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The Bond Legacy

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ABSTRACT

Fred C. Bond is recognized throughout the mineral processing world as the father of comminution equipment applied science and engineering. The Bond Work Index became a universal standard, and is the most widely used measurement tool for comminution energy consumption. This biography is the story of his lifetime of study, work experiences, experimentation, analyses and findings. His numerous published writings are reviewed. His legacy is one of comminution process engineering that will be used in perpetuity.

INTRODUCTION

Fred Bond was a strong student; an analyst; an engineer; and a writer. He was also a spiritual thinker, which the writers have concluded contributed importantly to his technical achievements because of the honesty and humility so instilled in him. Bond never allowed his preconceptions to cast doubt on measured data. If there is a primary lesson to be learned from the study of his professional life it is that creating a valuable legacy requires unbiased acceptance of the all the facts.

Bond long struggled with how to measure "size reduction" from one complete size distribution to another, a requirement of relating size reduction to energy input. Rittinger's premise based on new surface area appeared logical, but could not be proven (or dis-proven) with any certainty because of the difficulty of measuring surface area, as well as the undoubtably different efficiencies of different breakage machinery. Taggart's eighty percent passing size was therefore essential to Bond's discovery of his Work Index relationship. However, much of his working life from the time of this major discovery he spent dealing with its limitations and inadequacies, applying "correction factors" and the like. His final publication on the topic of his "Third Theory" literally stunned these writers.

Nevertheless, nothing can diminish the absolute brilliance of a simple equation that empowers process metallurgists to compare any size reduction (machine or circuit) energy usage to any other one on the planet. The Bond standard of the equivalent energy to reduce rock from infinite size to one hundred microns remains the most powerful and wisely used measurement tool in comminution process engineering.

This is a biography of Bond's professional life. He was also a detailed journal keeper and photographer, historian, and theologian. He wrote prolifically on these as well as technical topics, and completed a personal autobiography. The reader is referred to the chronology in the Appendix for a summary of his education and working life

THE BOND LEGACY

Part 1. Before Allis-Chalmers, 1899–1930

> *"Who knows what's good and what's bad?" An anonymous farmer.*

James Bond emigrated from Devonshire, England, arriving in Philadelphia in 1846. His son, Frank J. Bond, and Harriet L. (Songer) Bond, were Colorado ranching pioneers of the 1860's. Their son, Fred Chester Bond, was born June 10, 1899, at Belcher Hill, now Jefferson County's White Ranch Park, near Golden, Colorado. He had two younger sisters, Grace and Dorothy. As a child he suffered a shoulder injury from a fall. It was not treated properly, resulting in a permanent dislocation that slightly affected range of motion. While not bothersome, nor even noticeable, it nevertheless limited him athletically and, although he registered for the draft during World War I, excluded him from military service. Thus, Fred Bond was more inclined towards intellectual pursuits, both scientific and spiritual.

Bond attended the Fruitdale primary school, graduating at the top of his class (of eight) in 1913. His time at Wheatridge High School, where he graduated as Salutatorian in 1917, included a field trip to a gold mine, and was highlighted by being part of the school competitive drill team. With the aid of a scholarship, he attended the University of Denver from 1917–18, focusing on chemistry, at which, along with mathematics, he enthusiastically thrived. He transferred to the Colorado School of Mines (CSM), again focusing on chemistry and now also metallurgy, and working as a lab assistant, to obtain the B.S. degree of Engineer of Metallurgy in 1922. His summer job in 1921, his first in the mining industry, was as a surveyor for the Radium Luminous Materials Corporation mine in Naturita, Colorado. He wrote a graduating thesis paper (not required) on the concentration of radium ore by flotation (1922).

Upon graduation he accepted a job as assayer for a new gold mine owned by Barton Gulch Mining Company near Virginia City, Montana. This was at the request of a new manager who also graduated from the Colorado School of Mines. His assay results soon revealed the mined material to be essentially worthless, and the operation shut down two months after Bond's arrival.

Bond quickly found a new job as silver assayer for the U.S. Mint in Denver, but the routine and bureaucracy were stifling. He soon left and took a fellowship (instructing labs and taking classes in chemistry) back at the Colorado School of Mines. This lasted for only about one semester when his previous manager at Barton Gulch, who was now starting up a new silver and gold property at Sabana Grande in Honduras for the New York and Honduras Rosario Mining Company, hired him once again as assayer. It was late 1922 when he left for Honduras on a two-year contract.

Figure 1. Fred C. Bond, student in metallurgy (*The Prospector 1923*, Annual of the CSM)

The job went well for Bond at the new Sabana Grande property, where he learned about the flotation circuit and began to learn Spanish, in which he became fluent. He was soon called on to replace the retiring head assayer at the nearby and same company-owned Rosario property, a major world class silver producer. The number of samples could total a hundred or more a day, and assays were the key inputs to the financial performance of the mine and the mill, and the keen competition between them. Here he also learned about the cyanide plant, and witnessed the operation of around fifty Allis-Chalmers stamps followed by tube mills. He noted that these mills were converted from the use of imported pebbles to those sourced from hard rock from the mine, for enormous cost savings (and much later also noted them as early autogenous grinding mills). He was encouraged to write about the mill pumps, which writing was incorporated into an article on the operation that was published in *Engineering and Mining Journal Press* (E&MJP) in 1923. This marked the birth of his interest, and skills, for technical writing, and he authored or co-authored five articles related to precious metals recovery by cyanidation for the same journal by 1926.

Collecting and weighing tiny gold residue particles at Rosario contributed to Bond developing eyestrain and short-sightedness. This forced his transfer to the underground mine as a surveyor. One morning Bond slipped from a gangplank and fell sixty feet, feet-first, into soft mud, but was knocked unconscious by the falling plank. He was rescued, semi-conscious, by rope, and transported to surface, shaken but barely injured. Refusing to go back to assaying, he was given the highly undesirable job of cleaning in the refinery, locked in for security reasons and exposed to heat, chemicals, cyanide fumes and the like.

The Honduran revolution broke out in 1923 following a disputed election. Fighting took place all over the country, including around the mine. Company payments to both sides apparently kept them unmolested. With transport shut down, they hid enormous values of accumulated bullion. The manager granted Bond's request to cut short his contract by several months. He and four others were shipped off on pack mules, with a guide, on a circuitous route through the mountainous jungle, back to rebel occupied Sabana Grande. A few days later he was carried by transport truck to the port of Amapala. Several more days passed before given passage on a cargo steamer which could accommodate a few passengers. He arrived three weeks later, less his baggage, in San Francisco.

Bond returned to the Colorado School of Mines as Instructor ("Fellow") in Chemistry in late 1924, a position he held until 1929. Walter Landon Maxson served there as an Associate Professor of Metallurgy, and would later recruit Bond to join him at Allis-Chalmers. Bond spent the summer of 1925 as a Designer (draftsman) for Tennessee Copper Company. He married Margaret Jean Lowe in 1925, and completed his M.Sc. in 1926. During the summer of 1926 he worked on studies of reverberatory furnaces for United Verde Copper Company in Arizona. The summer of 1927 he spent as assayer and mill man at a cyanide gold mill near Breckenridge, Colorado, owned by Steiner Bros. of Denver.

Bond spent the summer of 1928 teaching and left the School of Mines in the spring of 1929 to return as a draftsman to Tennessee Copper Company.

From 1926–29/30 he wrote two articles on chemistry of metallurgical processes, a teaching booklet on introductory chemistry, and a number of others on topics of general interest. Note that "Viscosity of Mill Solutions" addressed the effects of temperature, dissolved salts, etc., on cyanide solution viscosity and reactivity, and was not about mill slurries.

The recession led to a short stay at Tennessee Copper, a company takeover to another short stay with a chemical (cyanide) production process design firm in Niagara Falls, N.Y., and his return to the Denver Mint. He turned

Figure 2. Fred C. Bond, instructor at CSM, 1927 (courtesy of Bruce F. Bond)

down a Fellowship in Chemistry leading to a Ph.D. from the University of Minnesota because of the need to provide financially for his family. His former Professor, Walter Maxson, now with the Allis-Chalmers Manufacturing Company, then recruited Bond to head their Laboratory of Mineral Dressing near Milwaukee, Wisconsin. He started at Allis-Chalmers in June, 1930, rejoining a former fellow CSM student, Frank Cadena, who was also employed there.

