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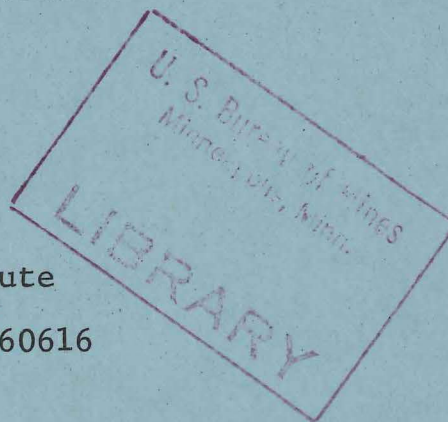
*One crushing & grinding -*  
BIBLIOGRAPHY OF SIZE REDUCTION

Volume 1:

- Guide to Bibliography and Index
- Literature Reviews

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## FORWORD

This report, bound in nine volumes, contains a literature and patent bibliography on size reduction and related topics. Volume 1 contains an introduction explaining the use of the index. Volume 2 contains an author index; Volume 3 contains a subject index. Volumes 4 through 6 contain references and abstracts compiled in 1967, under the sponsorship of a group of eleven industrial companies. A previous bibliography, the British "Crushing and Grinding Bibliography," should be used as one volume of this report. It is available from Chemical Publishing Co., 200 Park Avenue South, New York, N. Y. 10003. Volumes 7 through 9 extend the coverage through mid-1973, and were compiled under the sponsorship of the U.S. Bureau of Mines. The author and subject indexes were also updated to include all references, including those of the British Bibliography.

This report was prepared by IIT Research Institute, Chemical Engineering Research, 10 West 35th Street, Chicago, Illinois 60616 under USBM Contract No. S0122069. The contract was initiated under the Organic Act and Department of the Interior Appropriations Act. It was administered under the technical direction of TCMRC with Mr. Arthur F. Colombo acting as the technical project officer. Mr. George A. Honold was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period May 5, 1972 to April 4, 1973. This report was submitted by the authors on May 24, 1973.

The support of the following companies for Volumes 4 through 6 is gratefully acknowledged: Corning Glass Works; Cleveland-Cliffs Iron Co.; General Refractories Co.; Hanna Mining Co.; Ideal Cement Co.; Kennedy Van Saun, Inc.; Oglebay Norton Co.; Phelps Dodge Corp.; Pickands Mather & Co.; Micropul Division of Slick Industrial Co.; and United States Steel Corp. The new volumes were typed and edited by Nancy Robinson. Others who contributed to the work include Ronald Wiegel, the late Lincoln Work, and Edward Fochtman.

This technical report has been reviewed and approved.

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## BIBLIOGRAPHY OF SIZE REDUCTION

### 1. INTRODUCTION

This compilation of literature and patent references is a continuation of the British "Crushing and Grinding Bibliography,"<sup>1</sup> which should be considered as a part of this report. The first reference number in this report follows the last reference number in the British bibliography. A complete subject and author index covering both works is included.

Although the literature on size reduction is voluminous, much of it is repetitious and some is worthless, because the standards of publication in this field are lower than in many other fields. Nevertheless, access to a key article can save workers in the field from repeating the efforts of others, at a cost of tens of thousands of dollars. The key to this access is through a comprehensive subject index. Preparation of this index has been a main part of this work.

In the bibliography, the order in which the references appear is arbitrary. Access to references of a certain subject or author is through the indexes, described below. Missing numbers refer to duplicates that were subsequently removed from the bibliography.

#### 1.1 Use of the Subject Index

The index is designed to be used by combining groups of subject concepts. Thus, the user interested in the subject "wear of liners in ball mills" should lay before him the subject index pages for "wear", "liners", and "ball mills"; and select the document numbers that are common to all three subjects. In this way he will find the document numbers 487, 1077, 8315, 8316, etc.

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<sup>1</sup>Dept. of Scientific and Industrial Research, Britain, "Bibliography of Crushing and Grinding," Chemical Publishing Co., New York, N.Y. 1960.

For convenient comparison, the document numbers are arranged on the page grouped by thousands.

In addition, the comparison process is made easier by two codes that appear after the document numbers. These indicate the type of article and the general subject matter. By looking up the document number under the decade of publication, the user can find two other codes that identify the language of the article and the region where the work was done or published. Thus Ref. 487 was published in the 1940's in Britain, and is in the English language. Details are given below in Section 1.2.

To make it easier to find the appropriate subject entries, several lists of subjects are given in this volume. The first is an alphabetical list of subjects used in the index. The second is a list of topics grouped under broad subject areas. The third list is a thesaurus of additional subject concepts with cross-references to actual index topics that should be consulted. In searching the index the user may broaden the search or narrow it, by adding or removing topics from the combination of topics he is considering. In the example above, he might broaden it by removing "liners"; or narrow it by including "polymers" to consider only wear of rubber liners, and thus eliminate 487 and 1077.

The second key to finding the most valuable references is by reading the abstracts of the documents retrieved by the subject index. Most of the abstracts contain enough information to enable the reader to judge each article for himself and thus to avoid the necessity of reading the individual articles. This judgment can be made on the basis of the subject matter, the premises that the author brings to his work, and the availability of the article. Such judgments are bound to be subjective.

A preliminary screening device is provided by a subject index term called "original or significant research results." This term has been applied to a few hundred articles, which are identified by a star after their document number in the subject

index. The user would do well to begin with these articles and then broaden the search if more information is needed.

Another method of narrowing the search is by use of review articles. Reviews may be found in the subject index, and a compilation of recent Annual Reviews of Size Reduction is included in this volume.

At least half of the articles are in a foreign language, German being the most extensive. A source of translation is listed for many of the foreign articles. The most common source is the National Translation Center (NTC), John Crerar Library, Chicago, Illinois 60616. This center maintains a card file of 180,000 translations. This was searched for works of certain authors and for certain journals, such as Chem.-Ing.-Tech., Zement-Kalk-Gips, Glastechn. Ber., and Aufbereitungs-Technik. Other translation sources are government agencies; Associated Technical Services (ATS), Glen Ridge, New Jersey; and Consultants Bureau translations of Russian journals.

Reprints of articles can be ordered at a reasonable cost from Crerar Library in Chicago and from the Engineering Societies Library, 345 East 47th Street, New York, N.Y. Both are cooperative, and have excellent collections in this field.

## 1.2 Subject Codes

The document's numbers may be followed by one or two codes giving additional information. Codes in the first column indicate the nature of the document. Codes in the second column indicate the general subject area. These codes are listed below

First column		Second column	
*	Original research result	M	Mills and milling
R	Review article	F	Fracture mechanics
N	Novel	S	Particle size analysis
D	Data	C	Classifiers
P	Patent		
I	Industrial practice		

If two topics occur for one entry, the first one on the list is printed.

A different set of topics is coded for entries under the subject "Decade of publication." The first code indicates the language of the article, and the second indicates the country or continent where the work was done or published. These codes are

Language		Region	
First column		Second column	
E	English or translated	W	Western other than USA
R	Russian	S	Scandinavia
O	Other language	R	Russia
J	Japanese	G	Germany, Austria
G	German	E	Europe, other
F	French	B	Britain
		\$	Asia
		=	Africa
		+	Australia
		U	USA

### 1.3 Preparation of Index

A name index to the complete bibliography is included in this volume. The subject index was prepared by computer.

The mechanical process of preparing the subject index involved the typing onto paper tape of a list of three-letter concept codes and the document number for each document. The

codes were edited by a computer program and corrected using a time-sharing computer. Finally they were sorted and printed by a Univac 1108 computer.

The bibliography contains nearly 10,000 references. The 1958 British bibliography contained 2500 references. The difference reflects partly an increasing rate of publication since 1958. Partly it reflects the incompleteness of the previous bibliographies; in fact, this one is also incomplete.

#### 1.4 Sources of References

The extensive General Mills bibliography<sup>2</sup> is not readily available, and therefore all pertinent references from it have been included in this report.

The following abstract journals were searched:

<u>Source</u>	<u>Coverage</u>	
	<u>From</u>	<u>To</u>
Chemical Abstracts	1958	1972 Vol. 64, No. 6
Engineering Index	1958	1972
Applied Science and Technology Index	1958	1972
List of Publications of U.S. Bureau of Mines	1910	1960
Ceramic Abstracts, U.S. and British	1961	1972
Copper Abstracts	1961	1965

<sup>2</sup>General Mills, Inc., "Survey of Technical Literature on Grinding and Separation," Report on Contract DA-18-064-CML-2336, 1953.

The terms searched were:

Abrasion	Comminution
Mills	Milling
Grinding	Size Reduction
Fracture	Crushing
Fineness	Mining related to comminution
Wear	Pulverization
Impact	Rupture
Separation (reviews on)	Particles (size of)
Ore (treatment of)	Breaking
Fracture mechanics.	

The card catalog of Crerar Library in Chicago was also searched.

The references from annual reviews published by Lincoln Work, R. V. Riley, and Hans Rumpf have been incorporated in the bibliography. Rumpf's reviews yielded many European references that would otherwise have been missed. References from several books and extensive review articles, such as those by C. C. Harris and Bela Beke, have been included. Those by Beke contain a number of Russian references.

Several South African and Australian journals were consulted, since the industry is active there. These revealed recent publications.

An extensive compilation of patents has been included, especially U.S. patents through 1966. Many patent references were obtained from the sources already mentioned. The General Mills Patent Survey<sup>3</sup> gave 230 U.S. patents up to 1952 that may be most important.

The U.S. Patent Gazette was consulted to review all patents in class 241 (solid material comminution or disintegration) from 1952 to 1966. Of the 1700 patents included, reprints of 170 were

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<sup>3</sup>General Mills, Inc., "Patent Survey of Fine Grinding Technology," Report on Contract DA-18-064-CML-2336, 1953.

ordered. In addition, a list of chemical patents concerning grinding was purchased from Information for Industry, Inc. This list contained about 200 pertinent patents in other classes. Patents since 1966 have been obtained only from the abstracting sources mentioned previously.

Foreign patent references were obtained from bibliographies and review articles only. For example, an article by Waeser<sup>4</sup> gives one-sentence descriptions of 200 German patents from German patent class 50 (milling and comminuting...) from 1870 to 1950. A further systematic search of foreign patents would be time-consuming and probably not justified, since important inventions are likely to be patented in more than one country and hence would be in our file from one source or another. Since the Derwent foreign patent indexes are available for the past few years only, they were not searched.

The following journals were searched for current articles from 1966 to 1972:

J. Franklin Inst.  
Ver. Deut. Ing. Forshungscheft  
Australasian Inst. Mining Met. Proc.  
Can. Mining Met. Bull.  
Can. Mining J.  
Eng. Mining J.  
Inst. Mining Met. Bull.  
Metal Mining Proc.  
Mines Chem. Eng. Rev.  
Mines et Metallurgie  
Mining & Mineral Eng.  
Mining Congr. J.  
Mining Eng.  
Mining J.  
Mining Mag.  
S. African Mining Eng. J.  
Trans. Am. Inst. Mining Eng.  
Trans. Faraday Soc.  
Kolloid Z.

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<sup>4</sup>Waeser, B., "Mahlen," Kolloid-Z. 2, 149-153 (1952).

S. African Chem. Inst. J.  
Brit. Chem. Eng.  
Can. J. Chem. Eng.  
Chem. Eng. News  
Chem. Proc. Eng.  
Chem. Eng.  
Chem. Eng. Progr.  
Chem. Eng. Sci.  
Chem. Process  
Chem. Soc. Japan, Ind. Chem.  
Chem. Week  
Chem.-Ing.-Tech.  
Ind. Eng. Chem.  
Trans. Inst. Chem. Eng.  
S. African Ind. Chem.  
Trans. Brit. Ceram. Soc.  
J. Glass Studies  
Minerals Process.  
S. African Inst. Mining Met.  
Iron Age  
Pit Quarry  
Powder Tech.  
Rock Prod.  
Bull. Missouri Sch. Mining Met.  
Die Muhle Beilage  
Verfahrenstechnik  
J. Soc. Chem. Ind.  
J. Soc. Glass Tech.  
Trans. Inst. Mining Eng.  
Mining Met. Soc. Am. Proc. Bull.  
Trans. Can. Inst. Mining Met.  
Dansk Teds  
Tek Ted Upsala, C. Kimo  
Chem. Eng. Practice  
Physik  
U.S. Patent Bull.  
U.S. Bur. Min. Bull.

## 2. REVIEWS OF SIZE REDUCTION

These reviews are compiled from the Annual Reviews of Size Reduction published 1966 to 1972 by Snow (8895-9) and by Snow and Work (9236). They present in narrative form some of the more interesting articles on size reduction, and provide one way to gain access to the literature. Numerous other reviews have been published and are locatable through the subject index topic "reviews." A series of general reviews was contained in the 1958 British Crushing and Grinding Bibliography. For more complete access to articles on a given subject, the subject index may be consulted.

### 2.1 Fracture Behavior

Improvement of comminution can come about by learning more about the subprocesses that occur in mills, such as transport of the particles to the zone where they are stressed; the stressing of particles to a level high enough for breakage; removal of the fragments that are smaller than the desired product size from the grinding zone; and prevention of agglomeration of fines once they are formed. Fracture phenomena are basic to these size reduction processes; hence our interest in this subject.

