a decrease in temperature of the mill discharge after the change was made. Lower density should lower the temperature because the extra water will carry away heat. The decrease in horsepower and lower density should combine to make an appreciable change of temperature.

"Stray" chemical reactions that take place in grinding mills will increase their rates of reaction with increase in temperature. The writers know of two mills, both treating copper-pyrite ores, that improved their metallurgy by lowering the density of the pulp in the ball mill to reduce the temperature of the pulp. In one case improved results were being had on night shift compared to day shift. The cause was traced back to a tired ball mill operator who always opened the ball mill water line to prevent the mill from plugging while he "rested". In the other plant it was found that with the coming of spring and warmer water, grade and recovery both fell off. The density of the mill was lowered and results became normal. Towards summer the condition became such that further lowering of the density (under 60% solids) affected grinding and, to keep the temperature down, the ball load was decreased. In the latter case it was noted that when the temperature of the mill was allowed to go up, the reducing power of the pulp increased, grade fell off, recovery of the copper was lower, and excess reagents had little or no effect on the situation.

We have always had difficulty in correlating the grinding data published by the gold mill operator, where he is grinding for the dissolution of gold by cyanidation, and data supplied by the base metal operator who is grinding as a means of liberating a mineral particle so that it may be physically lifted out of the circuit. It appears to us that when grinding for cyanidation, one should strive for the maximum of attrition which will cause the solvent to act on the freshly ground faces and at the same time spend any excess energy in the form of heat to increase the rate of reaction. This is the antithesis of grinding for flotation, of sulphide ores, where the ideal condition would be to have all minerals separated at their maximum size, and their surfaces conditioned to float only when wanted. Real confusion starts when efficiency is expressed in terms of dollars recovered, per ton of ore treated, by the processes that follow.

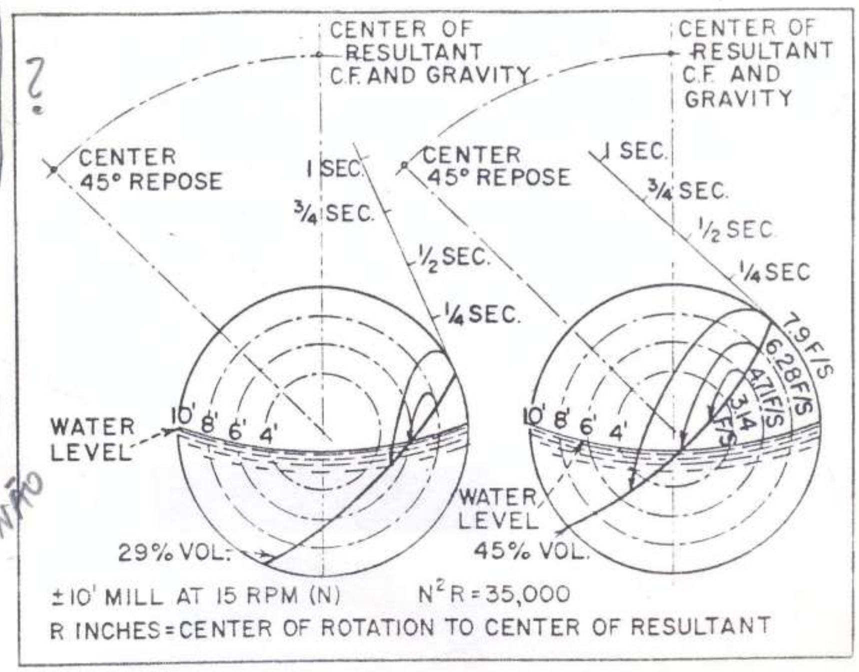

FIG. 2. Gates calculates theoretical ball paths and indicates that improvement in performance is due to the marked difference in ball action.

A. O. GATES
Utility Engineers, Inc.
Salt Lake City, Utah

THE DIAGRAMS (Fig. 2, above) of the conditions inside the ball mill at Copperhill are my contribution to the discussion of grinding at Copperhill. They show a marked difference in the falling ball action.

Of course the approximation of a 45-deg. angle of repose for the balls is arbitrary; a smaller angle would make less drop to the balls, and vice-versa, but the difference would still be marked.

The formula, N^2R equals 35000, where N is rpm and R is radius in inches measured from mill center to the center of the resultant forces acting upon the material in the horizontal rotating cylinder, comes from making centrifugal force equal to the force of gravity in the units of ball mill practice.

Critical Speed is taken as that of the shell of the mill; by the above formula for 10-ft. diameter it would be about 24.1 rpm, and 63% of critical figures at 15.2 rpm which is a good enough check on the assumption that it is a 10-ft. mill at 15 rpm. Of course the real critical speed should be taken inside the liner and at the center of the average ball against the liner. Due to wear variations however, that is impractical and is not absolutely necessary when there are other variables unmeasured like the slipping of the balls on the liner and each other.

The water levels are swung from the resultant center which makes the forces against the surface equal at all points when the mill is rotating; probably it would rise slightly on the right.

For any further guesses, it would be nice to see the screen analysis of the feed and the products given only as 200 mesh: say at least five values split around the 200 mesh.

L. E. DJINGHEUZIAN
Department of Mines
Ottawa, Ontario

MR. F. M. LEWIS MUST BE CONGRATULATED on the remarkable results obtained from his experiments. There is very little doubt in my mind that

(Continued on p. 202)

Copperhill
(Continued from page 88)

when the significance of these results is understood, it would be found that a new fundamental contribution has been made to the budding science of grinding.

Having studied the discussion, it seems to me that Mr. B. S. Crocker offered a very good explanation when he referred to ball paths. It stands to reason that most efficient ball load is a function of the critical speed at a given temperature with all other conditions being constant. And the efficient performance of this ball load is expressed through the ball paths. So, when Mr. Crocker concludes his discussion by saying: "It may be that the phenomenon recorded at Tennessee is common to slow speed mills only," he is pointing out a very interesting possibility that the ball paths, hence the ball loads, must be tied directly to critical speeds.

I would like to go further:

I think that at a maximum efficiency or when Bond's work index is at its lowest, there is a definite relationship between ball loads and critical speeds. In other words, if:

W = ball load (% volume)
N_0 = operating speed (% critical),
then $W = f(N_0)$.

In the case of Tennessee we have:
$W = 29\%$, $N_0 = 63\%$.

In the case of Lake Shore:
$W = 50\%$, $N_0 = 81\%$.

Now, the question is: What are W's between $N_0 = 63\%$ and $N_0 = 81\%$? Could the mill operators supply the answer to this question? It is, of course, realized that this is not a question which could be easily answered, especially since the data must be tied to maximum efficiencies. However, it is hoped that at least a few of the mill operators might be able to help. And once we have a few values for W between $N_0 = 63$ and 81%, it is my hunch that the answer would be a mathematical relationship, probably a very simple one.

In conclusion, I venture to offer a tip: to the experienced mill operator, the most efficient ball load, under given conditions, produces a sound which is like a symphony to his ears, and it is the ball paths which compose this symphony.

E&MJ wishes to thank those men who have contributed their knowledge and experience to this discussion which has appeared in the June and September issues.