Part 2. Allis-Chalmers, 1930–64

Bond's initial job at Allis-Chalmers was to carry out assays and design gold recovery processes from clients' samples. Allis-Chalmers designed and constructed complete processing facilities at the time. Cadena and Bond, led by the sales engineer, Maxson, also helped with the development of a ball mill closed circuit grindability test that Allis-Chalmers used to size mills (more on this later). By 1932, Cadena was laid off, and Bond worked only half time. With little new business coming, in 1933 he was assigned to the construction of the uranium plant at Port Radium, on Great Bear Lake, Northwest Territories. Here he learned to speak Canadian. The plant had a crusher, rod mill, two ball mills and a flotation circuit, all line-shaft belt driven by a diesel motor. The plant was started up in January, 1934, and Bond left in April. He returned to Milwaukee with growing interest in rock breaking science. In hopes of gaining a better understanding of rock breakage, he enrolled in night classes in physical chemistry at Marquette University. But in 1935 he was sent to assist in the construction of the Compania

Minera Nacional, S.A., gold plant in the Andes mountains of Peru. He was joined there by his family. At start-up he ran the grinding and flotation circuits. He visited numerous mines in the area, including Bolivian tin plants, on behalf of Allis-Chalmers. He helped clients' make major improvements to gold cyanidation operations, at which he had become recognized as an expert. He turned down an offer to extend his stay in South America to continue doing such work, and returned to Milwaukee in late 1936. This was largely for family reasons, but also to cultivate a growing interest in comminution.

Bond's first published article related to comminution was entitled "Calculating Average Particle Size from Screen Analysis" in *Engineering and Mining Journal* (E&MJ), July, 1931. It provides a method to represent a complete size distribution by its "50% median grain diameter" by interpolation between the sieve openings passing above and below the 50% cumulative passing. Although not suggested in the article, this could be considered necessary to relate energy used to measured breakage, the "average" particle size before and after comminution.

In his first major coauthored publication on grinding, the 1933 "Grindability of Various Ores," Bond first mentions a timed, laboratory, batch ball mill grinding test that was used early on at the Allis-Chalmers laboratory to compare ores, similar to the method of Lennox (1919). Mill sales engineers (including Walter Maxson) used this information and data they collected (and zealously guarded, in their "little black books") on plant mills' grinding performances to help size mills for new customers' plants. But they discovered that a locked-cycle test was needed to deal with a hard to grind fraction in the ore. The timing of the transition to the locked-cycle test is not precisely mentioned. However, Bond prepared the paper on the new method, along with example calculations and more than seventy test results on identified ores and other materials, and presented it to the AIME meeting in New York in February, 1933. He listed W.L. Maxson, F. Cadena and himself, in that order, as co-authors. The Allis-Chalmers grindability test that they described in 1933 remains today as the universal standard for the industry. Although later renamed the Bond Work Index Test, given Bond's relatively short tenure at Allis-Chalmers at the time, beyond writing the paper Bond likely played a lesser role in developing the test compared to the others listed as first and second authors.

Bond suggested that this publication "marked the beginning of the end of secret little black books of grinding results." But it provided only the half of the data related to the ore needed for mill sizing. The second half was the (unidentified) plant grinding mill performance associated with each of the grindabilities. The latter would be revealed publicly over a decade later.

The paper also included tables of the test feed, product, and circulating load particle mean diameters, as calculated by the method in the previous reference. No analysis of these was attempted. They also reported on running the test wet, vs. dry, showing a 1.5 to 2 times higher net production rate, depending on percent solids. They suggested that the same test could be used to study numerous other grinding variables like mill speed, media load and size or shape, mill lining and circulating load.

It was at that meeting in New York that Bond also first met Prof. A. F. Taggart. Taggart later (1945) described the Allis-Chalmers test as a variation of the Yancy developed ASTM procedure for the relative grindability of coal (Yancy et al, 1934). The shorter and simpler, yet locked-cycle, method for coal was being developed at the same time as the Allis-Chalmers method. However, there is no suggestion that the two laboratories ever discussed their respective work. No test on coal was listed by Allis-Chalmers in 1933. Later, the U.S. Department of the Interior (Obert et al, 1946) adopted the Allis-Chalmers method as the sole means to suitably characterize the ball mill grindability of rocks and minerals.

It should also be emphasized that both these, and other, test results were recognized and referred to as "relative grindabilities" of ores, correctly indicating that changing the test conditions, and resulting interactions with different ores, could change even the relative outcomes. Batch vs. locked-cycle test results clearly exemplified this.

Despite his lengthy assignments abroad from 1933 to 1936, Bond, along with Maxson, produced "Crushing and Grinding Characteristics as Determined from Screen Analyses," submitted it to the AIME in August of 1934, and it was published in the transactions in 1935. They described how examination of screen analyses could reveal both ore characteristics (e.g., a hard grinding fraction accumulating at a certain size) and comminution conditions (e.g., a narrower product sizing from less overgrinding). They noted that Gaudin's (1926) observation of log-log linearity for the fine fractions of ground material size distributions was highly prevalent. They also expressed that "practical efficiencies" should compare relative grindabilities to equipment power used at the same grind sizes, and that these did not follow Rittinger based "absolute power efficiencies" estimated from calculations of new surface areas.

In 1935 Bond also wrote an article for the June *CSM Magazine* entitled "The Theory of Crushing." This was a highly theoretical analysis of new surface area produced with breakage of rectangular cuboids into specific geometric shapes. He concluded that Rittinger's law, which states that the useful work done in crushing is proportional to new surface area produced, is only valid for particles of the same relative shape (height to width to thickness ratios).

Bond's 1937 article in AIME'S *Mining and Metallurgy*, "Determination of the Circulating Load in a Wet Closed-Circuit Grinding System," presented use of the two-product formula to calculate classifier solids split from the percent solids of the classifier streams, or the circuit feed tonnage from the water dilution rate. He stated that this was better than using individual screen sizes, which, even with small measurement errors, gave highly variable results with different mesh sizes. In 1950 Bond updated the method. As an alternative to using the stream percent solids, error was reduced by using graphed size distributions, and, perhaps most significantly, "the suggestion by Professor Taggart (1941), … the size which 80% passes."

In the 1938 *Engineering & Mining Journal* article, "Reduction Ratio Curves for Crushing and Grinding," Bond showed that the amount of size reduction measured by certain cumulative size passing ratios between the feed and product could be related to energy consumption. This was suggested at the time to hold potential promise for comminution machine power specification.

Presented at SME in 1938 and published in 1939, Bond and Maxson's "Grindability and Grinding Characteristics of Ores" firstly expanded the ball mill grindability tables given in 1933. It followed with a method of calculating surface area from screen analysis, and subsequently, the new surface generated on ten-gram samples with the net energy (work) input from an Amsler pendulum impact testing machine. They proposed this method of generating new surface area to be "absolutely efficient." Comparison of test results on several ores ground with the Allis-Chalmers grindability test ball mill (estimated energy input of 85.7 joules per revolution) put its relative efficiency at close to 60%. Commercial, wet closed-circuit ball mills, they said, produced relative efficiencies averaging 63.5%, but that these were affected by circulating load. They finally concluded that new surface area generated per revolution of the test mill is constant for any given ore ground to different finesses, in agreement with Rittinger's law.

Bond's paper on the sedimentation balance (a precision balance pan suspended in liquid that collects and weighs settling particles with time) for measuring fine particle size distribution was published in 1939 and presented to the AIME in 1940. It covers a lengthy, extremely detailed description of the equipment and procedure from an intensive investigation carried out at the Allis-Chalmer's laboratory. He also provided a table to convert size fractions into surface area, again to be able to interpret grinding results in terms of Rittinger's law. Numerous complexities and assumptions meant that it did not develop into a practical tool for his, or plant operators' purposes, as he had hoped.