The subject is divided into general theories on fracture phenomena and studies of the effect of the properties of particular materials being broken. Workers in size reduction either catalog the performance — e.g., grindability — of a variety of materials, or study in more detail the breakage resistance and fragment-size distribution of single particles of particular materials.

For more references on this subject, see subject index topics under the general category of Fracture Mechanics, p. 90.

#### 2.1.1 Initiation of Cracks

A familiar fracture situation arises when a particle is

pressed against another surface; this is how particles are usually stressed in mills. The initiation of fracture of spheres stressed in this way is governed by the Hertz theory. In an experimental and theoretical study on glass spheres, Frank and Lawn (7565) demonstrate the repeated formation of ring cracks as increasing load is applied, until a load is reached at which the crack deepens to form a cone crack. Their photographs show how the size of flaws that happen to be encountered at the edge of the circle of contact can result in a distribution of breakage strengths. Studies of the mechanics of this situation are continued by Hamilton and Rawson (7706), who interpret their data in terms of a flaw distribution. Conversely Green (7656) derives equations to deduce the flaw distribution from strength data for glass rods and laths. He also considers limitations of the statistical theory of distribution of flaw strength.

The scanning electron microscope has opened up a whole new world for study of the details of fracture surfaces and mechanisms. An annual symposium is edited by Johari (7893), which present techniques and applications especially to metals. Another example is the work of Homer and Crawford (7809) on the examination of etched glass surfaces showing the sites of minute surface cracks that are believed to account for the distribution of breaking strengths of brittle materials. Abrasion during manufacture and handling appears to account for some of these surface cracks. Kambour (7919) investigates the part played by crazing in the fracture mechanism of glassy polymers.

Semenov, Papualskas and Ryabov (9852) find that the strength of glass is dependent on its surface roughness which is varied by dissolving surface layers with flowing water. The fracture energy of polystyrene also depends on flaw size, according to Murray and Hull (9765). Surface features relating to brittle fracture are discussed in a review by Symegash (9889). Barron (9490) reports on the brittle fracture of isotropic and anisotropic rocks.

Billinghamurst et al. (7198) point out that when flat surfaces are placed together, the points of real contact are small, and the pressures can be very high. If the surfaces are slid over one another, high tangential forces can greatly increase the incidence of brittle fracture. Gilroy and Hirst (7621) show that the critical load to produce a ring crack in the Hertz experiment varies with the coefficient of friction when a sliding load is applied.

The Hertz theory considers only local deformations and not wave phenomena. Sears (9266) includes these effects in his analysis of longitudinal collision of rods with rounded ends. An approximate solution of the Sears equation is obtained by Zegzhda (9266).

The effect of chemical agents on Hertzian strength of brittle solids is investigated by Langitan and Lawn (8100). Although grinding aids are effective for other reasons, such materials can affect crack growth.

### 2.1.2 The Breakage Process

After considering the conditions under which a crack is initiated, we turn to considerations of the breaking process itself. Three papers analyze the stresses that occur in specific shapes, especially spheres, under single particle breakage conditions. Rumpf et al. (4868) present high speed spark cinematographs which clearly show the growth of bundles of cracks in small glass spheres breaking under compression. They then (9831) consider the classical analysis of stress near the contact point according to Hertz, and attempt to extend this analysis a short distance into the sphere to see how the stress might influence the crack propagation. Actually, they carry the analysis beyond its range of validity, pointing out that no other approach is available. Habib et al. (9869) show the form of breakage cracks in disks and spheres of rock and attempt to interpret the results in terms of the theory of stress distribution of Sternberg and

Rosenthal (8926), which is applicable everywhere except near the contact points. It becomes clear that directly under the contact zone, there is a region where neither theory is valid, and where each gives different results. The complex equations of Sternberg and Rosenthal (8926) for the stress at a point in the sphere are put in convenient explicit form by Hiramatsu and Oka (9964).

Arbiter et al. (7052) measure the fracture pattern of glass and cement spheres and compare these with stress patterns determined by photoelastic methods before breakage. There is a correlation. Johnson and Holloway (7897) relate the shape and size of fracture zones to the stress distribution in glass-bending tests.

Glathart and Preston (7626) elucidate by high-speed photographs the mechanism of impact breakage of glass sheets. Failure may begin under the impactor, when it is governed by the Hertz formula; or on the opposite side of the sheet, when it is governed by a flexural formula. Shand (8832) gives further results on this subject. Solntsev and Fridman (8904) study 10,000 cases of cracks or fracture in glass, vitreous enamels, and other silicate materials. They observe that one of the cracks is normal to the maximum tensile stress, and the length and shape of this crack depend strongly on both applied load conditions and the inherent strength and shape of the sample. Barsom (7117) shows that the fracture of thermally tempered glass sheets is related to the stored nonuniform strain energy, and they correlate the maximum tensile stress with the particle size produced.

Another school of thought deals with fracture as related to the statistical distribution of flaws in the material. Actually, it is only crack initiation which depends on surface flaw distribution. This determines breaking strength. Crack growth and breakage depends more on the internal stress state, as the above articles indicate. These effects, not the flaw distribution, determine the fragment size distribution produced. These papers are by Gilvarry (3069-71, 3573-7) and Gaudin and Meloy (3067, 3559).

### 2.1.3 Crack Propagation and Inhomogeneities

A review of the fracture of brittle materials by Pugh (8586) presents clearly this subject, of which those interested in size reduction should have some knowledge. Pugh discusses theories of crack growth according to continuum, atomistic, and energy theories. He discusses models for crack nucleation, such as pile-up of atomic dislocations. Flaws which are not sufficient to nucleate a crack can be aided by fatigue phenomena such as slip until they are sufficient. But cracks can be stopped by inclusions and grain boundaries, so that heterogeneous materials can be stronger than their components. This mechanism of dispersion-strengthening a glass matrix is also discussed by Hasselman and Fulrath (7746).

Articles by Bailey and Hill (7098), Kelly (7958), and Hasselman (7746-7750) investigate the strength of ceramics, which is strongly influenced by their porosity, grain structure, and crack density. Griffith crack theory is invoked to explain why ceramics fail far short of their theoretical strength; it is hoped that better understanding can show how to improve strength.

Hall (7704) finds that decreased porosity increases the strength of ceramic materials, as does decreased grain size, the addition of sintering compounds, and other effects. Lund (8189) reports that fine grinding of the raw materials increases strength of ceramic products. Hall (7704) states that strength is often affected by surface conditions; Gutshall and Cross (7687) suggest that a strong ceramic will result from a fine-grained surface layer with a large-grained interior. The small-grain surface reduces the size of cracks on the surface resulting from loading, thus increasing the stress required to cause fracture. The coarse-grained interior increases the stress required to propagate a crack through it.

Tsai and Kolsky (9061) study the fracture produced by impact

of steel balls on larger glass blocks. Considerable information is obtained which bears on the further growth of cracks which leads to destruction. Hicks (7780) reviews factors affecting glass homogeneity. They concur in a 1937 proposal of Smekal (4316) that the ultimate structure of glass consists of 10 to 100 Å crystallites of cristobalite. This conclusion has bearing on an old controversy about the limit of grinding, supposed to be due to the limiting size of the basic mosaic structure of matter. The limit of grinding is usually in the micron range.

It is commonly thought that crack-branching occurs when a crack reaches a definite velocity in a given material, but Congleton and Petch (7370) find that it can vary with the stress on the crack. They give a theory for inducing persistent growth of a new crack ahead of a running crack. Their work is extended to alumina (7371).

Examination of the fracture surfaces is one way to gain information about the fracture process. Cotterell (7384) finds the density of markings proportional to the toughness of organic glasses. The electron microscope reveals to Klaus (8005) that the mirror zone of a fracture is by no means a flat surface; hackle marks produced by very high fracture velocities are discussed. Hoskins (7816) examines rock fracture surfaces with a scanning electron microscope.

New tools for studying fracture include the scanning electron microscope. It can reveal crystal dislocations and flaws, and may be a useful tool to study the mechanism of fracture propagation. Examples of such use are shown in an article by Willard (9208). For example, the microscope can distinguish between fracture along grain boundaries and across them, and could be used to settle some long-standing questions about fracture of heterogeneous materials.

Kerkhof (1976) continues his pioneering work on fractography, or the study of lines induced on fracture surfaces by interaction of the crack front with impressed acoustic waves. Krushchov (1986) reviews scratch test methods and concludes that the scratch test is a useful rough measure of the microhardness of minerals, although its fundamental significance is not clear.

#### 2.1.4 Grinding Limits — Plastic Behavior

It is well known that a limiting fineness is attainable in a given type of mill. There is a current demand for grinding to finer sizes in new technologies, such as pressed ceramics, Xerox toners and polymer powder coatings. It has long been thought (as suggested by Bradshaw (268)) that reagglomeration is responsible for limiting the attainable fineness, especially in ball mills. Schönert and Steier (1986) suggest two other causes as well: plastic deformation of normally brittle materials, and the difficulty of stressing small particles to their breaking point. They devise experiments to determine which of these mechanisms is most important in the grinding of glass, limestone and quartz.

The second possible cause is deduced from Griffith crack theory, which requires that the particle must have enough stored stress energy to allow a crack to propagate. This energy depends on the elastic constants, such that a 10- $\mu\text{m}$  glass particle requires a tensile stress of 140  $\text{kp}/\text{mm}^2$ , while a metal requires this stress for a 1000- $\mu\text{m}$  particle.

Brittle materials can deform plastically on a small scale, as Rumpf et al. (1981) observed in crushing glass spheres. In the present work scanning electron microscope photos show that plastic deformation occurs in crushing limestone particles as large as 3-4  $\mu\text{m}$ , and quartz particles of 2-3  $\mu\text{m}$ . This deformation spreads the stress that would otherwise produce brittle fracture.

Recent experiments on the breakage of 0.2-0.4- $\mu\text{m}$  magnesium

oxide crystals apparently prove that plastic deformation is an important mechanism to limit the practical attainable fineness by grinding even with a material considered brittle. Gane (9583) breaks these crystals in an electron microscope by applying  $2 \times 10^{-4}$  g force. The crystals behave in a fully plastic manner on this scale without cracking, up to 70% strain. No work-hardening is evident. The strengths average  $180 \text{ kg/mm}^2$ , which is 15 times that of large MgO crystals but 1/10 the theoretical strength. Verma, Das and Biswas (9114) prepare and characterize spherical glass particles of subsieve size, which have been used in such fracture experiments.

Agglomeration has not been directly observed in ball milling, but Schönert and Steier (8786) notice that in crushing single particles of limestone as large as  $100 \mu\text{m}$ , the fragments are briquetted or agglomerated between the platens, and this happens with quartz as large as  $5\text{-}10 \mu\text{m}$ . This effect is controlled by the stress energy stored in the particle, which gives the fragments enough kinetic energy to fly out from between the platens before they are caught again. However, this is not the same thing as the reagglomeration of previously broken fragments in a ball mill, as postulated by Bradshaw (268). Thus the results of Schönert and Steier (8786) shed new light on the limit of grinding, but there is still need for direct observation of the controlling processes in ball mills.

#### 2.1.5 Scratch Tests and Plastic Behavior

Microplasticity of glass is also observed in scratch experiments with a diamond pyramid. Dick (7435) observes raised plastic flow regions; the material in front of the tool is so greatly deformed that individual small fragments are still firmly bonded to the substrate, and curled crack splinters are also seen. This behavior occurs with other brittle materials, too.

The nature of surface scratches in glass, which has practical

applications in drilling and wear, is intriguing; since it is not immediately apparent how a tool can get a start in the initially flat surface. Ernsberger (7518;7519) suggests that previously observed microplastic effects do not actually involve plastic flow, but densification, which he measures. The critical stress for densification, rather than the tensile strength, determines the scratch hardness. Neely and Mackenzie (8397) reach the same conclusion in studies of scratching by a Vickers diamond. Dick (7436-7) and Grosskopf and Scholze (7673) also measure scratch hardness.

The micro-indentation method continues to be a favored research tool for fracture investigations. Ball indentation experiments with glass are analyzed by Peter (8522) in terms of the Hertz fracture strength theory. He reports strength data for three glasses. Robredo et al. (8669) use the Vickers diamond pyramid method, and study the scratch produced with scanning electron and other types of microscope. Suggested mechanisms of indentation are densification, shifting of material under shear stress, tearing away, and local heating; the extent of each varies with the type of glass.

Koranyi (8030) reviews investigations which favor the Rockwell technique. These show that glass has a surface layer 0.06  $\mu\text{m}$  thick which is harder than the bulk of the glass. A similar surface effect in borosilicate glass is attributed to a chemical differentiation by Kuczynski and Herbert (8069), who find that the surface is enriched in silica.

Plastic deformation has previously been postulated to occur at the front of an advancing crack, and this makes it difficult to apply classical calculations to determine the conditions under which a crack will propagate. For example, Wiederhorn et al. (9199) state that plastic blunting at the crack tip can affect the measured value of the fracture surface energy in sodium chloride.