Up to this time Bond's theoretical work results largely supported Rittinger's law. The difficulties in putting this to practical use for equipment design, in particular the specific energy needed for a given amount of size reduction, were significant. Surface area of ground materials was difficult to measure. Screen analyses were used in industry as grinding liberation proxies, and did not convert readily to surface area. The finest fractions dominated surface area, and did not reflect useful grinding, but rather over-grinding in terms of mineral liberation and often downstream recovery. And different machines clearly displayed different size reduction "efficiencies," depending on the means by which they applied their energies. Classification in closed circuit systems added to the complexities. Theoretical size reduction efficiency versus practical terms for machine, or circuit, relative comminution "efficiency" was recognized, but the two were not reconcilable.

Bond presented and published "Wear and Size Distribution of Grinding Balls" in 1940. He starts by referring to the above Bond and Maxson (1938–39) work which showed that Rittinger's law of surface area creation is proportional to the work input holds with different ball sizing, even though the resulting distribution by size class varies. He then discusses ball wear from over nine years of continuous records of rates of wear of each ball size using their standard laboratory dry testing ball charge. They concluded that larger balls wear slightly faster than smaller ones, as would be expected due to impact forces. Equilibrium ball charges were so calculated, from charging a single size, from 5" downward. From this the total surface area of an equilibrium charge is calculated, as are relative total ball consumption rates. Bond follows with a theoretical discussion of matching mill feed size distribution with the best suited ball size distribution to maximize production rate through a given screen size, the most common objective in ore grinding. In passing, he notes that "the use of a circulation load and short detention time in the mill," are also best for this objective. He concludes that "rationing" (addition of a second smaller size) would be beneficial in most cases. But, as noted, the relevant discussion in the paper on the best suited ball sizing for grinding a given grinding circuit or mill feed is strictly theoretical, and no practical guidelines are provided.

In 1940 Bond also co-authored "Deleterious Coating of the Media in Dry Milling" with F.T. Agthe for AIME, which was also published in *Rock Products* (1941) and

Building Science Abstracts (1942). Numerous materials were lab ball mill tested and showed that most tended to result in ball coating when ground finely enough, although a few (glass, for example) did not. The possible mechanisms (electrostatic, adsorption, mechanical) and the roles of moisture and certain mixtures were discussed, along with the role of grinding ball material. Small quantities of a lubricant (such as coal) or a patented liquid reagent (containing lignin) were shown to almost eliminate ball coating.

Bond's 1941 paper on "Measuring Surface Area in Grinding" provided a method for estimating total surface area produced in grinding based on that of individual mesh sizes, once again needed for demonstrating Rittinger's law. It required the existence of a "grind limit" below which further breakage would not take place, an assumption which was challenged by Prof. Schuhmann in subsequent published discussion of the paper.

Bond followed with "Shape Factors of Comminution Products." Dimensions A, B and C were defined as the largest dimension, largest dimension at right angles to A, and largest dimension at right angles to B and C, respectively. C is measured by screen analysis (square openings). He compared five crusher products, noting how the "shape factor," the deviation from an ideal ellipsoid, changes with size reduction of different materials.

In 1942–43, Bond provided equations that could be used in sand blending for *Rock Products* magazine. They provided the ratios of materials needed to be added or removed in order to achieve a desired size distribution specification.

In 1943 Bond and Maxson updated the 1933 and 1938/39 tables of the ball mill grindability tests, and added a table of eighty-five "standard rod-mill grindability tests." Rod-mill grindability tests were never previously mentioned, but had "become increasingly important," apparently with the growth of rod milling. No discussion was provided of its development at Allis-Chalmers, which presumably took place mainly since the previous 1938/39 publication. The test was described in detail, and used the same equipment and procedure that is prescribed today.

In 1944 Stanley D. Michaelson solely (notably, almost inexplicably, without Bond) published the paper on "Determination of Ball Mill Size from Grindability Data." This revealed exactly how to select a ball mill for a new operation based on a grindability test of the circuit feed. A series of plant "standard operations" were studied to determine net (amount in the circuit product minus that in the circuit feed) production (or grinding) rate of a given particle size per kilowatt-hour (for example, the net tons of new minus 200 mesh size per kWh). Grindability tests were performed on samples of the circuit feeds taken during the plant studies so the net circuit production/grinding rates could be compared to ball mill laboratory test grindabilities on the same ore. A comparative (graphical) data base of grindabilities of these ores at different grinds was created. For a new circuit, the ore's grindability at the same mesh size would be compared to a higher and lower grindability ore, and the new plant required kWh/t estimated from those of the two "standard operations" by interpolation. An adjustment could be made for known efficiency factors, such as that for grate versus overflow discharge (providing approximately 4% higher efficiency) and mill diameter (not quantified by Michaelson). The kWh per ton times the design tonnage provided the needed mill power. Mills of appropriate diameter and length were then selected on the basis of reference mills which provided power draw per ton of grinding media.

Although referencing four of Bond and Maxson's jointly written papers, Michealson acknowledged only "the staff of Allis-Chalmers Manufacturing Co., under the direction of W.L. Maxson" at the end of the paper. As the author he identified himself as Ore Dressing Engineer currently (Dec., 1944) serving as a Major in the U.S. army. Michealson had joined A-C circa 1936 (a relative, nee 1913) newcomer, compared to Bond in 1930, and Maxson previous to that), served in the army 1941–46, and left Allis-Chalmers in 1947. He then worked for U.S. Steel and Kennecott, advancing to Chief Engineer at both companies. He was active in the SME, for which he became president in 1958.

Michaelson's sole authorship is extremely odd. The importance of the topic suggests high level clearance would be needed. The work was not much of his doing. It was not presented at any conference. He acknowledges the above mentioned for "their review and approval of the subject matter." Does exclusion of others, and his later professional success, suggest great ambition? He also references a paper by himself, Wolf and Maxson "read at AIME in February, 1938," but not written, on the effect of circulating load on grindability test results (these are "rather minor," they said, over the range of 100% - 1,000%).

In "Cushing Tests by Pressure and Impact" (1946), Bond describes the development of impact crushing tests at Allis-Chalmers, culminating in the twin pendulum crushing tests still in use today. It is notable that they avoided drop-weight methods on the grounds that an indeterminable portion of the energy is transmitted into the base.

In a complete change of topic, Bond wrote "Thickening and Settling" (1946) describing fundamentals and testing methods for the design of industrial thickeners. At the time he was involved with the development of a new thickening devise for Allis-Chalmers, which unfortunately did not prove to be successful. According to his son Bruce, the senior Bond joked that the topic reflected the response of his body to aging at the time. A pre-cursor to this work was "Speeds Thickening Capacity Tests," *Engineering and Mining Journal*, January, 1940, in which he described a method to shorten the time needed to conduct the usually tedious thickening settling tests in graduated cylinders.

Bond's discussion of ball wear as a function of ball size in fine grinding was published in 1946 *AIME Transactions*. He wrote that Allis-Chalmers laboratory experience was that ball wear at low mill speeds is related to their surface area (or diameter squared), but at high mill speeds is related to their diameter to the power 2.29.

In 1947, Bond again updated tables of ball mill and rod mill grindability tests, this time with the addition of impact crushing tests. The same year he co-authored "Rod Milling—Plant and Laboratory Data" with J.F. Meyers of Tennessee Copper Co. (the leading author) and S.D. Michaelson. In it they tabulated the operation of 25 industrial rod mills and one roll crusher for which they also conducted grindability testing on the feed. New surface areas were calculated from mill feed to product using three methods, as were reduction ratios based on Taggart's (1943) method of using the 80% passing (P80) sizes. Relative efficiencies were calculated based on the comparative surface areas of plant grinding versus that of the grindability test, and also by the ratio of net product per kWh to grindability at the same product size. The rolls crusher was considerably most efficient. Many trends were noted, but aside from stating that rod mills were clearly more efficient on harder to grind ores, conclusions were limited to the apparent lack of consistent effect of many variables (for example mill speed, diameter, and reduction ratio) on their grinding efficiency. Lack of certain data (in particular rod charge level) was also noted. They said Rittinger's law was supported by the lesser effect of variables on surface area efficiency than size production efficiency, although the latter was more useful for mill operators.

In a preprint prepared for the 1948 annual AIME convention, Bond reported on "Ball Segregation in Grinding Mills." A series of tests in laboratory mills showed that spiral liners and tapered mill shells have a similar effect on ball segregation, that is the migration of larger balls towards the feed end of the mill.

Bond had been promoted from Metallurgist, Mining Department, to Head, Processing Development Laboratory, to Director, Basic Industries Research Laboratory (reporting to the Manager of same) in 1944. That year they also moved into a larger, newly constructed processing research facility. But in his own words, "It became clear to me that I was not a good manager, administrator or executive. I was not good at delegating." In 1950, one of his staff member's technical errors led to loss of an equipment order, culminating in Bond's demotion to "Consultant" and his replacement by Will Mitchell. He called his staff of about twenty together and told them "You are being released from Bondage." His technical capabilities were never in question, however, either by Bond himself or Allis-Chalmers management. And while personally financially responsible, Bond was similarly somewhat unaware of economics. When driving through small towns apparently devoid of industry, going from Milwaukee to Denver on vacation, he commented "They must do each other's laundry." (B. Bond, 2012)

In 1950, Bond's discussion of a paper on "The Effect of Mill Speeds on Operating Costs," by H. Hardinge and R.C. Ferguson, was published. He supported low ball mill speeds (50–55% of critical), particularly for overflow (versus grate) discharge mills, from an operating cost perspective.

Bond co-wrote "A New Theory of Comminution" with Jen-Tung Wang in 1950. Wang was noted in the author descriptions to be "Professor of Machine Design, Chekiang University, China; on leave of absence at Allis-Chalmers Manufacturing Co., Milwaukee, Wis." Wang analyzed energy usage of a broad range of crushing and grinding machines and graphically presented an approximate, empirical relationship with particle feed and product sizing for a range of ores. The sizes were represented by Taggart's (1943 AIME paper and 1945 *Handbook*) eighty percent cumulative passing sizes. Specific energy usage in HP-h/t "is equal to one half of the square root of the term reduction ratio to the one-half power, divided by the product size in inches," and "hp-hr per ton = Ki x (n^0.5/ P8 0)$^{0.5}$, where Ki = 0.5 on average (medium hardness) materials, 0.25 for soft, and 1.0 for hard materials." The relationship HP-hr per ton versus the square root of reduction ratio divided by P80 (n^0.5/P80) plotted (with substantial scatter) as a straight line on a log-log scale. They termed it "the strain energy theory," and demonstrated that it compromised between the Rittinger (new surface area) and Kick (reduction ratio) theories. Until now, Bond, and others at Allis-Chalmers, had generally expressed support of Rittinger's theory, although troubled by the inability to measure surface area of extremely fine particles and its impracticality with regard to the plant product sizing needed for mineral separation purposes. They also admitted that it was inadequate in that it does not cover variations in operating efficiencies of equipment reducing large and small particles. And they hinted it may ultimately lead to an as yet undisclosed "correct theory," and "a more satisfactory concept of the theory of crushing and grinding" that would include these factors. In fact, in his autobiography Bond states that he had discovered his "Third Theory" some years previously, and was busy checking and validating it before public release. The published discussion strongly disputed this paper's findings, but it was nevertheless the harbinger of what was to soon follow.

In 1950 Bond also published in *Engineering and Mining Journal* the previously mentioned update of his 1937 paper on classifier separation calculations, as well as "Selecting Rods of the Proper Size for the Rod Mill." From his data base on industry operations, Bond presented an equation relating the rod diameter being used to the feed F80 size, the Allis-Chalmers rod mill ore grindability at 14 mesh, mill speed and diameter, and ore specific gravity.

In the July, 1951, *Pit and Quarry* magazine Bond co-authored the article "Principles of Crushing" with Frank E. Briber, Jr., of the Allis-Chalmers crushing equipment division, which they had presented at the National Crushed Stone Association convention. They covered crushing equipment types through rod milling, particle size distributions represented by the eighty percent passing size, the energy prediction equation of Wang, and stage-crushing flowsheets.

Bond first publicly presented "The Third Theory of Comminution" at the SME convention held in Mexico City in October of 1951. He presented it again at the New York meeting in February, 1952, and it was published in *Mining Engineering* in May of 1952. However, the first article written on it was "New Theory Explains Grinding" in the April, 1952, issue of *Chemical Engineering*. It was first to publish a brief, concise summary. "The new theory states that the total work useful in breakage is inversely proportional to the square root of the diameter of the product particles and directly proportional to the length of the crack tips formed." And also "Wi is the work index or total kWh per ton required to reduce from infinite size to eighty percent passing 100 microns." It cautioned that specific problems may call for correction factors in its application, but wonderfully concludes that "now chemical engineers can shoot for more efficient operations through closer predictions and more accurate comparisons of all crushing and grinding operations." The article was not attributed to Bond, and the brevity and clarity was such that it is attributable to a professional writer, but it clearly underwent his review and approval.

The full publication of "The Third Theory of Comminution" in *Mining Engineering* went into much more detail, including large numbers of laboratory experimental data and plant operating data. Empirical equations to convert ball and rod mill test grindabilities and impact crushing test values to work input values were given. He explained these "represented the average of a number of installations," but were directly relatable to "a wet grinding overflow ball mill, 7 ½ foot in diameter inside the shell operating in closed circuit with a classifier. The rod mill equation applies to a wet grinding overflow rod mill 6 foot in diameter inside the shell, operating in open circuit." Correlation of the "Third Theory" (as Bond termed it, following the theories of Kick and Rittinger) was first carried out with 559 laboratory ball mill, rod mill and crushing impact tests on 144 materials upon which multiple tests were performed. The consistency of work index values at different screen closing sizes for the ball mill and rod mill tests, as well as the impact crushing tests, where available, all done on the same sample, he considered validation of the theory that energy consumption was related to the square root of particle sizing. No statistical proof or measure of variability is given, and variability far exceeded the stated experimental error estimate of five percent. "Difference in the breakage characteristics" at different product sizes is mentioned. A second table compared thirty-three plant "operating" work indices from data published by Taggart (1945) to laboratory (crushing, rod and ball mill) tests.

Once again, no statistical analysis is given, but the trend is clear. No explanation is given of how laboratory test samples were obtained that would necessarily correspond with the given plant data, i.e., their associated sampling error. Later mentioned are "correction factors" for a number of

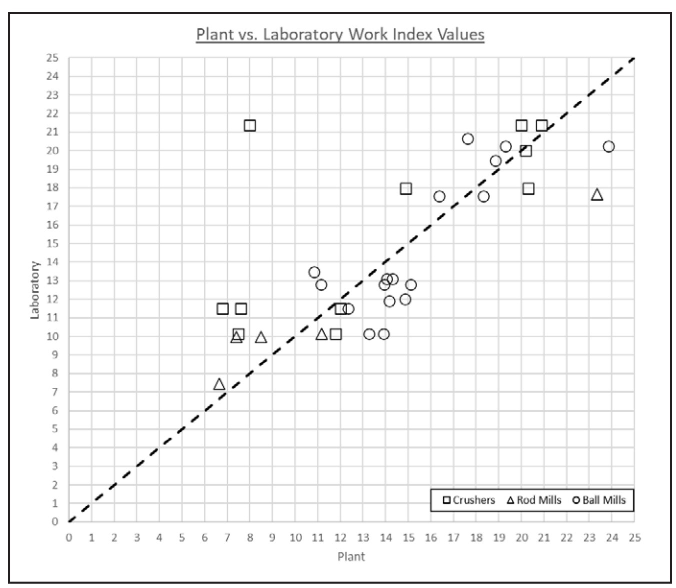

Figure 3. Bond's plant vs. laboratory Work Index values, 1952

Figure 4. Fred C. Bond, circa 1952 (courtesy of Bruce F. Bond)

variables. It is clear that Bond was mainly focused on showing the trends of square root of particle size versus energy usage. He also states that "Comparisons of the relative efficiencies of different plants can be made by dividing the plant work index by the laboratory work index," thus providing a definition of plant grinding efficiency for the first time. Scale-up design of new installations is not specifically mentioned, although it is implied, and "closer predictions," as well as "more accurate comparisons of all crushing and grinding installations," are noted in the closing paragraph.