### 2.1.6 Experimental Breakage Data

Single-particle breakage experiments in the laboratory can be correlated with the grinding behavior of materials. Experimental and theoretical principles of fracture physics are applied to this process by Schönert (9844). The paper summarizes data from numerous publications from the Technical University of Karlsruhe, Germany. The breaking strength must be expressed by a distribution, since particles that are apparently similar break at a variety of applied loads. The resulting size distributions of fragments are experimentally determined; they depend on the strength of the material, as well as on the experimental method of applying stress. The experimental method must therefore be logically defined. The application of these results awaits development of a simulation model based on the physics of milling. Buss and Schubert (9525) make a start in this direction by expressing their results of single-particle impact breakage in terms of a breakage function, which for their experiments is expressed in log-normal coordinates.

Hildinger (7783-5) reports experimental results on the probability of breakage of single particles by drop-weights, an experimental condition for which few data were previously available. He tests glass spheres and particles of quartz, cement clinker, and limestone of sizes 1 to 12 mm and gives fragment size distributions correlating the results in terms of Rittinger's constant (new surface/energy input). Buss and Schubert (7305-7) report similar correlations of impact breakage of grains of sodium chloride. The grains are propelled against a wall by air pressure, and velocities are measured. The Rittinger constant is a maximum at a velocity of 10 m/sec. Linkson (8164) describes an instrument for crushing-strength experiments on particles which range to very low strengths.

More detailed fracture data for limestone, quartz and polystyrene are presented by Steier and Schönert (9875). Particles

from 1 to 1000  $\mu\text{m}$  are broken by slow compression, and the results expressed in terms of a reduction ratio. The harder materials tend to fly apart on breaking, while the softer materials crumble and are subjected to further crushing as the platens descend, and some of them may even form agglomerates or briquettes. In such an experiment, the first breakage event is likely to be the breaking-off of an insignificant corner of the particle; therefore, the particle is defined to be broken when the fragments are smaller than a certain reduction ratio. Everell, Gil and Sirois (9571) devise a different method for focusing attention on the first important breakage event. They stop the platen descent as soon as a break occurs that cuts substantially through the particle. Their results are comparable to experimental data obtained from drop-weight experiments in which there is no problem of defining the main breakage event.

In ball mills and ring-roll mills, it is not single particles that are stressed, but beds of particles. Hoffmann and Schönert (9636) define experimental techniques to study this situation in the laboratory. Important parameters are the fraction of particles that break when the bed is compressed to a certain reduction ratio, and the force and energy needed for this breakage. Results are presented for mixtures of glass spheres of two sizes in various amounts. The presence of large spheres increases the amount of fine ones crushed; the presence of fine spheres protects the large spheres.

Because particles exhibit a statistical distribution of breaking strengths, the Karpinski-Tervo (2944) impact testing machine is a useful way of rapidly obtaining a large amount of data on the size distribution of fragments from numerous impacts. In this device particles are dropped in front of a rotating paddle in vacuum, while fragments are collected in a rubber chamber. Results of tests conducted at the Canadian Mines Branch Laboratory are reported by Lyall and Tervo (9724)

including data on a variety of rocks. Results by a similar experimental technique are reported by Lenkewitz (9709) for coal, limestone and cement clinker grains at impact velocities between 33 and 140 m/sec. The technique is considered as a way of studying the action in impact mills. Shand (8832) investigates the impact breakage of glass and measures impact energy and velocity, peak impact force, and breaking stress. He concludes that fracture processes of glass under medium-speed impact are the same as under slow-compression loading. There are experimental pitfalls, since the design of the whole apparatus affects the stress transmittal, not just the particle and striker.

Many tests have been proposed to correlate physical properties of minerals with their grindabilities. Terichow and Larson (9007) show that the rate of slowing of a pendulum, caused by scratching of a mineral by a pair of diamond-tipped fulcrums, can be correlated with the surface energy of the mineral. To obtain a linear correlation, the weight of the pendulum would have to be increased with harder minerals, since otherwise they are scratched less than softer ones. In a second paper Engelmann et al. (9569) report the effect of grinding aids.

#### 2.1.7 Shock Waves and Blasting

Under certain conditions, the shock waves that diverge from the point of impact in a sphere or disc can be focused to cause tensile failure at a point  $2/3$  of the diameter on the symmetrical axis. These stresses are calculated by Gildemeister and Schönert (9591), and cracks are observed by high-speed photographs. Jacquesson and Migault (9651) review the theory of shock waves in solid media. Long and Brantley (9720) study ballistic fracture in ceramic materials and describe the fractures obtained. Shock wave propagation has an application in rock blasting. The impulse breakage of rock slabs is limited by the energy that can be transmitted by a compressive pulse through the specimen, according to Hakalehto (7698-9); thus the damage from a blasting

charge may largely be limited to pulverization adjacent to the hole.

Field and Ladagaard-Pedersen (9576) suggest that reflected waves play a major role in determining which fractures develop from the region of the explosive bore-hole, and the directions or propagation. Break-out angles are computed, and a method is suggested to give greater control over fracture growth during rock blasting. Thum (9902) discusses blasting on an energy basis related to the amount of explosive required and the sizes of fragment for surface and underground operations.

#### 2.1.8 Surface Energy

Surface energy values are important as a basis for comparison to assess the theoretical efficiency of industrial grinding processes. The classic experiment of Obreimov (4339) is considered the most reliable way to measure the surface energy of crystals. By driving a wedge into a cleavage crack the crystal is measured. Two new studies by Raasch (9803) and by Burns (9522) consider the energy lost in bending the two halves of the crystal, and conclude that corrections up to +50% are needed in the measured surface energy of materials such as NaCl, LiF, MgO, CaF<sub>2</sub>, BaF<sub>2</sub>, CaCO<sub>3</sub>, Si and Zn.

Kerkhof and Richter (9673) measure the specific energy of fracture of glass by a method of ultrasonic fractography. The monograph by Kuznetsov (106) remains the definitive work on surface energy.

#### 2.1.9 Thermal Stressing

Several articles consider the thermal stressing of particles as a mechanism or aid to breakage. Geller (9588) uses heat transfer calculations to study the thermal stressing of spheres, and the results can be applied to the grinding of preheated rocks. Blauel and Kerkhof (9504) also study brittle fracture processes caused by thermally induced stresses.

Hasselman (7750-2) studies thermal shock fracture in ceramics

and develops a theory of crack initiation and propagation.

Experimental results on fracture by thermal shock in disks is given by Wilson (9222), who correlates the results with surface stress, which can conveniently be calculated for this geometry. King (7991) reports experiments in which thermal shock causes fracture to originate in the interior of glass specimens and finds tensile strength as high as 1% of the theoretical strength.

King and Webb (9680) measure the breakage of glass spheres caused by up-quenching from 77° to 1000°K. The only specimens that break are those having a pre-existing internal defect, while the rest show internal strengths in excess of  $4.5 \times 10^9$  dyne/cm<sup>2</sup>. The data are used to estimate the apparent surface energy of glass using the Griffith (195) criterion. The strength degradation in thermally shocked alumina is reported by Gupta (9608), while Balalaev (9488) investigates the ultrasonic fracture of plastic and brittle rods.

## 2.2 Mill and Circuit Simulation and Control

The most significant recent development in size reduction is the simulation method of analyzing mill behavior in terms of grinding rate and breakage functions. A review of this subject by Snow (9963) includes an evaluation of available data concerning the grinding parameters, as well as a summary of scale-up methods for designing large ball mills.

The present review includes articles on a variety of simulation topics.

### 2.2.1 Data on Grinding Coefficients

Development of grinding circuit simulation mathematics has outstripped the ability to apply the results because of a lack of data concerning coefficients in the theory. Most early published examples of simulation applications have been based on hypothetical data. In fact, the rate and breakage functions were only recently measured in pilot- or full-sized mills, because

laborious tracer methods are required to determine these functions directly and independently.

Tracer experiments reported by Kelsall, Reid, and Restarick (7965) show for the first time some features of the behavior of the rate function. Kelsall uses quartz of a particular size as a tracer in a mixture of sizes of calcite feed, and by dissolving the calcite he measures the appearance of quartz in the screen fractions of the product from a 10-in. diameter mill. Rate function of the finer feed sizes decreases exponentially with size, and this agrees with results of the kinetics of grinding; see for example Herbst and Fuerstenau (7774). In addition, Kelsall's (7965) data show that there is a maximum rate function.

Szantho and Fuhrmann (8979) use a radioactive tracer to measure rate and breakage functions of several minerals in a 7-in. ball and rod mill. The curves of rate function versus size of particle broken exhibit a maximum at a certain size, and they decrease with the logarithm of decreasing particle size.

Curves of this form can be fitted by the following equation containing three parameters

$$\frac{S}{S_{\max}} = \frac{1}{e} \left( \frac{X}{X_{\max}} \right)^{\alpha} \exp - \left( \frac{X}{X_{\max}} \right)$$

where

S = rate function

X = feed particle size,  $\mu\text{m}$

$S_{\max}$  = maximum value of rate function

$X_{\max}$  = value of X related to maximum S

$\alpha$  = slope of curve for fine feed particle sizes

e = 2.78

That a maximum must exist should be apparent from the 1933 observation of Coghill and Devaney (1204) that there is an optimum ball size for each feed size; conversely there must be a size of feed for which the selection function is a maximum. The data

show that the position of this maximum depends on the ball size. In fact the feed size for which  $S$  is a maximum can be estimated by inverting the formula for optimum ball size given by Coghill and Devaney (1204).

The data of Berlioz (7178) for dry ball milling of single feed size fractions of dolomite are analyzed, and presented both as grinding rate functions and as total grinding rates by Kapur and Agrawal (7932). The charge of feed to the mill and the feed particle size are varied. For coarse and intermediates feeds, the total rate increases with feed charge until the ball voids are filled, and above this point the rate is constant. For fine feed particles the total rate is nearly constant when the mill is starved, but it starts to increase when the mill is overloaded. This behavior is unexplained.

Herbst and Fuerstenau (9627) present data on grinding function parameters for dry milling of dolomite in a laboratory batch ball mill. The nonlinear parameter estimation method used by these authors appears to be effective for back-calculating the grinding parameters from mill data. Sufficient experiments are done to determine the effect of mill speed and ball load on these parameters. The data for dry grinding behave in a more straightforward way and are easier to analyze than wet-grinding data. The authors use a combination of experimental and simulated results to determine the optimum conditions for closed-circuit grinding in this system.

A number of investigators report the results of their grinding rate studies in terms of the grinding rate function, which makes their results particularly suitable for simulation studies. Radioactive tracer measurements by Korn, Simonis, Szantho and Wilke (8033) are reported for dry and wet ball milling with different ball sizes, compositions, and slurry solids contents. The rates are different than when single sizes are ground alone.

Miyawaki and Fujisaki (8310) find that the observed rate function varies with the grinding time, although for simplicity it is usually assumed constant.

Methods of simulating grinding mills and circuits have not often been applied to industrial operations as yet. One reason is that few data have been obtained on the grinding rate and breakage functions in large tumbling mills, in which the most costly grinding operations are conducted. The first measurement in a large rod mill is described by Stewart and Restarick (9880). Barite is used as a tracer in a mill grinding pyrite. The breakage function and residence time distribution are similar to those previously reported for a small laboratory mill. The rate function shows higher rates for the fines in the rod mill. An additional mechanism of classification or sedimentation occurs in the large mill, preventing coarse particles from appearing in the product. Tests in a full-sized ball mill were less conclusive, due to the fact that the ball mill was close-circuited with a cyclone classifier that started to recycle tracer even before most of the material had discharged from the mill. The need for open-circuit measurements is indicated.

Snow and Meloy (9869) describe a nonradioactive tracer method that is being used to measure grinding functions in a large ball mill. Tracers are necessary to obtain sufficiently detailed information on the breakage and rate functions, as well as the residence time distribution, although ordinary grinding experiments can yield values of the rate function alone. Rare earth elements can be analyzed to good sensitivity by nuclear activation analysis; these are used to tag synthetic magnesia feed sizes that are added to the regular ore being processed. The results show a moderate variation of rate function with grinding time in a laboratory mill.

Cameron, Kelsall, Restarick and Stewart (9530) use simulation

methods to analyze the performance of a concentrator, including a simple wet circuit with ball mill, cyclone and classifier. Grinding rate, classifier and flotation coefficients are determined for lead, zinc, and gangue components. It is concluded that only the ultrafine portion of the mill product is not effectively separated by flotation. In a subsequent paper Kelsall, Restarick, Stewart and Weller (9671) attempt to improve performance by placing two mill/classifier systems in series. The grinding rate function becomes less selective as a result of increased flow through the mill, producing more fines; but the cyclone performance improves, and the net result is little change in beneficiation.

The values of breakage function determined by Stewart (9880) generally show a steeper slope at the coarse sizes of fragments than at the finer end of the curve, when plotted in Schumann coordinates. Austin and Luckie (9485) show a similar effect in data from grinding of dry cement in a laboratory ball mill. They fit these data by combining two Schumann expressions, each with a different slope. Furthermore, they find that the breakage function is not normalized for this case, so that the relative proportions of steep and less steep Schumann curves differ depending on the size of original particle being broken. The result is a four-parameter expression to fit the non-normalized breakage function. If such an expression is not used, errors may be absorbed in back-calculated values of the rate function, and the results will be difficult to interpret.