Bond soon followed with mill selection calculations ("New Grinding Theory Aids Equipment Selection) based on work index in *Chemical Engineering*, October, 1952, and a table of "Average Work Indexes" for fifty-eight materials ("Work Indexes Tabulated," *Mining Engineering*, March, 1953). He expanded these works into more complete treaties on use of work index for rod and ball mill selections in the following publications.

Bond originally presented "Mathematics of Crushing and Grinding" to IMM in London in September, 1952, and it was published by IMM as part of those conference proceedings in *Recent Developments in Mineral Processing.* He again starts by comparing his Third Theory with those of Kick and Rittinger. Equations were given to derive work index values from Allis-Chalmers crushability and rod and ball mill grindability tests. The work index equation was used to calculate kWh/t at each step. Mills were sized from power draw per ton of grinding media, as Michealson had in 1944. He thusly specifies two stages of crushing and selects the rod mill and ball mill, completing the conventional plant comminution circuit of the time. Rod and ball mill media sizing was also included, along with equations to estimate metal wear. He presented an updated variation, "Crushing and Grinding Calculations," to the CIMM in April, 1954, and it was subsequently published later that year in both *CIM Bulletin* and *CIM Transactions*. He presented the same at SME in Chicago, February, 1955, and it was updated by Allis-Chalmers Press in 1956, 1961 and finally again in 1962 replicating its publication in two parts in *British Chemical Engineering* in June and August, 1961. Copyright privileges were apparently shared by Allis-Chalmers, not signed over, throughout.

Meanwhile, in 1954, Bond compared the efficiency of blasting to that of coarse crushing in "What is the More Efficient Rock Breaker?" (*E&MJ,* Jan.) He used the work index equation and some broad assumptions to suggest that they are approximately equal in efficiency. Also in 1954, he wrote of how to "Control Particle Shape and Size." (*Chemical Engineering*, Aug.). He defined shape factor by comparison with an ideal ellipsoid. While he stated that material characteristics dominate product particle state, he noted that machines that break by impact versus abrasion produce more cubical products. He described work index again in the same article. Finally, the same year his comments on "Some Grinding Tests with Spheres and Other Shapes," by C. Chad Norris, were published in the November *Bulletin of the Institution of Mining and Metallurgy.* He used work index calculations to conclude that "This paper is valuable because it offers detailed proof that spherical grinding balls are more efficient than any of the other five shapes of grinding media tested."

In January of 1955, Bond presented "The Role of the Rod Mill in the Grinding Circuit" to a forum on crushing and grinding hosted by the Canadian Institute of Mining and Metallurgy. It described the development of Allis-Chalmers rod mill power draw equation, and the application of the Third Theory to rod mill size selection.

In 1955 Bond summarized his Third Theory in "How Does Rock Break" for *The Scientific Monthly*. He noted great inefficiency in that "Reduction is now accomplished by undirected brute force," and that "Some method of obtaining comminution by a directed energy flow may revolutionize the breaking of rock and result in a great saving of power and steel." This perhaps foretold a later move in that direction by high-pressure grinding.

Bond compared "Wet versus Dry Grinding" at the American Mining Congress in 1956, which was published much later in German (*Aufbereitungs-Technik* nr. 3/1962). He summarized advantages and disadvantages, concluding that the choice "is dictated by extraneous circumstances." He noted that wet grinding would typically provide a Work Index of 12, compared to 16 for dry.

In 1956, the Portland Cement Association published its then internal-confidential report to its membership describing the Allis-Chalmers ball mill grindability test and Bond's Third Theory equation using the test to size ball mills and to quantify the relative efficiency of plant grinding installations "to check all the variables in any grinding set-up." It expounded on the accuracy with which the method predicted full scale milling energy usage. "The Allis-Chalmers ball mill test is recommended for adoption as a standard grindability test for the cement industry."

In the March, 1957, *E&MJ*, Bond responded to questions raised by J.F. Meyer concerning the interpretation of his theories considering a very low speed (59% of critical), low (20%) ball charge ball mill displaying 40% lower Work Index than a parallel one at normal conditions. While sufficient data were lacking for proper analysis, Bond suggested that "in mill classification," or preferential grinding of the significantly heavier mineral, played an important role in this instance.

In September, 1957, Bond presented "Tumbling Mills and Structural Clay Products" to the American Ceramic Society. He presented his Third Theory, and made general observations regarding the use of rod and ball mills for the preparation of structural clay products.

That December of 1957 Bond published "Comminution Exposure Constant by the Third Theory" in *Mining Engineering*. This was a largely theoretical work which attempted to quantify how much larger particles are preferentially exposed to work input. A variation of an earlier unpublished method (see Figure 5) to fit particle size distributions to an equation was presented. He also stated that the best overall size reduction "efficiency" is obtained on single sized particles. Using the Work Index equation, he showed how more narrowly sized particles in closed-circuit ball milling result in better grinding efficiency compared to open circuit, and the resulting product sizing is also narrower. While the matter is compounded by classification effects (which are neglected), as well as the grinding environment's effectiveness on different particle sizes, this paper does suggest that there is a grinding benefit with fines removed from ball mill feed.

In the May, 1958, issue of *Mining Engineering* in "Grinding Ball Size Selection" Bond updated his recommended ball sizing equation from that which he gave in 1952 in "Mathematics of Crushing and Grinding," adding "theoretical considerations" related to his Work Index

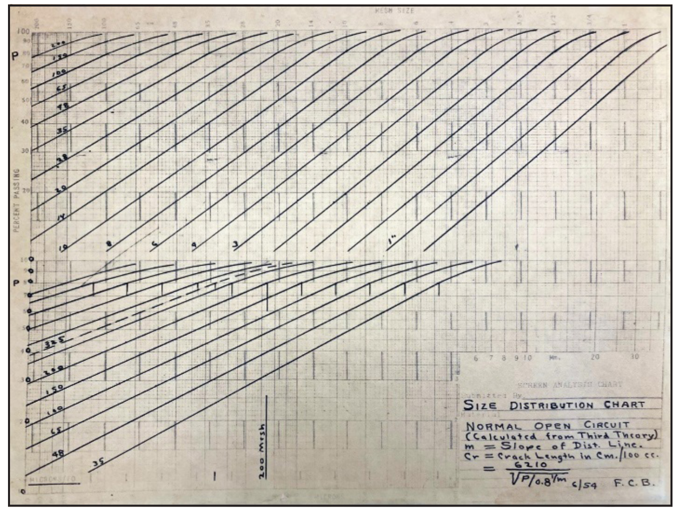

Figure 5. Size distribution chart (courtesy of Robert S. Jermyn, Allis-Chalmers)

theory. (It was later amended to that used today.) He also provided an updated rod sizing equation and tables for start-up equilibrium ball and rod charge media sizes and gave average media wear rates expressed in consumption "per 24-hour day for each 100 hp drawn grinding silicious materials."

Bond and B. B. Whitney (General Superintendent at Inspiration Copper Company in Arizona) presented "The Work Index in Blasting" to a Colorado School of Mines rock mechanics symposium in April, 1959. From the estimated power yield of dynamite and three blasts conducted there with different loading they concluded that the Third Theory can be applied to blasting. Analysis of blast data from other properties indicated that crushing Work Index is likely lower than that for blasting.

"Confirmation of the Third Theory" was submitted to SME by Bond in November, 1958, presented in San Francisco in February 1959, and published in *AIME Transactions* in 1960. Bond used experiments in the 12" × 12" laboratory ball mill and crack length assumed to be related to surface area to demonstrate the Third Theory premise that useful work done is directly proportional to length of new cracks formed, and so the inverse of square root of particle size. He introduced the correction factor to be used for P80 less than 70 microns ((P80 + 10.3)/1.145 x P80) "to account for the increased work done in producing sub-grind-limit particles." He states when material has part of its fines removed its resistance to size reduction based on the 80% passing size is increased, and provides a needed correction factor to apply to that value.

In the same paper he also presented a new "Third Theory size distribution plot" to deal with unaccounted coarse end curvature in log-log Schuhmann (1940) and Rosin-Rammler (1933) plots, and which revealed grain size grindability effects. This was in order to explain observed variations in work index with particle size. This "modified semi-log" plot included the energy input (or "energy register," as he termed it) as a factor in the in the exponent relating particle size to percent passing, and steps to calculate the actual (theoretical) "crack length." While this plot was mentioned in his subsequent writings, it was not material to the basic work index calculations as described in his other key writings like "Crushing and Grinding Calculations," Parts l and ll, in *British Chemical Engineering*, 1961.

Interestingly, this paper also included, in Appendix D, Bond's observation on the effect of circulating load on the 12" laboratory ball mill test results. He said the results demonstrated "no increase in efficiency of new crack length production," i.e., grinding itself. The reduction in calculated test work index (e.g., from 13.5 to 12.2 kWh/t, or just under 10%) in going from a circulating load of 150 to 390 percent he attributed to the increase in "the efficiency of grinding to pass a certain size," and subsequently provided quite small correction factors for open vs. closed circuit grinding (BCE, 1961). This did not consider that plant classifiers impose very different (far less sharp than lab screening) separation, and worsening, in fact, separation performance with increasing circulating load, and despite this worsening classifier performance, overall circuit efficiency increases significantly (Davis, 1925) with increasing circulating load.

In "Action in a Rod Mill" (*E&MJ* March, 1960), Bond used Work Index to show a major loss of rod mill efficiency with broken rods which create void spaces in the charge. He introduced the correction factor for excessively high reduction ratio, and a new (but later amended) recommended rod sizing equation.

The "Three Principles of Comminution" that Bond published in *Mining Congress Journal* in August of 1960 were as follows. First, comminution energy input is the difference between the energy register (in kWh/t) of the product minus that of the feed, the "energy register" representing strain introduced into the particles. Second, energy register increases as particle size decreases, following some exponent, valued at one by Rittinger, zero by Kick, and 0.5 by Bond's Work Index. Thirdly, variations in Work Index at different product sizes are governed by the flaw structure of the material. He discussed these in greater detail in "Principles and Progeny in Comminution," presented at the 1961 SME, adding updated (today's) equations for calculating work index values from rod and ball mill grindability tests. He also re-presented the above-mentioned correction factors for P80 less than 70 microns and feed with fines removed.

As "The Third Theory" became known, Allis-Chalmers used Bond's new notoriety to promote its equipment business. They hailed him in advertising as "A Living Legend" (*Engineering and Mining Journal*, Jan., 1963) which he found to be quite unsettling. A number of following articles, besides the "Crushing and Grinding Calculations" noted above, repeat the "Third Theory" and "Three Principles" themes of presenting both the work index equation and its variations due to grain size and certain design and operating conditions. These include "Principles and Progeny in Comminution" presented at SME in March, 1961; "Crushing and Grinding with Pyro-Processing," *Pit and Quarry*, January, 1962; "New Ideas Clarify Grinding Principles," *Chemical Engineering*, February 5, 1962; "The Laws of Rock Breakage," Zerlkeinern Symposium, Verlag Chemie, Dusseldorf, 1963; "More Accurate Grinding Calculations," *Cement, Lime and Gravel*, March, 1963; "Constant Work Index from The Crack Length," *Engineering & Mining Journal,* March, 1963; "Some Recent Advances in Grinding Theory and Practice," *British Chemical Engineering*, September, 1963.

In the June, 1963 issue of *Canadian Mining Journal*, Bond provided a brief and very general discussion of "Particle Size Reduction—Theory and Practice." He broadly covers types of size reduction machinery, from crushers to rod and ball mills, impact crushers and vibrating mills, and also describes autogenous and semi-autogenous primary mills. He describes his Third Theory, comparing it to Kick's and Rittinger's. He finally notes the modern trends of increasing mill size (up to 4,000 HP) and degree of automation. He mentions the "lower unit grinding costs of these giant machines."

Bond first published on the topic of autogenous milling in *Engineering and Mining Journal,* April of 1962, with "Rock on Rock Grinding—A Growing Technology." What he referred to as "rock-pebble" autogenous mills used ore pieces removed from upstream to grind finely in small diameter to length mills, as practiced widely on South Africa gold ores and on some Canadian uranium and gold ores. These of course qualified as "autogenous" mills. He clarified the terminology and covered the history from the first dry "Hadsel" mill, which mimicked dropping the ore through the mine ore passes with a "large-diameter ferris-wheel" using elevating scoops. These evolved into the "wet primary autogenous" grinding mills of large diameter to length ratio (initially motivated to facilitate better air sweeping in dry grinding) fed by run-of mine or primary crushed ore. With fully autogenous in mind, he provided many useful guidelines covering mill internals, speed, diameter, power draw, feed sizing requirements and desired operating conditions, much of it based on Canadian pilot plant testing (Djingheuzian and Kinasevich, 1959). In "Fundamental Considerations for Rock Grinding," a paper written for (but apparently not submitted to) the 1963 AIME annual meeting, Bond mentions the need for large (5 or 6 inch) steel ball addition, that is "semi-autogenous" grinding, to address critical size (1 to 3") build up for practically all but very soft ore processing. He suggested the option of coarse screening of the large rocks to use as media, intermediate size crushing, then grinding of the minus size fully autogenously with the large rocks.

He followed in May, 1963, *Mining Engineering*, with "Rosario—Pioneer of Autogenous Grinding." Bond pointed out that Rosario, one of his previous employers, had processed more than two million tons of silver ore with autogenous milling from 1918 to early 1940's. They initially used "rock-pebble" mills for fine grinding. When the pebbles imported from Denmark or Normandy became prohibitively expensive, they converted to the use of hand-picked ore fragments, thus making these mills "full-autogenous." By comparison of operating to estimated ore work index, Bond concluded that they operated quite efficiently. He pointed out that this early record of autogenous grinding showed that the then current "new advancements" in autogenous grinding was re-discovery of previous engineering knowledge.

Just before his retirement Bond wrote a very detailed historical review which was published in *Engineering and Mining Journal,* August, 1964, entitled "An Expert Reviews the Design and Evolution of Early Autogenous Grinding Systems." In describing origins, Bond first covered the history of the very first rotary "tube mills," as they were originally referred to, whether using pebbles or grinding balls. He said that his investigations revealed that Rosario was actually the fourth mining district to use autogenous milling, following other applications at the Geldenhius Deep and Crows Deep mines on the Rand in South Africa, Santa Gertrudis in Mexico, and Consolidated Goldfields and Aurora Consolidated in Nevada, all gold milling operations. The pioneer of primary autogenous grinding, without question, Bond said, was A.D. Hadsel, who built and installed the first unit at Beebe Gold. The Hardinge Company took over its rights and installed many more, later developing air sweeping and then adapting it for wet grinding as well. In October, 1964, Bond sent a follow-up letter to the magazine editor to explain that a reader, Charles F. Thompson, of Mine and Smelter Supply Company, Denver, had contacted and corrected him on the first rod mill installation, which took place at Morenci concentrator of the Detroit Copper Company in 1914, along with several others, before the one Bond had listed as first by International Nickel Company, near Sudbury, in 1928.

In December of 1963 Bond presented "Metal Wear in Crushing and Grinding" at the Annual Meeting of the American Institute of Chemical Engineers. It was published in *Chemical Engineering Progress* in February of 1964, and in June, 1964, *Engineering and Mining Journal* as "Lab Equipment and Tests Help Predict Metal Consumption in Crushing and Grinding Units." It provides a description of the Allis-Chalmers abrasion tester, which was adapted from the earlier Pennsylvania abrasion tester. It consists of a rapidly rotating (SAE 4325 chrome-nickel-moly steel hardened to 500 Brinell) paddle inside a 12" drum also rotating to shower 400 grams of ½" to ¾" particles in its path for four periods of fifteen minutes. The weight loss of the paddle is the abrasion index, Ai. Over 170 test results were correlated with plant data for steel liner and media wear (in mass per kWh) in wet rod mills, steel liner and media in wet and dry ball mills, as well as liner wear of crushers. Abrasion indices did not correlate with test work index values. Wear of Ni-hard liners was excluded. No correlation coefficients were discussed, but steel wear estimates are clearly approximate as both media sizing, other different wear materials, and many other varying operating conditions are included in the plant data.