### 2.2.2 Simulation Theory

Callcott (7317) presents a summary of matrix algebra for those not familiar with its use in size-reduction circuit analysis. The matrix language facilitates deriving formulas for various circuit-classifier arrangements, and these formulas are readily evaluated with computer routines. Callcott (7316) makes an important contribution by finding a solution for closed-circuit

grinding when the mill is fed at a constant rate and the grinding functions are constant. Previously an iterative solution was required.

Lynch et al. (8195) present sample calculations of milling circuit performance based on the matrix method. Such calculations can find the optimum recycle ratio, which depends on classifier selectivity as well as on mill performance. An appreciable increase in productivity is found to result from such mill circuit simulation studies at Mt. Isa Mines in Australia. Callcott and Lynch both err in applying the matrix method with too large a step size, since the matrix method is essentially the Euler method of numerically integrating the grinding equation. Their selection functions absorb this inaccuracy and will give incorrect results when applied to other mill throughput rates. Nevertheless, the matrix method is valid when applied to small increments of mill length. Meloy (3859) shows how the effect of many steps can be computed by raising the resulting matrix to a power, an operation easily done by a computer. This is possible because the particular triangular matrices involved are commutative.

A large concentration of papers on this subject is included in the International Computer Symposium (9932) of the September 1969 AIME Meeting. Each of several investigators develop different mathematical techniques for back-calculating the grinding rate function (previously called the selection function) from mill performance data. Grandy, Gumtz and Fuerstenau (7653) formulate a regression procedure in terms of the matrix representation of the batch grinding equation, and fit their data from locked-cycle grinding (Bond experiment) to simulate closed-circuit grinding. Freeh and Horst (7567) demonstrate the possibility of back-calculating the breakage function as well as the grinding rate function. Their results obtained by linear programming show an unnatural trend, but the principle is sound.

Mular (8351) describes a gradient search method to back-calculate the grinding rate function from a single batch rod mill experiment with an assumed breakage function. Thirty-five iterations are required to reduce error to 1%.

The simulation method using a simplified breakage function for batch milling described by Horst and Freeh (9630) is extended to a continuous mill, and simulation results are compared with pilot mill data. Another simulation model for batch mills is presented by Roman and Becker (9820). By assuming a  $\sqrt{2}$  sieve series, the Schumann breakage equation is combined with the grinding equation. To explain nonlinear effects, the rate function is assumed to be reduced by the fraction of particles coarser than the size being broken. Parameters are back-calculated by a trial-and-error fit to laboratory mill data for batch grinding of quartz, presumably in a wet mill.

A series of papers in the Second European Symposium of Size Reduction concerns simulation of the ball milling process. Patat (8496) summarizes the work done at his school over a number of years, in which the conditions leading to various orders of kinetics are clearly brought out by suitable experiments. Other grinding kinetics data are presented by Mempel (2869,2888). Mika et al. (8298) solve the equations of grinding in ball mills for first-order kinetics and discuss the difficulties in obtaining an adequate fit to experimental data with this assumption. Austin et al. (7081) present their finite difference method of solution of the equations of grinding and discuss its relation to other methods.

Schönert (8782) presents model calculations for a simpler type of mill. He considers an idealized impact mill provided with a sieve in closed circuit. He then applies his own size distributions from breakage of single limestone particles and determines the effect of sieve sizes, number of breakage steps, and loading intensity on the performance of the system.

Schönert (8785) considers the most general practical case of ball milling with transport of feed through the mill, and summarizes the available models in terms of a second-order differential equation. A first approach to solving this equation is formulated.

A number of popular presentations of the methods of mill simulation are presented in various languages. An article by Rao and Sen (9805) introduces this approach to mineral technologists in India; Huber-Panu (9641) presents a similar paper, in which he unfortunately relies on the Charles law, which is not always valid; Austin (9484) reviews the simulation equations of grinding and includes several cases that have been solved.

Three investigators analyze the Bond grindability test in terms of the mill simulation model based on breakage and rate functions. If these functions are known, it should be possible to compute from the model the Bond grindability for any product mesh. Gumtz and Fuerstenau (7681) show that the simulation is satisfactory, and they investigate other aspects of the grinding process. They find no simple relationship between batch and Bond grindability test results, although the two cases can be related through the breakage and rate functions. Kapur (7931) analyzes Bond test data for 19 ores, and derives from the model a simple equation to predict the Bond grindability and work index from only two stages of the test. The results are verified by experimental data. The Bond test normally requires 7-15 cycles.

Miwa (8308) applies concepts of kinetics of milling to the Bond grindability test method. The total number of mill revolutions, usually adjusted by trial and error, may be predicted with an equation given by Shupov (3832, 4123).

The integro-differential equation describing the grinding process in terms of the breakage function and the grinding rate function has been solved only for special cases. This is one

reason for the slow adoption of modern comminution theory for practical applications. Kapur (7927) presents a similarity solution of this equation for batch grinding. Kapur and Agarwal (7929) notice that certain elements of the grinding matrix should be negligible, and this allows them to rearrange and simplify the batch grinding equation to obtain an approximate solution.

Kapur (7928,7930) presents methods of simplifying the grinding equation. The fit to experimental data is improved compared with the result reviewed last year. These simplifications follow from neglecting certain terms in the matrix obtained by multiplying S and B, the grinding rate and breakage functions. However, the improved results are obtained by keeping more terms, so that the final equation is not much easier to solve than the complete analytical solution of Reid (4024). The savings may be of value only in control computers where data storage is at a premium. The results give insight into the basis of some empirical grinding-particle size relationships, however,

Another energy-size reduction relation derived by Kapur (7933) includes the Charles equation as a special case. The derivation shows what assumptions will lead from the differential equation of grinding to this relation when the product is forced to fit the Gaudin-Schumann or Rosin-Rammler (9960) equation.

### 2.2.3 Residence Time Distribution in Ball Mills

In a batch ball mill the charge of feed and the residence time are set by the experimenter; in a continuous mill the holdup and residence time are determined by the transport behavior of the mill, and only indirectly by the feed rate. Few data on mill residence time and holdup have been published, but a number of investigators are presently conducting experiments. Kelsall et al. (7970) report the distribution of residence time in a small continuous wet ball mill. The residence time distribution is

measured by adding an impulse of quartz tracer in the product as a function of time. A similar impulse of aluminum shot gives the effect of particle size with no confusion owing to particle breakage. The data show that particle size has only a 20% effect on residence time. The holdup weight changes drastically with feed-slurry solids content, and somewhat less with mill speed; mean residence time is directly affected by mill holdup.

Molerus and Paulsen (8235) report an extensive experimental investigation of feed transport in a large cement mill and a pilot mill under dry grinding conditions. They also determine the variation of holdup along the length of the mill and its effect on the power uptake of the mill. Sectors of the discharge grate are covered to alter the mill holdup, and the small mill is also operated as a batch mill. Maximum power draft for the batch mill with smooth walls occurs at a holdup of 80% of the ball void volume for a ball loading 38% of the mill volume; it occurs at 110% of the void volume for a 30% ball loading. These points check an empirical correlation given by Rose and Sullivan (2889). For the continuous mill with step-liners the results were similar, except that power was somewhat lower when the holdup was doubled by blocking the discharge grate.

Molerus and Paulsen (8235) determine residence time distribution, using an impulse of salt as tracer. (This method is suitable in dry grinding, but it cannot be used in wet grinding, because the residence time of the liquid differs from that of the solids) (Gow, 1093). The results are analyzed in terms of bulk flow with superimposed diffusion. Values of the diffusion coefficient are measured. They increase with feed rate, decrease as the holdup increases, especially above the void volume, and exhibit a maximum at a ball loading of 27%. Some reflection occurs at the end walls; this is unimportant in a long cement mill, but it may cause a short mill to act more like a perfect mixer.

The use of residence-time distribution data for estimation of parameters in the axial dispersion model is described by Michelson and Ostergaard (8295), and may be applied to tumbling mills.

Keienburg, von Seebach and Straus (9669) report an extensive investigation of the effect of mill parameters on the residence time of feed material in dry cement mills. The mixing of material in the mill results in product emerging in a distribution of residence times, and thus being exposed to different lengths of grinding. For accurate mill design, the effect of residence time must be predicted in terms of parameters such as mill diameter. The authors determine that ball size is an important variable, which is reasonable when we consider that the falling balls have a stirring effect on the feed. Mardulier and Wightman (9732) describe the use of fluorescein for determining residence time distribution in dry mills, and present some results.

Furuya, Nakajima, and Tanaka (9581) study the effect of mixing on a simulation model of a closed mill circuit. To do this, they observe that actual mill residence time distributions can be approximated by a plug flow portion followed by a perfect mixer portion; the ratio of time spent in plug flow and mixed portions measures the degree of mixing. Some additional assumptions allow the grinding equation to be solved, and particle size distributions compared. For many cases, the plug flow model is found to be a reasonable approximation.

#### 2.2.4 Mill Circuit Control

Until recently mill circuit control was mainly an art. The experienced operator set the feed rate so that the falling balls in the mill sounded "right" to him. Recently, simulation methods and the beginnings of on-line sensors have begun to take over the control of circuits.

A significant article on the control of large grinding mill circuits is published by Stewart (8937). He summarizes the eight practical methods that have been suggested or used to control circuits, and makes use of computer simulation models based on grinding rate functions, breakage functions and classifier functions to calculate the performance of the system as a whole. He concludes that grindability of the feed is the main variable necessitating control, while changes in feed size distribution are of less importance. The method of maintaining a constant rate of fresh ore feed by a belt weigher results in wide fluctuations in size distribution of product from the circuit as well as recycle ratio, and may cause control of recycle ratio to become unstable. The best control systems include regulation of the fresh feed rate to compensate for changes in grindability. Comparing the computer results with the behavior of systems known to be in use suggests that conventional control methods can be improved by choice of the best feed-back control method. Further details and experimental verification of the analog computer model are given in an article co-authored with Kelsall and Reid (7971).

Another investigation using a computer model to examine the advantages of various control methods, similar to that of Stewart (8937), is given by Putman and Samuel (8588). Reid's (4024) analytic solution of the grinding equation is used as a model of the mill, with values of grinding coefficients from laboratory experiments of Herbst and Fuerstenau (7774). Two systems are investigated: one in which the fresh ore feed to the circuit is held constant, and one in which the total feed to the mill including recycle is held constant. The latter gives the best results, in agreement with Stewart (8937). Performance of a reverse system, in which the feed is first scalped through the cyclone, gives a finer product and lower production rate with less stable control.

Another computer simulation of transient response of a mill circuit by Haskell and Beaven (7745) is based on Callcott's (7316) matrix solution of the grinding equation.

Lynch and Dredge (8198) describe a control scheme that is in use for an ore mill circuit with a hydrocyclone. The system maintains constant the circulating load from the classifier by varying the fresh ore feed to the circuit. Watson (9155-6) presents plant data obtained with this control scheme, and compares it with the method of maintaining total mill feed constant. Samoilenko (8739) gives an equation for control stability.

#### 2.2.5 Control and Instrumentation of Ball Mill Circuits

Control of grinding circuits has always been based on feedback principles, because no practical method is available to predict grindability of the incoming raw ore or the size necessary for beneficiation. A novel technique to determine the latter requirement before-hand is suggested by Williams (9936). His method is to sample the dust produced by the primary ore crusher, separate it into different sizes, and concentrate each by the method used for that ore, such as magnetic separation. The size which can be acceptably separated is the necessary size to which the ore must be ground. Test results show the validity of the method.

Nabiscevic and Gel'fand (8379) point out how advantageous it would be if the feed grindability could be sensed before it enters the mill, since changes in grindability are only reflected later in changes in flow of various circuit streams. A Russian cement plant with a process computer is said to calculate grindability from a combination of sensors. A study by Icchakin and Chorol'skij (7845) describes a circuit with ball-mill and screw classifier; 14 transducers are included. Most of these are standard types, but especially described is a transducer for ore particle size and concentration where each magnetic ore particle induces an electric impulse whose height indicates the particle size. Another device is an optical system to indicate the ore color, which is related to grade for this particular ore. Another is a resistance thermometer to indicate the

temperature rise of the mill discharge over the feed, thus measuring the power absorbed by the mill. Another is an inductive device to indicate amplitude and frequency of mill load oscillations owing to ball surging. Another is an electric ear. All transducers are connected to a central computer.

The above report suggests prediction of grindability based on color of ores in the feed stream; Stow (9882) describes the use of reflectivity measurements as a guide to the chemical composition of phosphate ores.

The control of grinding circuits is often limited by lack of instrumentation. The measurement of particle size distribution of the mill output stream is still the limiting quantity in circuit control, although on-line size analysers are beginning to appear. Brookes et al. (7270) install a pilot mill circuit with three control loops on mill density, cyclone feed density, and total mass flow. Results are used to derive a mathematical model of the circuit. Murdock (8363) discusses use of telemetry instruments to fix variables, as well as design problems related to starting synchronous motors for mills. Experienced operators have gained considerable insight into the response of mill circuits to important variables and suggest control strategies. Such observations are given in articles by Crosby (7389), Furhmann and von Szantho (7582), Fahlstrom (7530) and Cross (7392).