In January of 1964 Bond attended the First Annual Meeting of Canadian Gold Metallurgists in Ottawa where he presented "Crushing and Grinding Calculations," and had further discussion recorded in the proceedings covering several topics during the session on comminution. These included abrasion and metal wear, recommended ball mill speed, open versus closed-circuit grinding, plotting of screen analyses, and power draw of pebble versus ball mills.

Bond completed his 34-year career, officially retiring from Allis-Chalmers, on June 30, 1964.

Part 3. Post Allis-Chalmers, 1964–77

Bond was retained as a consultant, and worked extensively for Allis-Chalmers throughout his retirement. On their behalf in 1965 he traveled to Broken Hill Pty. Ltd., Whyalla, South Australia, and added a consulting visit to Mt. Isa Mines on the same trip. On a second trip for Allis-Chalmers in 1970, he supervised the Mount Gibson grinding and concentration test work conducted at Australian Metallurgical Development in Adelaide, then a government facility. He also consulted for many non-competitors of Allis-Chalmers, including Lithium Corp., Molybdenum Corp., Cyanamid Ltd., Bechtel Corp., Colorado School of Mines Research Institute, Duval Corp, C.F. & I. Steel Corporation, and Climax Molybdenum Company, to list some.

Bond was honored with the SME Richards Award at their annual meeting in January, 1965. The citation on the award read "For major contributions to increased knowledge of crushing and grinding processes and for industrial application of this knowledge to advancement of the milling industry." In his acceptance speech, he reminisced about early experiences, from Northern Canada to the Andes mountains. He noted that the industry still practices methods that are near primitive in terms of "squeezing and chipping" to break rock. And finally, he criticized the then current scientific community for lack of concern for applied practicality (*Mining Engineering*, 1965, Apr., p.96).

Bond's retirement writing can be classified into three main categories. He wrote a monthly column for *Rock Products* from 1965 to 1970. He also published a few (three) journal articles. Finally, he contributed to SME's *Mineral Processing Handbook*, which was published in 1985, eight years after his death.

Starting in June of 1965, Bond contributed a monthly column for *Rock Products* entitled "On Line: An expert looks at the care and nourishment of processing equipment." The topics varied widely through fifty-seven installments, continuing into 1970. The first addressed plant layouts, in particular allowing ample room for clean-up and maintenance and the possibility of future expansion. Another talked of the history of comminution equipment, from the arrastra (a large grooved stone around which animals dragged a rock) to modern crushers. The history of tumbling mills, that of autogenous grinding, Bond's Third Theory following those of Kick and Rittinger, the work index equation, and metal wear in crushing and grinding, all taken from previous work, were covered in the tightly packaged snippets. Bond spoke of the challenges and benefits of technical writing, the nature of consulting work, and pursuit of excellence in one's field. His second-last was a discussion of parallels in the lives of Isaac Newton and Albert Einstein. While adding no significant technical knowledge, being addressed to aggregate plant operators, he explained things very clearly, but without simplification. Every article was titled only by the name of the column mentioned above, but a full list of each of the topics he addressed is provided in Appendix B. These articles were reprinted, with the publisher's permission, in different order and to a reduced extent, in the British *Cement, Lime and Gravel,* out of London, starting in 1970, and subsequently in *Cantreras y Explotaciones*, out of Madrid.

In June, 1967, Bond published "Autogenous Grinding Evolution" in *Mining Congress Journal*. He pointed out the earliest "autogenous" mills used pieces of the ore to replace Danish pebbles in fine grinding tube mills. He made the corrections to the history noted above, which may have driven the desire to write this paper. He distinguished the new approach of "primary autogenous grinding" from the former, and the use of steel media added to create "semi-autogenous," or "ersatz autogenous" grinding, as he said it should be properly named as an inferior or compromise approach. He also described "intermediate (or "selective") autogenous grinding," in which coarse material (say, plus 3") is screened off as media, the remaining material is stage crushed (to, say, minus ½"), and then the two are combined to grind autogenously. He also re-emphasized that "True autogenous wet grinding will find more application when the importance of maintaining a low pulp level in the mill is realized." Separately, he blamed the need to add steel grinding media to a mill intended to operate fully autogenously on a high slurry level in the mill, and recommended in a letter (1966) to Allis-Chalmers that they develop a peripheral discharge.

In December, 1967, Bond published "A New Look at the Old Problem of Separator Performance" in *Rock Products* magazine. He repeats his "separating size" formulation from "Crushing and Grinding Calculations" (1961), which he defines as the size which the cumulative percent passing in the undersize equals the cumulative percent retained in the oversize. He then provides two-product formulae for calculation of circulating load ratio for forward and reverse closed grinding circuits, and added those for "sharpness of separation" and "separator efficiency." He suggests that these values can be used to quantify and thus compare performances of plant separators. (Author's note: However, soon size by size recoveries to oversize and bypass fraction were becoming standard separator performance characterization tools, rendering Bond's, and others' similar approaches, moot.)

On the request of the editor, Bond contributed "Crushing and Grinding—There Should be a Better Way" to the January, 1968, issue of *Mining Engineering.* This was part of a broader article on industry long-term research and development needs. He pointed out that 95–99% of compression energy ends up as heat, and then speculated on different "non-pressure" methods of breakage that may hold promise for the future through research and development. These were centrifugal force; induced vibration; high voltage underwater discharge; induction heating; water or steam injection; lasers; and penetration with an ultra-hard sharp point. He noted equipment size growth, and the need for increased separator efficiency. Finally, he again expressed his reservations about semi-autogenous grinding.

Bond's final published technical writings were for the SME's *Mineral Processing Handbook*, which was published in 1985. He participated early on (the early 1970's) in the planning of this major publication, and is acknowledged for having done so in the list of editorial committee members. However, he found it very difficult to act both as a major writing contributor, as well as an editor, and so resigned from the editorial committee to focus on the former. To this end he compiled eleven chapters covering all the aspects of his grinding expertise.

Because he passed away in 1977, almost a decade before its publication, Bond was not aware that only four of his contributions were chosen for the final publication. Apparently frustrated with the pace of progress, in November, 1976, Bond submitted the entirety of his eleven chapters to Prof. W.A. Cunningham at the University of Texas for the planned *Encyclopedia of Chemical Processing and Design.* The responding request back to him for condensation of the materials was sent two months after Bond's death.

Section 3A of the *Mineral Processing Handbook* was on "General Aspects of Comminution." Bond wrote Ch. 5. "Testing and Calculations." He covers particle sizing, from screen analyses, to options and difficulties in measuring size analysis of fines. He provides the work index equation for calculation of work required, and then a series of applicable "ball mill efficiency adjustment factors." Also similar to previous "Crushing and Grinding Calculations," he provides the equations for mill critical speed and recommended ball sizing. He includes a table of ball mill diameter efficiency, also related to mill speed, extended to 18', which shows increasing efficiency up to, but not including that size, at which a drop in efficiency is shown. He reviews his equations for circulating load ratio and classifier performance, followed by ball and rod mill grindability tests, and calculation of work indices therefrom. He ends this section with a description of the Allis-Chalmers abrasion test, and its application to estimate steel wear rates in crushing and grinding.

Section 3C was on "Grinding." Within Ch. 4 on "Autogenous Mills," Bond wrote the "History of Autogenous Grinding." Here he reiterated much of his previous writing, from the earliest tube mills that replaced chert pebbles with pieces of the ore, to the then growing trend towards large diameter, secondary, semi-autogenous mills. He also co-authored Ch. 8. "Other Grinding Machines" with K.J. Edmiston and M.H. Kahn, covering a large variety of grinding machines and methods outside of the usual ball, rod and (semi-) autogenous tumbling mills. Besides rollers, impactors and stirring devices, they briefly described many unusual means of input energy into rock particles, as examples vibration, high-speed attrition, supersonic sound and high voltage electrical discharges.