A control scheme applied to a 2x10-m cement mill by Uteus et al. (9087) varies the mill speed within limits to compensate for changes in feed grindability. (See Section 2.3.4 for discussion of the possibility of varying the speed of full-sized mills.) An electric ear senses the grinding conditions in the mill and gives a signal that varies the mill speed. The resulting cement has a higher surface area by  $500 \text{ cm}^2/\text{g}$  on the average, and falls into a better grade, although the specific energy consumption is lower. Another application of the electric ear for control of grinding and drying in a cement plant is discussed by

Stürmer (8953). Laurich and Claussen (8116) also study the use of sound measurements to control a cement mill. It increases throughput 20% by maintaining mill filling, but a separate method is needed to control recycle ratio when grindability changes.

The case for automating milling circuits in the asbestos industry is presented by Cossette (7383). Control is presently an art, with manual adjustments of feeders and screens by men of long experience. Increased cost of labor requires the mechanizing of these decision-processes. Automation may result in fewer errors and production of more high-quality fiber. But this is not possible until suitable measuring devices are available for on-line use. Laboratory testing methods such as sieving, air permeability, and strength testing are inherently batch tests rather than continuous on-line tests. In addition, they impose problems of obtaining a small representative sample of a large process stream. Cossette (7383) proposes some ingenious schemes for making these measurements continuous, but his main thesis is that more research is needed on this subject.

#### 2.2.6 Control of Other Mills

It is not usually recognized that fluctuations in product size distributions occur in impact crushers, as well as with other mills. Maeder (8213) shows that such fluctuations can be avoided by adjusting the feeder. He gives an example for a 75 kW impact mill. According to a patent issued to Rheinische Kalksteinwerke (9439), a hammer mill closed-circuit with an air separator is controlled by the load on the separator, similar to the method often used for ball-mill circuits.

The automation of a cone-crusher installation is described by Eibs (7503). Those cone crushers which have hydraulic adjustment and sensing of the discharge opening can be regulated so as to maintain the motor current constant. This increases throughput 20% and eliminates the need for an operator. A

similar load-control system for pulpwood grinders is described by Hooper (7811).

### 2.2.7 Simulation of Other Mills

Simulation studies are being made for particular types of mills other than ball mills. Wahl, Pangborn and McCurdy (9927) model the high-speed dispersing of pigments in terms of a first-order rate expression. They apply this to a Cowles disperser, a type of turbine mixer-disperser. Tschorbadjiski (9905) attempts a mathematical representation of the grinding in a hammer mill. This type of mill is susceptible to prediction of rate function based on laws of physics.

Buhlmann (7290) presents a stochastic model of impact pulverization. Von Szantho and Kirsch (8975) also apply the tracer method to grinding of coal in small impact, roll, and disk mills. In the roll-and-disk mill, the rate function decreases more steeply with particle size broken than in the impact mill. The breakage function in vibratory mills is investigated by Kuwahara et al. (8085). Klimpel and Austin (9683) describe simulation of a rotary cutter of the type used for plastics, based on the assumption that it is fully mixed, and find that the predicted results agree with experimental data. Gottberg (9598) further investigates the forces in such a cutter. He finds that material characteristics can be described in terms of stress-strain behavior and friction coefficient. He experimentally determines optimum speed, angle of knife and sharpness. The energy consumption of a cutting mill can be predicted from the results. Arjas (7062) reports the influence of residence time on the beating of wood pulp in a refiner.

## 2.3 Mill Performance

### 2.3.1 Grindability

Grindability is simply the rate at which material below a certain size is produced in a particular mill. Matsui (8262)

reviews measurements of grindability as does Snow (9960).

The relation observed between the rate of comminution and speed of sound in brittle solids is explained by Dahloff (7402) on the basis that lattice force constants determine both molecular vibrations, and hence speed of sound, and the strength of the material.

Chandler (7337) experimentally compares methods of measuring the grindability of 11 coals with roll crushing, attrition, scratch hardness, and surface energy. There is no good correlation among the standard grindability methods of these tests, except under limited conditions of low grindability and fines removal. The tests are either too laborious or do not simulate well the industrial conditions of coal milling.

Agus and Waters (9471) determine the grindability of coals, shales and minerals by a modified Hardgrove machine, and then they (9472) predict grindabilities of coal-shale mixtures. Remenyi (9813,8629) investigates the mechanism of grinding of mixtures of limestone and salt in a Hardgrove machine, as well as grinding of the individual components. The components affect the grinding of each other positively or negatively depending on the grinding time. The grindability coefficients are not additive.

### 2.3.2 Crushers

Ohe (8451-2) studies single particle breakage of limestone and cement clinker in a roll mill, giving special attention to the attrition due to differential roll speed. Attrition reduces energy efficiency, except for high reduction ratios for small feed particles. In the latter case the improvement is due to more effective disintegration of compacted agglomerates.

The advantage of differential rolls lies not in finer grinding but in the more certain elimination of very hard particles, at the expense of 20-40% increased power cost. Adamski (7004-5)

gives further data on application of his IJB mill which features acceleration of the feed particles before they enter the nip (5042).

Millier (9748) investigates the capacity of cone crushers for fine crushing, based on movement of material in the cone gap. Agglomeration of fines can limit production, and this is influenced by shape of crushing chamber, cone eccentricity and speed. Beech (7141) reports experiments with a dry-pan grinder provided with feed and recycle control. Important factors are rate of feed, moisture content of feed, and correct balance between grid aperture and screen aperture.

Schauer (9836) reviews the present development of ring-roll or bowl mills, which have recently become simpler and larger. Attempts are made to predict performance based on grindability tests of the feed materials. Schauer (9836) claims that they are being more used for cement raw material grinding, and proposes to use them for cement clinker too, instead of ball mills.

### 2.3.3 Ball Mills

Extensive data on wet grinding in laboratory ball mills is reported by Clarke and Kitchener (7357). The main effect of slurry viscosity is to alter the lift of the balls by the mill walls, and hence change power consumption and grinding rate. Independent of this, there is another effect of viscosity that gives a flat maximum at about 100 cp. Results are in agreement with the traditional rule that for fine grinding, the slurry should be thick enough to coat the balls, but not so thick as to be impenetrable to impacts.

Both (7245-6) determines ball motion in a mill by cinematography at 200 frames/sec. He observes that ball interplay does not change greatly with addition of feed material to the mill. Yang et al. (9242) describe a laboratory ball mill, 10 in. in diameter by 11.5 in. long, with eight lifter bars and a torque-measuring cell. They propose that researchers standardize on

the design of test mills. The use of lifters is desirable to eliminate the variables associated with wall slip from experimental consideration.

The slip between the wall and the ball load in a mill influences wear, power draft, and grinding. Manz and Schönert (9730) describe a new method, using inductive detectors to measure relative motion between the outer layer of balls and the mill liner. In a further paper, Manz (9731) reports that slip is decreased by increasing ball load above 40%, and by using smaller balls. Dry powders have small influence on slip. Pietch (9791) presents results of grinding experiments done with a batch laboratory mill equipped with a torque sensor to measure instantaneous power draft. Curves show an initial decrease in power due to slip, followed by increase to a steady value; these effects are attributed to change in fluid properties of the feed slurry as fines are produced. The curves are similar to those of Clarke and Kitchener (7357).

Fujinaka, Majima and Jomoto (9580) also describe a laboratory mill equipped with a torque sensor, and propose to measure scale-up effects based on an energy index similar to Bond's. Snow and Meloy (9869) propose a method of scaling up which makes use of a modern simulation model, while taking into account the different power drafts of various sized mills. The method is based on a "grindability function," which is a grinding rate function expressed in units of energy/ton of mill feed.

Sterne and Stratton (8928) experimentally determine scale-up of dry ball mills for grinding ceramic alumina from 9 in. to 6 ft diameter mills. Effect on production, power consumption, and wear of media are presented for milling times up to 24 hr, and media/charge ratios of 4/1 and 8/1. No evidence of material packing occurs, but addition of a grinding aid improves efficiency by about 35%.

In continuous ball milling there is an optimum load of balls that should be maintained as the balls wear. Rauth (8614) obtains a formula for the optimum load by combining the Davis torque concept with Bond's empirical relation for the power consumed by the mill, assuming that best results are obtained when power consumption is maximized. The results check a few available plant data, and can be used for control of milling conditions.

Patat and Schulz (8497) assume that the optimum milling conditions are those under which the order of grinding kinetics is zero, and deduce these conditions from their previous kinetic studies. A study by Balasubramanian and Hohmann (7104) conducted in a batch pilot mill shows the effect of mill holdup and grinding time on the dry grinding of calcite. The maximum attainable specific surface is  $7000 \text{ cm}^2/\text{g}$ , beyond which ball coating develops. The kinetics of wet grinding in a ball mill are reported by Matejka (8258), including the effect of peripheral speed. Oeckel (8446) finds that the load of media should be 50 to 55% of the mill volume for the fastest grinding rate and the least wear; lower media loadings are often used.

Optimum ball size is experimentally determined by Tovarov and Shevchenko (9038) for cement and limestone in small mills, and they conclude that smaller balls should be used than is usual practice.

Cleemann (9537) reports that cement can be finely ground in open circuit with grinding aids and media of 3-4 mm diameter. Special means are used to separate these media from the mill product, since they would plug a discharge grate. Power consumption is 10% below that of conventional dry grinding methods for cement.

Data from the Mines Branch, Canada, on an open-circuit pilot ball mill is presented by Kelly (7959). The statistically designed experiment shows that grindability of the feed is the most

important variable, although in a sense this is begging the question since grindability is also measured with a ball mill. The mill holdup and mean residence time are affected by solids content of the wet feed; the product size distribution is affected by feed rates, size distribution of feed, and grindability of feed.

Several articles discuss the power uptake of large ball mills. Manz (8232) compares the equations of Blanc and of Rose and Sullivan (2889) and presents a form that combines both. He also shows the effect of volume loading on the power draft of compartment mills. Beeck (7142) compares these equations with the results of plant tests, which are found to give slightly lower results. Instead of correcting the equations, he recommends basing calculations on the plant data, using scale factors.

Practical considerations in the selection of drives for large grinding mills are discussed by Mälzig and Scheuch (8229, 9729), Holland (7807) and Thomas and Dickman (9023). The last evaluate costs of alternative systems and recommend two types.

#### 2.3.4 Large Ball Mill Drives

The size of ball mills is limited by the power transmitting capacity of the drive gears. Gears can be eliminated by making the mill the armature of an electric motor. Several such mills of 10,000 hp or more are scheduled for startup in European cement plants, according to Hale (7703). The motor is of low-speed synchronous type, driven by low-frequency current. A converter transforms 60-Hz current to the low frequency. The low frequency simplifies design and gives a high motor efficiency. The converter can vary the frequency during start-up, avoiding large current inrush. Incidentally, the variable-speed capability presents new possibilities for optimizing grinding conditions. Speed of mill is known to be an important grinding variable, but in conventional installations nothing can be done to change the speed once the

mill is installed. A series of articles in Brown Boveri Review (9298-9302) give details of a 6400-kW installation, and an earlier article by Kapoor (7922) describes a 3000-hp dc drive. In more conventional drives, Ackle (7001) describes a two-stage planetary gear for a 6000-hp mill, which is the present limit for mill gearing.

#### 2.3.5 Fine Dry Grinding

Ball and impact mills are discussed here; jet mills in the next section.

The question is often asked what is the finest particle size that can be produced by grinding. In this connection Sanner (8742) reports experiments to determine the finest dry grinding of anthracite, and achieves 2.2  $\mu\text{m}$  mean size with a batch ball mill, and 6  $\mu\text{m}$  with a continuous ball mill. Finer sizes can be produced by wet grinding or jet milling.

Lauer (8112-3) reviews the state of the art of crushing in fine impact breakers. Weser and Weinberg (9185) attempt cinematography of the action in a pin mill. Although their work is limited to low rotation speed, they estimate free path of particles and collision frequency.

#### 2.3.6 Jet Mills

Requirements for finer grinding have arisen because of new processes and products in the chemicals, ceramics, and pigments industries. Limitations of fineness of product attainable by grinding, and limitations of the rate and cost of grinding to such fine sizes have both been of increasing concern to engineers in those industries. This accounts for the increasing concern for use of the jet mill in the chemical industry. For example, Rink and Giersiepen (9817) describe the advantages of this type of mill when grinding heat-sensitive substances, because of the cooling effect of the expanding air jets. They also compare

costs of jet-milling and wet grinding mills. A guide to jet mill air and power requirements and mill output is given by Baines (7100). Cooling by the air stream in hammer mills, pin mills and jet mills is also discussed by Pebworth (9788).

Kurten and Rumpf (8080) describe jet milling triboluminescent material. Such a material gives off light when it fractures, thus revealing the location of breakage events. Design of the mill can be varied to find optimum conditions.

Kurten et al. (8081) use triboluminescence to measure the grinding in an opposed-jet mill, and find that the best results are obtained when the jets are directly opposed rather than impacting at an angle. Rudinger (8692) investigates the gas-particle flow in nozzles at high loading ratios, and Okuda (8459) reviews jet mills. Muschelknautz et al. (8857) explains uses of jet mills in the chemical industry. Muschelknautz et al. (8371) investigate three types of jet mills (micronizer, oval type, and opposed-jet). They calculate the pressure/throughput characteristics of the nozzles. They investigate the classifying characteristics which may determine mill performance of the micronizer and oval types, and give some data for the performance of all three mills with several industrial feed materials.

Dobson and Rothwell (7456) determine the effect of the feed rate and the size distribution of an alumina feed in two jet mills, one with milling and classification in a single chamber, and the other having an external classifier. Ramanujam and Venkateswarlu (8603) report 239 experiments in an opposed-jet mill grinding calcite. This seems to be the first attempt to bring together the variables involved, to suggest conditions for optimum feed and choking, and to develop quantitative relationships concerning feed rate and size, product size distribution, residence time and grinding rate, nozzle pressure and size. Theoretical equations governing particle acceleration and particle free path are referred to (4075).

Cosic (7382) describes the micronizing of several minerals to produce filler. The fineness depends on the density of materials and the amount of steam used as accelerating fluid. Experiments by Prochazka (8583) in a particular jet mill reveal that the finest size of product easily reached is 2-3  $\mu\text{m}$ . A fraction as fine as 0.1  $\mu\text{m}$  can be attained at high cost, but it agglomerates readily. Crystalline materials such as mica retain their structure and are readily ground, but amorphous materials such as graphite must be tested to determine suitability of jet mills. Jimbo (7887) also discusses the limiting fineness attained in a circulating-type jet mill. Applications of the Trost opposed-jet mill are described by Haese (7692-3). Baines (7100) reviews the practice of jet milling, with information to guide air and power requirements and mill output. Sentyurikhina et al. (9855) give optimum grinding conditions for producing the lubricants molybdenum sulfide, graphite, and boron nitride in a jet mill.

### 2.3.7 Vibratory Mills — Fine Wet Grinding

Wet grinding mills that can attain very fine product size are vibratory, stirred attrition, and planetary ball mills. A review of articles on vibratory mills is given by Kosaka (8037). Maeder (8214) describes a new vibratory mill with short tubes suitable for continuous milling with short residence time.

Podmore and Beasley (8559) point out the versatility of the Vibro Energy Mill, giving efficient fine grinding of a wide variety of materials under many different conditions. Beasley and Slinn (7133) describe features of the horizontal and vertical mill types, and point out that vibratory mills require less space, less capital cost, and less energy consumption than conventional ball mills. Disadvantages are the need for small feed particle size, high maintenance costs, and the possible presence of a small proportion of unground grains in the product.

Vibratory mills continue to be developed in Germany. Reiners (8626) describes a new large mill with two chambers. A central supporting tube gives additional energy-transferring surface, and mechanical rigidity allows operating at a frequency of 1500 Hz. The grinding rate is 2.25 times higher at this frequency than at 1000 Hz. An English article by Vogeno (9125) describes a large Germany vibratory mill with a throughput rate of 15 to 20 ton/hr at a power of 110 kW; product size is below 10  $\mu$ m for grinding of materials varying in hardness from clay to silicon carbide.

Hummeler (7837) reports performance of a 50-kW vibratory mill installed in a quicklime plant. The mill has two grinding chambers in series, and is closed-circuited. The energy required per unit surface area produced is slightly higher than that required by a ball mill, and in this respect the soft lime differs from the hard quartz or alumina discussed above. The product size is related to the feed rate and grinding time by an empirical formula from the Russian literature, similar to that mentioned by Harris (7735). Vedaraman, Raghavendra and Venkateswarlu (9914) describe experiments on vibratory grinding of mineral feeds having a variety of properties. The effects of ball charge and density, and ratio of feed to balls, are investigated and comparative data are obtained for ordinary ball milling. Hagiwara and Mikamo (9613) derive equations for the power draft of vibratory mills and check their predictions with experiment.

Lesin (8140) surveys the sizes, capacities, and construction details of Soviet vibratory mills. Hartman and Wyman (8740) examine experimentally the operating conditions, and report that fineness increases with decreasing throughput rate, or increasing amplitude and frequency. Bertume (7188) surveys the art of vibratory grinding in East Europe. He reviews formulas for inertial force of eccentric mechanisms and pictures several

designs. The larger number of ball impacts makes the method more effective than conventional ball milling, so materials can be ground to 1  $\mu\text{m}$  size. This results in greater strength of ceramics, produces settable plaster without dehydrating, and gives 5% greater enrichment of iron ore. Echalaz (7494) reports tests on vibratory milling of gold ore in South Africa. The mill consists of two rigidly connected chambers vibrated at 17 Hz, containing 1½- to 2-in. balls. Tabular data indicates that power consumption compares favorably with conventional ball milling.

Papacharalambous (8486) points out practical advantages of vibratory milling of hard materials such as silicon carbide, alumina, and boron carbide. Ju-Chung et al. (7905) report a study on the impact period of the grinding media. They discuss application of the results to the optimum design and operation. Zagury (9258) proposes a new type of vibratory mill using rods instead of balls and called "Vibrotub." It is said to be more efficient than a conventional rod mill.

Smith (8883) reports tests on the grinding of hard materials such as carbides and refractory metals, and soft materials such as ductile metals and graphite, in a vibratory mill of experimental design. The mill operates at an unusually high frequency of 2800 Hz with rubber mountings. Both hard and soft particles are reduced from 10 to 1-2  $\mu\text{m}$  in several hours. With graphite the grinding rate decreases with time, but can be increased again by increasing the energy input.

Luedeceke and Patat (8187) report the rates of grinding of quartz in a vibratory mill. They express results in the form of kinetic equations similar to those of chemical reactions, and compare the results with their previous work on ball mills. The behavior with respect to mill filling is similar. The rate varies in a complex way with ball size, particle size, and vibration frequency.

Several articles compare the efficiency of vibratory and ball mills. Pivinskii (8552) gives results of experiments on ball milling of quartz for 175 hr, yielding a powder with a surface area of  $14,000 \text{ cm}^2/\text{g}$ ; grinding 40-60 hr yields values half this high, but the product is suitable for slip casting or pressing dense quartz objects. Maurer and Richter (8268) compare four milling methods at  $1200^\circ\text{C}$  including vibratory and ball milling, for preparing barium ferrite powders. Maximum density and remanence are obtained by vibratory milling. Carr (7327-8) finds that finer organic dyes are prepared in a shorter time with sand milling than with ball milling. An ICI disc centrifuge reveals that the ultimate particle size is not attained in a practically acceptable time by either method; i.e., agglomerates persist.

Hey (7778) compares the power expenditure required for dry milling quartz sand to cement fineness in a ball mill and in a vibratory mill. To reduce a 2-mm feed to 80%  $-0.1 \text{ mm}$  requires 30 min in the vibratory mill and 90 min in the ball mill. To reduce to 99.85%  $-90 \text{ }\mu\text{m}$  requires 1 hr in the vibratory mill and 5 hr in the ball mill. The energy per unit of surface produced is also higher — by sixfold in the ball mill. Thus the vibratory mill is better suited to very fine grinding. Kalita et al. (7917) also compare the performance of a vibratory and a ball mill for grinding of a very hard material, fired alumina. The ball mill requires 20 hr dry milling to attain the same mean-particle size that the vibratory mill attains in 2 hr. As the firing temperature is increased from  $1450^\circ$  to  $1750^\circ\text{C}$ , the alumina becomes harder, and the preference for the vibratory mill increases. To produce 90% particles  $-2 \text{ }\mu\text{m}$  requires 2 hr in a dry vibratory mill, 50 hr in a dry ball mill, and 100 hr in a wet ball mill. Iron contamination is much greater in the ball mill.

### 2.3.8 Stirred Media Mills

A treatise on fine grinding in vibratory and stirred (or rotary) media mills is published by Conley (9544). The difference

in the two types of mills is largely in the energy of individual impacts, the stirred type giving more impacts of lower energy. The two types of mills have a somewhat different, but overlapping field of application. Dispersion of pigments is at the low-energy range; Conley publishes photomicrographs proving that some of these pigments actually do consist of sub- $\mu\text{m}$  particles agglomerated into large flocs, and he shows for the first time the effective break-up of these flocs by a stirred mill. Media for use in these mills are limited to a minimum size of 50  $\mu\text{m}$  only by difficulties in separating them from the product. But media are available ranging in hardness and density from carbides to nylon; and the choice depends on the energy required for the grinding task and wear considerations. Conley (9544) also reports experiments relating fracture in grinding to crystal structure and anisotropy in various pigments.

Möller and Hörnle (9754) report an investigation in wet attrition grinding in a mill using small media such as sand, the media being set in motion by rotating discs. Such mills are much used in the paint industry to deagglomerate pigments and produce particles of size 0.3-1.5  $\mu\text{m}$ . Of 44 factors investigated, the most important are size of media and size of disc; the size of media governs the minimum size of product; the size of disc also affects limiting product size, suggesting an impact mechanism.

Möller and Hörnle (9754) give a ranking of types of mills similar to that of Conley, but they show the range of viscosities as well as the grinding energy in which the mills operate. The position of the mills would be different for coarse grinding.

A number of improvements in the category of stirred ball or sand mill are noted. Talpey (8999) obtained a patent on a rubber-lined sand mill for pigment dispersing. Du Pont sand mills are manufactured under license by Chicago Boiler Co., Chicago, Ill.; Moorehouse-Cowles, Inc., Los Angeles, Calif.;

Epworth Mfg. Co., S. Haven, Mich.; and Ateliers Sussmeyer, Brussels, Belgium.

Smith (9868) measures the rate at which pigments disperse during mixing. Zakharychev, Kaverinskii and Ermilov (9945) report that increasing the temperature to 40°C increases the dispersion rate of titania in a paint mixture with a ball mill. Herbst (9628) compares the dispersion of pigments in vibratory and attritor-type media mills, and confirms the effect of temperature.

### 2.3.9 Planetary Ball Milling

Planetary ball milling is a method of increasing the gravitational force acting on balls in a ball mill. Burke (7297) reports that thoriaurania can be ground to 80% -5  $\mu\text{m}$  in 90 min, while 40 hr are required by conventional ball milling. Majac fluid-energy mills can do the job quickly, but there is danger from the toxic dust. Dobrovol'skii et al. (7455) explore the grinding of refractory metals and carbides in a planetary ball mill. The useful centrifugal force can reach 10 to 50 g, and the apparatus is capable of producing 1 to 2.6  $\mu\text{m}$  particles in 5 to 20 min.

Bradley (9513) reports experiments on planetary ball milling. As the centrifugal field is increased up to 100 g, the critical speed and permissible speed of rotation increase; at the same time the size of the media must be reduced. A large mill operating at 8.3 Hz and 56 g drew 75 h.p. and produced 2.35 ton/hr of quartz finer than 74  $\mu\text{m}$ . No difficulty was experienced in continuously feeding and discharging mill product. A ball mill of this capacity would weigh 25 tons instead of 1 ton. Vock (9923) proposes that a planetary mill can be used to perform rapid tests to simulate ball milling of materials. He also suggests a design for a continuous planetary ball mill.

### 2.3.10 Fluid Shear Mills — Colloid Mills

Various types of grinding and dispersing apparatus from various countries are evaluated by Doorgeest (7466) for preparation of lacquers. Turner and McCarthy (9070) mathematically analyze mechanisms operating in Kady, colloid, and pigment roll mills, where soft particles are ruptured by fluid shear. The results check experiment and appear to give a good understanding of the behavior of such mills. Krekel (8054) studies comminution of agglomerates by shear in colloid mills and masticators and experimentally checks the load at which particles yield. Zimmerman and Levine (9271) describe Kady colloid mills and give capacities as well as costs.

## 2.4 Applications

A large number of articles discuss the application of mills to various industrial tasks. Nijman (8415) reviews applications of ball and pebble mills for which they are pre-eminently suited despite other new competing mills.

Applications of size reduction in the following industries are noted: cement, ceramics, coal, ferrites, pigments, metal powders, plastics, cereals, fertilizers, iron ore, pharmaceuticals, chemicals, safety, and laboratory arts. Only a few are mentioned here, but many others are accessible through the subject index.

### 2.4.1 Cement

Beke (7146) discusses cement grinding problems, especially the hardening characteristics of cement as a function of particle size and its distribution. Locher et al. (8169) present experiments investigating the same subject.

Beke and Opoczky (7150) investigate the grinding behavior of  $C_2S$  and  $C_3S$  in cement. They find that the  $C_2S$  has the greatest tendency to adhesion and agglomeration, while  $C_3S$  can readily be ground to fineness. The particle size distribution of cement is

seldom quoted, since usually only the surface area is determined by permeametry. Blezard (7210) investigates size distributions, which can range from 100 down to a fraction of a micrometer. The largest contribution to surface area will come from material below 2  $\mu\text{m}$ , where gypsum tends to accumulate, and perhaps  $\text{C}_3\text{S}$ .

In the cement industry, impact crushers are often used for limestone. Andreas (7040) describes modern rotary crushers that have full-width impact bars. Since these have more inertia than narrow hammers, they can break rocks up to 55 in.

Kirste (9681) describes six European cement quarries where portable crushers deliver product to belt conveyors to minimize handling costs. A similar system in the U.S.A. is described by Gaskin and Lordi (9585).

Schneider and Zeisel (9840) describe a precrushing installation for cement raw material using a coarse hammer mill to reduce the feed to 10 mm. The plant production increased 40%, and overall process savings are claimed.

Heinrici (9623) discusses the most practical ways to crush cement clinker before ball milling, in order to decrease the over-all cost of the operation. Preliminary crushing in gyratory, roll, and impact crushers each have different wear rates and different reduction ratios, and are more efficient than ball milling. However, the cost of the total operation is greater than when only ball mills are used, because of the greater complexity of the circuit and the larger number of equipment components to maintain. Although the ball mill is known to be inefficient, its rugged simplicity continues to give it an economic advantage over other means of grinding tough materials.