But the most striking was what he wrote under "History," in section 3A on "General Aspects of Comminution," reserved as a final note in this biography as one of his most important, albeit last, contributions to his legacy. He first briefly covered methods and machinery, from man's first use of hammers, to the first jaw crusher, the first tube mills, up to primary autogenous grinding and the large (18-foot diameter) ball mills at the time (again, early 1970's) of writing. The next section described "Theoretical Issues," comparing the Kick and Rittinger theories, followed by what he surprisingly termed the "Bond Compromise." He deemed the Work Index equation as "derived empirically as the result of experimental testing," and although "theoretically proportional to the length of crack-tips formed," such concept was "of little value because the length of crack-tips formed is indeterminate except as the square root of new surface area," the latter also an assumption because such surface area could not be measured. Bond thusly acknowledged his Work Index relationship to be an empirical observation, and while highly useful, lacking proof in any theory. His following brief discussion on the gross inefficiency of compression breakage methods concludes with "Because of widely distributed zones of low resistance, rock is not homogeneous to breakage, and there is no basic theory of comminution that can be generally accepted."

Fred Bond died suddenly of an apparent heart aneurism on January 23, 1977, in Tucson, Arizona. His wife, Margaret Jean, died in 1988. They are buried at the Golden Colorado cemetery.

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Topic

1. Importance of room for maintenance and clean up in plant design
2. Importance of dust control during plant design
3. Story of crusher screen opening resulting in too coarse rod mill feed
4. History of the wheel, bearings, and lubrication
5. Calculates wasted energy of atomic vs. conventional blasting
6. Story telling of safety incident
7. Ancient history of man breaking and shaping rocks
8. Continuation of above history
9. History of grinding machinery (including the arrastra)
10. History of rotating mills
11. Early ball and pebble mills
12. Early to present autogenous grinding history
13. Autogenous to semi-autogenous, critical size
14. Primary autogenous grinding
15. Rittinger a sound theory but difficult in practice
16. Kick and Rittinger
17. Kick, Rittinger, then Taggart, Gaudin
18. Work Index
19. Work Index and the three principles of comminution
20. Standard sieve sizes, particle size distributions, the P80
21. Work Index and grindability, F80 and P80, Hardgrove
22. Tabulation of Work Indices, mill power needed
23. Critical speeds, dry vs. wet grinding, media coating
24. Big, slow vs. high energy machines, wear
25. Rock breakage, strain energy, knowledge of zones of weakness needed
26. Farm soil is fine rock
27. Vast technical information is the bane of specialists, key words, titling, referencing and cross-indexing needed
28. Metal wear, abrasion, corrosion, poorly understood and needs research

29. Metal wear abrasion index test
30. Estimating wear of rods, balls, liners, wet and dry
31. The importance of writing
32. Consulting challenges, woes and rewards
33. History of crushing and grinding
34. Measurements of time, distance
35. Measurements of length, weight, volume (our system is archaic)
36. The metric system development
37. The need to adopt the metric system in US
38. Early human life
39. Early man and rock-working
40. Lao Tzu, the practice of writing when retired from a life of work and learning
41. Classifier equations, efficiency
42. Original thinking, knowledge, practice, excellence
43. Early rock workers
44. The Bond Work Index
45. Separator efficiency in cement grinding
46. Ball coating in dry grinding
47. Size reduction theories of Kick, Rittinger, Bond, and three principles
48. Mining in the oceans
49. Noise and hearing, legislation needed
50. Time, Einstein's equation, space
51. Rock, atoms, protons, matter
52. Antimatter and the boundary of space
53. History of earth, time, antimatter
54. Size distributions of broken material
55. The existence of ether, one matter comprises all
56. Einstein and Newton
57. Nothingness and material substance

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1977, Bond, F.C., YouTube recording of a talk on *To Know What We Are*, given at the United Presbyterian Trinity church in Tucson, January 23, 1977 (the same day as his death).

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APPENDIX

Brief Chronology, Fred Chester Bond

Born June 10, 1899, Belcher Hill, near Golden, Colorado.
1917–18, Denver University.
1922, B.S. Engineer of Metallurgy, majoring in Chemistry, Colorado School of Mines (CSM).
1923–24, Assayer and Millman, New York and Honduras Rosario Mining Co., Honduras.
1925, married to Margaret Jean Lowe, Aug 29. Sons Robert Franklin, 1926, and Bruce Frederick, 1933.
1925–29, CSM, Instructor in Chemistry.
1926, M. Sc. in Mining Engineering, CSM Department of Chemistry.
1929–30, Designer, Tennessee Copper Corp.
1930, Cyanamid, State of New York.
1930–64, Allis-Chalmers Manufacturing Company:.
1930–33, Metallurgist, Minerals Research Laboratory.
1933–34, Engineer in Charge of construction and operation, uranium concentrator, Eldorado Gold Mines Ltd., Northwest Territories, Canada.
1935–36, Engineer in Charge of construction and operation, gold concentrator, Compania Minera Nacional, Huachon, Peru.
1936–44, Metallurgist, Mining Department.
1944–50, Technical Director, Basic Industries Research and Testing Laboratory.
1950–60, Sr. Staff Engineer, Process Machinery Department.
1960–64, Consulting Engineer, Process Machinery Department.
June 30, 1964, retired from Allis-Chalmers.
1964–77, Contract Consultant for Allis-Chalmers, and numerous mining companies, other non-competitors of Allis-Chalmers.
Died January 23, 1977, Tucson, Arizona.

Memberships

A.I.M.E. (Chairman of Comminution Research, Crushing and Grinding Committees, 1948–51; confidential reviewer of technical paper submissions)

Canadian Institute of Mining and Metallurgy
American Chemical Society
American Association for Advancement of Science
Milwaukee Engineering Society
Astronomical Society of the Pacific
Milwaukee Astronomical Society
P.E., Wisconsin
Mining Club of the Southwest, Tucson.

Awards and Honors

1952, CSM Distinguished Achievement Award.
1963, Wisconsin A.I.M.E. "Man of the Year".
1965, A.I.M.E. Robert H. Richards Award.
1982, A.I.M.E.'s *Design and Installation of Comminution Circuits* is dedicated to his honor.
1988, National Mining Hall of Fame, Inductee No. 1.
2015, International Mining Technology Hall of Fame, Inductee in Comminution

24-086

The Potential of Lithium: Peruvian Case

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ABSTRACT

Lithium is a top-quality mineral in the energy market, with growing demand. It has many applications in medical, nuclear, and energy industries. The purpose of this article is to quantify and analyze the economic potential and projected global demand for lithium annually. It aims to determine Peru's (specifically Puno) positioning in the global context in 2025 and 2030. The article also seeks to identify the main regulatory, environmental, and social challenges to sustainably exploit lithium in Peru.

The study employs applied research (mixed approach), descriptive-correlational scope, and observational, cross-sectional design. The methodology demonstrates the use of statistical techniques to model and make predictions about this energy-transition metal. Academic sources were reviewed to enable a comparative approach and projection into the future of lithium for development in the mining industry.

In the last 10 years, lithium demand has grown, noting a 600% increase in the economy and projected annual growth of +26%. Exponential growth in resources is projected, where econometric, R-multivariable and R-linear models estimate that Peru could supply 1.5% in 2025 and 3% in 2030 of global lithium. Estimated growth of 5–15% in socio-environmental conflicts is projected with the start of lithium exploitation (Peru – Puno).

The global potential of lithium demonstrates exponential growth. Lithium reserves in Puno - Peru would rank 13th between 2025 and 2030. It is necessary to establish a clear regulatory framework to avoid excessive increase in socio-environmental conflicts.

Nomenclature

Symbol	Definition
α	Estimated annual growth rate
b	Exponential growth base
y	Dependent variable (number of articles)
x	Independent variable (year)
a	Constant
y_1	Initial value (2015)
y_2	Final value (2022)
x_1	Initial year (2015)
x_2	Final year (2022)
X	Matrix of independent variable data
y	Vector of dependent variable data
X'	Transposed matrix of X
$X'X^{-1}$	Inverse matrix of X'X
ε	Error term
Y	Dependent variable (production %)
Price	Lithium price (in dollars)
Demand	Global demand for lithium batteries
Investments	Investments in lithium production capacity (in million dollars)
Costs	Lithium extraction cost in the country (in dollars per ton)
β_0	Constant term
β_1, β_2, β_3, β_4	Estimated coefficients