Nakajima, Tamura and Tanaka (9768) consider how large tube mills may be made and remain economic, based on their model of the grinding process and economic data. A diameter of 4-6 m is projected. Buchmüller (7289) gives examples of the largest

cement mill installations, which at present are 5 m diameter by 16.5 m long. Hoffmann and Trasky (9635) evaluate drives for such large mills.

Sillem (9863) surveys current German cement production practice. Larger mills are being installed, which require improved drives, and are shipped in sections. Usually they have two compartments with external classifiers, but some mills recently are using open-circuit design. Abrasion-resistant media are used, and boltless liners are used in mills up to 4.4 m diameter. An angular spiral liner system is being tried. Grinding aids are usually used, and these require good proportioning feeders. The use of mathematical models for optimizing conditions is still in the future. Flack (7553) reports a trial of an autogeneous mill for clinker in a U.S. cement plant. Blazy et al. (7209) find that flint rocks can be removed from cement raw materials by selective grinding in an autogenous mill.

#### 2.4.2 Ores

In the large-scale grinding of ores such as iron ore, the efficiency of the operation can make a substantial difference in annual costs. Dor (7468) compares primary grinding circuits used in several iron-ore concentrating plants. A dry circuit uses Aerofall mills, air classifiers, and screens, while a wet circuit uses a screen and wet cyclones. The dry circuit gives a product with a few percent higher iron assay for the same amount passing 325 mesh, and it also requires less grinding energy to produce the same grade of product. This is attributed to the use of a dry magnetic separator to remove a tailing from the mill recycle stream. Iron recoveries are about 1% higher for the wet circuit, however. In general, wet primary grinding has lower capital and operating costs than dry grinding, although this depends on circumstances. For second-stage ball milling of iron ore, Vetrova et al. (9115) compare ore pebbles with steel balls as media. The

percent of slimes was less with pebbles (17 versus 21%), and the flotation concentrate was more consistent in iron content.

A German symposium on ore-milling practice is edited by Clement (7359). Experience in Chile, Finland, and South Africa is compared concerning mill rotation speed and size. Included in the symposium is a paper by Burghardt and Kortmann (7296) comparing milling of iron ore in a 2.4 x 2.2-m autogenous mill with a tube mill 1.8 x 2.2 m. The milling capacity is determined as a function of rotation speed and filling, and costs are compared.

Fagerberg and Fahlstrom (7529) survey the crushing and grinding circuits used for processing iron ores in Sweden. Meisel (8282) discusses the way in which use of larger mills has affected design of ancillary equipment for ore processing.

Elliott and Goodfellow (9568) also discuss grinding circuits as systems, and compare practices in iron ore and base metal industries. They point out several problems that require sustained research effort, and suggest that research be supported by a group of companies.

Edgar and Pfleider (9565) consider the breakage of rock in mining operations as part of the over-all comminution process, and compare costs in the mining and grinding parts of the process.

Tyulenev (9911) considers the important problem of determining the optimum size to which ore particles should be ground for flotation. He concludes that there is a fairly wide range of acceptable sizes of product, but it is easiest to control the size at the lower limit of the range, which is 10% below the optimum in one case.

#### 2.4.3 Autogenous Milling

A number of ore processing installations of autogenous milling are described. Autogenous mills continue to make inroads in ore

processing because of lower media wear cost.

A symposium on autogenous grinding of ores includes discussions by MacPherson et al. (8208). The effect of mineral composition of iron ores on its autogenous grinding behavior is reported by Gritsai et al. (7669). Pevzner (8528) reports a similar study for gold ores, Bachman (7091) for copper ores, and Chernykh (7346) for lead ores. Large-scale dry grinding of iron ore is described by Rathburn (8610).

Jackson (7871) describes Aerofall milling of gold ore in South Africa and gives data on the economics of adding some steel balls. Telepnev (9013) describes economies resulting from autogenous grinding after a first stage of conventional gold ore ball milling in Russia.

Gubin et al. (9604) discuss the application of autogenous milling to flowsheets for processing Krivoi Rog iron ore, and conclude that this system yields lower recovery of iron than conventional grinding with steel balls. Previous reports, mostly from equipment manufacturers, have claimed the opposite.

Determination of the suitability of particular ores to autogenous milling has required extensive testing in large pilot-sized mills. Kerl (9675) demonstrates that useful results can be obtained in a laboratory-sized batch autogenous mill. Data are presented on the influence of pebble size, feed size, mill speed and load, and grinding time on fineness of grinding. Most companies would hesitate to rely on data from such a small mill. Clement and Kerl (7360) find that autogenous milling is possible in a 30 x 30 cm (1 x 1 ft) mill, but a fine product is more rapidly attained with steel walls than rubber, and even more rapidly with steel media.

Howard (7819) finds that feed materials can be tested for their suitability as autogenous media in a mill as small as 10 x 12 in., while a 2 x 2 ft mill is particularly useful for

testing larger pieces. Contrary to what others have stated, Howard (7819) feels that nearly all ores can be ground by autogenous methods. Many failures are due to trying to produce too great a reduction ratio in one mill; often two stages of mills would serve better. Where there is difficulty in maintaining enough lump in primary mills, the use of large lumps should be avoided because they break up very quickly. The use of large mills, especially at high speed, also causes rapid breakage of lumps to the point where they cannot grind the sands. Howard (7819) also gives some observations on the selection of ball sizes and media shapes other than spherical. The only definitive data on the effect of media shape that I know of is the work of Norris (1265), who shows that spherical balls grind better than any other shape in full-scale tests.

Digre (7443) surveys autogenous milling practice all over the world, from his Scandinavian vantage point. He feels that the U.S. practice of using mills of greater diameter than length is not economically justified, and he points to Scandinavian and South African practices for the advantages of mills of more nearly equal length to diameter ratio ("square mills"). He believes that autogenous mills should turn slower than ball mills, so as to reduce impact breakage of the large lumps, and promote cascading and multiple impacts sufficient to break smaller fragments. He presents no data to substantiate this view. However, Howard (7819) also states that excessive impact conditions should be avoided — why try to destroy the grinding media?

Razumov et al. (8615) conclude that size distribution of products from autogenous and steel-ball milling of ores is different, due to the different circulating load resulting from the different L/D ratios of the mills. This may explain claimed differences in release of valuable mineral components by the two methods.

#### 2.4.4 Coal

A literature survey with 52 references is published by Werkmeister (9178) on the comminution and handling of coal.

Buchmüller (9521) describes hammer mills used for coal grinding and discusses the limits of their application, including systems that link mill control to the coal-burning furnace.

Coal pulverizing is approached from the viewpoint of coal as a high-molecular-weight organic material by Dzhaparidze et al. (7490). Chemical composition changes are determined by extracting the product.

#### 2.4.5 Miscellaneous

Crushing is an important step in the recycling of solid wastes, and current practice is discussed by Iohn (7857). Griffiths (7668) discusses the manual control of grinding of glazes and vitreous enamels, with emphasis on practical problems of usage of mills and equipment.

#### 2.4.6 Wood Pulp

Gavelin (7593) studies the effect of variables in producing groundwood for paper manufacture.

The power consumed by a disk refiner for paper pulp is reported by Herbert and Marsh (7773). They interpret the results in terms of fluid and particle dynamics and propose a design modification to improve pulp beating characteristics. Laskeev (8109) presents a study to determine the physical and chemical changes that occur in wood fiber properties during grinding. Three main phenomena are singled out, namely reduction in fiber rigidity, increase of accessible OH groups of the fine fraction resulting in increased hydrophilicity of the wood, and partial hydrolysis of components such as pentosans. Defibrating action is located within the cell structure. The higher the initial modulus of elasticity of the wood, the higher should be the grinding

temperature, the lower the feed rate, and the longer the grinding time.

#### 2.4.7 Pigments

Although paint pigments are usually precipitated in sub-micron size, comminution is required to break up agglomerates, and to disperse the pigment in the vehicle. An electron microscope study of the effectiveness of the dispersion of pigment in paint films is given by Hornby and Murley (7814). Kogan and Bazilevich (8024) study the basic relations existing between critical pigment volume concentration, oil absorption, and specific surface of micronized iron oxide and talc pigments. Kafarov et al. (7911) report on the use of multi-stage sand mills for pigment grinding.

#### 2.4.8 Foods

There are important problems of size reduction applied to food products. One is the possibility of dry milling and degerming of corn. A literature review on this subject is presented by Vantwisk (9099). Niediek, Rumpf, and co-workers (8318, 8408-9, 8412-3) report studies to improve the process of milling and preparing chocolate. Usually the partly ground cocoa and sugar are masticated in conches. A more efficient and economical new process is described in which the materials are separately ground and then blended. Kleinert (8007) discusses the optimum particle size and grinding of cocoa.

Niediek (9733) reviews comminution in the food industry. He (9734) also reports investigations on the grinding of sugar in industry, and he reports (9735-6) on the performance of two particular mills for this purpose. Butters (9526) reviews comminution in the food industry, while Elias (9567) flour milling.

Several articles discuss the milling of cereals. The roller milling of corn dried at various moistures for degerminating is presented by Brekke (7262). Articles by Hutchinson and Martin

(7842), Kohler et al. (8025), and Shoup et al. (8852) discuss the effects of fine grinding and separation on the nutritive quality of wheat bran, on the digestibility of aleurone in wheat fractions, and the amino acid composition of sorghum fractions. Tschiers (9062) discusses the connection of the milling process to the quality of flour. The effect of dough properties owing to damage of starch by ball milling is discussed by Lorenz and Johnson (8184). Thomas (9019) discusses the art of oilseed grinding, while Wolter et al. (9230) report the effect of particle size and permeation during solvent extraction.

#### 2.4.9 Pharmaceuticals

The usefulness of many drugs depends on their particle size distribution. Fincher (7544) presents a review with 118 references on the subject. Small particle size increases the solution rate in the body, but sometimes too large a rate is avoided by using larger particles. Difficult experimental problems of measuring these effects are discussed. Particle size knowledge is not always a determining factor, but more knowledge is often needed.

Ritschel (9818) reviews comminution methods used in the drug industry. Miller and Fincher (9747) discuss the effect of particle size on the absorption rate of phenobarbital in dogs. Ikekawa et al. (9644) measure the rate of ball milling of 32 kinds of powders, and attempt to express the rate of ball milling as proportional to particle surface area, a relation that disagrees with findings in other industries. They also discuss the properties of products. The use of vibratory milling for the preparation of eye ointments is discussed by Quellmalz, Schmidt and Kastens (9801). They also discuss the use of mortars. Koz'min (9690) gives procedures for the effective dispersion of pharmaceuticals in mortars without loss of costly components.

The importance of size reduction and powder behavior in pharmaceutical engineering is discussed in a review by Fowler

(7562). Particle size affects the absorption of drugs, according to Marshall (8245), and tableting affects the particle size of aspirin, as reported by Vanooteg et al. (9098).

Absorption of drugs in man depends on their particle size, as Prescott et al. (8577) report for phenacetin, and Ljungbers (8167) for aspirin. Ezerskii (7527) discusses measurement of friability of antibiotic powders.

#### 2.4.10 Laboratory Milling

Grinding and mixing analytical samples can pose problems if one wishes the sample to be representative of a batch of material. Russian practice is described by Vulfson et al. (9129).

### 2.5 Mill and Liner Wear

#### 2.5.1 Wear Measurement

Hiorns (9634) reviews laboratory and plant-scale methods of measuring wear rate. Radiotracer methods are the most sensitive. A newly-recognized variation, charged-particle surface activation, can measure the composition of wearing surface layers. It is described by Konstant and Krasnov (9685).

Borik and Sponseller (9509) describe a test to measure the gouging abrasion resistance of alloys based on the use of a laboratory jaw crusher. Borik and Scholz (9510) then use the method to evaluate various alloys. Martensite in the microstructure and a high carbon content favor the gouging abrasion resistance.

Crushing tests on individual particles, and attrition during annular flow in a rotating-cup apparatus, are two small-scale tests that can be used for preliminary measurements of the relative attrition resistance of various materials of construction, according to Bjorklund and Dygert (7204).

In spite of development of laboratory tests, wear measurements are still needed in plant mills, because several wear mechanisms are involved that may not be measured by a single laboratory test. Clement and Voigt (9538) investigate wear by various ores in ball mills. Their results show that wear rate depends mainly on the strength of the mill liner materials and of the feed ore material, the mill speed and the solids content of the ore slurry. The wear rate is a maximum at 10 volume percent solids.

### 2.5.2 Wear Mechanisms

Maratray (8233) summarizes the various mechanisms that cause wear; different mechanisms predominate under different conditions. These are abrasion and erosion. Abrasion increases until the hardness of the abrasive is 1.4-1.6 times that of the metal; the angularity of the ore also plays a part, especially when resistance to abrasion is low. Pressure has more influence when abrasive and material are soft; velocity has a complex influence. Wear is greater in wet than in dry grinding; this, however, is still unexplained. Harder materials of construction may also fail by breaking, so a compromise has to be adopted between a fairly high hardness and an adequate resilience. The user must know, for the equipment under consideration, what will be the predominant type of abrasion, i.e., deformation, cutting, and impact or erosion.

When an abrasive grain gains access between two sliding metal surfaces, the wear of each surface depends on their hardnesses, in a way reported by Wahl (9137). The amount of motion has a greater effect than the velocity. Load, time and temperature have moderate effects. Further research on this type of wear is needed. For impact wear, Wellinger and Breckel (9174) determine the relation between the physical parameters and the deformation of metals under repeated impact, such as occurs between balls and liner in a ball mill. Wilman (9218) describes the nature of the

surface structure of abraded materials, mainly by means of electron diffraction at grazing incidence.

Tsenek (9065) interprets data on abrasive wear by a microscopic model of the system of contact. Parameters of the model are known properties: friction coefficient, size of abrasive grain, and an additional modulus which can be estimated theoretically or empirically. The problem of wear is found to be a problem of fluctuations of the friction forces with contacts.

### 2.5.3 Practical Applications

A French colloquium on wear published in Review de l'Industrie Minerale (9425-9438) includes articles by Maratray on wear mechanism of materials subject to abrasion, by Guillon on rock abrasivity, and by Milaplana on high-temperature abrasion. It also includes a users report on wear plates by Treguer et al., and articles on hard-facing of wearing parts by Rey, on slotted grates by Courcier, on grinding charges and mill liners by Bodu, on hammers in coal milling by Vial et al., on abrasion-resistant grinding parts by Milhoud, and on medium- and high-manganese steels by Hily. Wear in average French cement mills according to Bomblet (7238) amounts to 320 g/ton of dry cement raw material, 300 g/ton for clinker, and 90 g/ton for coal grinding. It can be reduced to 1/4 or 1/6 as much by use of hard-steel liners and balls.

Ball mill liner wear in South African practice is thoroughly reported by French and Lissner (7570), including photographs and data on wear of liners and discharge grates. The parts are designed to have the most metal in regions of greatest wear rate. When wear rate is plotted against metal hardness, the curve increases abruptly at a hardness equal to that of the feed, and hardness has less effect outside this region. Thus the wear rate with feldspar is twice as much for pearlitic steel as for martensitic, while the difference is less for quartz. But the

choice of material is limited by the resistance to impact of harder steels, and it depends on the extent of impact occurring in the mill. The greatest wear rate occurs at the inlet end of the mill, and primary mills suffer the most impact. Osborn liner bars, which accumulate an autogenous lining, are very effective in reducing wear. So far they have not been used in mills larger than 9 ft in diameter because of the difficulty in installing them.

Gommel (7639) compares the comminution and wear rates in impact mills. The grinding rate increases with increasing hardness of the impact elements, while the wear rate decreases, so long as the feed and elements are of the same hardness range. Kriegel (8060) finds that the wear rate of materials caused by flow of particles in a jet of air is influenced by the elastic modulus of the materials.

Although wear cannot be avoided, the cost of wear can be reduced by mechanized replacement of large mill liners, as described by Hinken and Dunn (9633). Techniques for successfully welding and rebuilding manganese (Hadfield) steel crusher parts are discussed in Pit and Quarry (9956). Behavior of the alloy on heating and cooling is important and should be understood.

#### 2.5.4 Rubber Liners

German experience in use of rubber mill linings is presented by Lange (8097) and Mohr (8316). Both Swedish and domestic rubber linings are now available in the U.S.

Rubber continues to replace steel liners in large autogenous mills grinding iron ore in Canada, according to Pickett (8538). These mills are up to 24 ft diameter. Perforated rubber screen is also being used.

Diehl and Griffiths (7440) summarize a symposium on rubber mill liners at which three iron ore companies present results from long-time full-scale tests. Rubber linings show longer life

and lower costs in all but the biggest mills. Rubber discharge grates are also being successfully used. One thing that was not previously known is the effect of rubber linings on the milling rate; all three companies report no change in capacity or grind, and two report a decrease in power consumption per ton ground. Rubber linings failed tests in the 20's and 30's mainly because no adequate method of attachment was found. Details of the two currently successful methods are given, both based on a rubber lifter bar that secures flat liner sheets. Adding more rubber to the wear areas increases life, and alters bar shape. Lifter bar shape greatly affects the wear rate, owing to angle of impingement, and it also affects grinding performance. Beebe and Merklin (7140) also describe experiments on the shape of rubber and steel lifter bars.

## 2.6 Crystal and Chemical Changes in Fine Grinding

Crystal and chemical changes caused by grinding are the subject of many articles; in fact, the literature in this area has exploded. Most of the investigators do not seem to be aware of the large number of others working on the subject, or of its history starting with Beilby (237) in 1921. Lidstrom (8150) reviews the subject with 115 references, and points to applications in mineral flotation and water purification, preparation of agglomerates, and a connection with silicosis. Investigations which seem only academic now may later prove to be important. On the other hand, there are so many unknown areas in comminution, that some of this effort might be better redirected.

### 2.6.1 Surface Effects

Gregg (7660) brings up to date his findings on this subject, and notes that the general effect of grinding is to make a substance more reactive. Usually the specific surface area increases up to a maximum and thereafter decreases, owing to re-adhesion of the particles. Distortion of the lattice may occur, and, in

extreme instances, polymorphic transition. Compaction also affects some of these properties. Schrader et al. (8789-8793) note an increase in catalytic activity or solubility of bohmite, hydrargillite, corundum, and bauxite on increasing grinding, and attribute this to lattice deformation or amorphotization as determined by x-ray, magnetic, and kinetic measurements. Khodakov and Edelman (7984) study the solubility of ground quartz in water. The defect energy value and solubility of amorphous surface layers depends on grinding parameters. Solubility increases on precalcination due to surface cleaning. Lidstrom (8150) observes formation of amorphous surface layers up to 0.15  $\mu\text{m}$  thick, depending on the method of grinding.

The surface area of crushed materials is sometimes measured by gas adsorption methods. However, Schwenk (9848) shows that the adsorption is not reversible. He crushes single particles in vacuum and measures the surface area by krypton adsorption both before and after exposure to air. Gammage and Gregg (9582) also measure the sorption of water vapor by ball-milled calcite.

#### 2.6.2 Crystal Phase Changes

The following investigations report crystal deformations as revealed by x-rays, thermal effects, increased solubility, or amorphotization. Danderand (7405) forms solid solutions of antimony and bismuth by grinding rather than by melting, and he also follows (7404) the transformation of calcite to aragonite by grinding. Senna (8822) observes a transformation of the crystal phase of lead oxide by wet ball-milling, while Lin (8155) forms galena by grinding. Gock (7629) lowers the reaction temperature of magnesia with titanium dioxide by first grinding them together; Saito (8734) measures x-ray line broadening of titanium dioxide by impact. Lattice defects in alumina due to grinding by vibratory- and five kinds of jet-mills are measured by Lecrivain (8121), who finds that the defects result in more rapid sintering when the alumina is heated; Sarker and Towner (8746) report the

removal of these defects by annealing. Gasparoux et al. (7591) study the recovery of defects by annealing of ground graphite, as a tool for understanding the transformation from rhombic to hexagonal structure involved in the graphitization process.

Although most studies of chemical and physical changes have no applications as yet, a few relate directly to improvement of industrial products. For example, a practical application in connection with changes in the magnetic properties of iron oxide is reported by Karasinska (7934), and Szantho et al. (8977) report the activation of titanomagnetite by vibrational grinding.

Magee et al. (9727) study the effect of raw material particle size on the formation of manganese zinc ferrite by calcining. Paudert and Stellenberger (9787) recommend vibratory milling of raw materials to produce barium titanate with optimum dielectric properties. Shirk and Buessem (9861) present a molecular model to correlate the effect of the particle size of barium ferrite powders on their magnetic properties. Davis, Carithers and Watson (9552) present empirical relations between calculated particle surface areas and density of green and sintered products made from refractory materials.

Some breakage of kaolinite particles occurs during the high-solids dispersion of clay, and this can be attributed to a form of low-energy autogenous grinding, according to Brociner (9519). Palmer (9782) studies the vibratory grinding of graphite, and finds that the breakage is evenly distributed between basal planes and crystal edges.

### 2.6.3 Chemical Reactions

In addition to crystal structure changes, there are numerous examples of chemical reactions promoted by comminution; a few of these appear to have some practical value. Augustat (7075) reports degradation of starch to polysaccharides in a vibratory grinder; Pazonyi et al. (8506) report degradation of poly(methyl metha-

crylate), PVC, and polystyrene in a ball mill; Scalan (8753) patents the decarboxylation of fatty acids by ball milling; Oprea et al. (8469) destruct polyethylene terephthalate by vibratory milling; Schrader et al. (8794) prepare methylchlorosilanes by disintegrating silicon alloys in a ball mill with methyl chloride.

Tomashev (9031) reviews the energy of disruption of chemical bonds, while Fox (7564) considers the fracture-induced thermal decomposition in brittle crystalline solids. Ocepek (8443-5) discusses in a general way the energy effects of pulverizing as well as mechano-chemical reactions.

Several investigators study the solid-state chemical reactions of two components during grinding. Lin (8155) reports the reaction of lead oxide and sulfur to produce galena by grinding.

Senna (9854) reports the rate of polymorphic transformation of lead oxide from the massicot to the litharge form by wet ball milling.

X-ray emission spectroscopy is used by Motoyama and Hashizume (9761) to follow the reaction of silica and zinc carbonate. Shifts in the silica  $K\alpha$  and  $K\beta$  x-ray energies are caused by bonding of zinc to silica.

The grinding rate of silica gel in four types of laboratory mills is compared by Menyhart and Domsa (9742). Several two-component reactions are then studied in these mills, including the reaction of magnesia with silica, sodium carbonate with alumina, zinc oxide with hydrogen sulfide, lead oxide with carbon dioxide, and zinc oxide with chromia.

Paudert et al. (8500) report that normally insoluble cassiterite becomes completely soluble owing to lattice distortion on prolonged milling. Harwood et al. (7742) conclude that reactivity of milled iron oxide cannot be deduced from surface area

alone. Von Szantho (8978) measures the activation of mineral powder surfaces caused by vibratory milling.

## 2.7 Grinding Aids

Interest runs high in the use of grinding aids as an easy way to increase grinding productivity of mills, especially in the cement industry.

Somasundaran and Lin (9871) publish an extensive review of the effect of grinding aids. They are concerned mainly with the effects of additives on the strength and fracture of brittle materials. They indicate that grinding aids can also affect slurry flow properties, but consider this an effect that interferes with measurement of the strength properties they wish to study. The evidence for the effect of aids on strength is convincing, but the evidence also indicates that this effect is not of practical importance in grinding. Rather, the main practical effect in wet grinding is by changing the agglomerating tendency, and in dry grinding by reducing ball coating.

Graichen (7651) reviews mechanisms and applications of grinding aids in general, while Ruzek (8724) reviews effects of grinding in different environments on the fineness and crystal structure of solids.

### 2.7.1 Wet Viscous Milling

Pigment dispersions have high viscosities. In pigment grinding, it is only necessary to break up the aggregates. A lower slurry viscosity results when agglomeration of particles is prevented (635), and this can affect the capture of particles. There is evidence that only enough surfactant as a grinding aid is needed to cover the pigment particles with a monomolecular layer. A table of the effect of 50 aids for pigment grinding is given in Ref. 622, and Ref. 635 gives more. In organic fluids, Quatinez (3996) reports on the grinding of powders of nickel and other metals, in both a laboratory ball mill and in an

Attritor (stirred ball mill). The grinding aids tried were mostly inorganic salts. Fochtman, Bitten and Katz (7555) found that certain organic surfactants aid the ball-milling of 200-mesh magnesium slurry in jet aircraft fuel. Also, Ref. 3327 reports on surfactants for grinding aids. The best surfactant differs with each system, and its selection remains an art.

### 2.7.2 Other Wet Milling

Less work has been done on the effect of grinding aids in the wet ball-milling of minerals. It appears that prevention of agglomeration can be an important mechanism, but the choice of the best grinding aid has not been comprehensively studied. For aqueous ceramic slurries (slips), certain inorganic salts are very effective dispersants and are also effective grinding aids (630). However, they are specific for clays.

It is well known that wet grinding is more efficient than dry grinding. Rose (2889) discusses this on page 239. Skaupy (4834) reports that wet grinding of iron powder is many times faster than dry grinding. Therefore the fluid medium itself can be considered a grinding aid.

Von Szantho (649) measured the effect of additives in wet milling of quartzite and limestone with a laboratory ball mill. He found that the new surface produced increased 100% with 0.025 wt. % of added Flotigan (a flotation surfactant). It increased less with oleic acid and actually decreased with some other agents. See Rose (2889), pages 245-249, for details. The effect decreased with excess additive, and Szantho showed that this was due to a lubricating effect, since it lowered friction between the balls and the smooth mill wall. Rose explained that friction affects the lifting action of the mill wall. So this effect may not occur in mills equipped with lifters.

Gilbert and Hughes (3472) found that various electrolytes had either no effect or a deleterious effect on the grinding of

quartz or limestone in a Hardgrove ring-ball machine or in a ball mill or rod mill. The additives they picked were a silicone oil and the alkalies sodium hydroxide, sodium carbonate, and sodium silicate. But Kukolev (640) found that sodium hydroxide accelerated the grinding of magnesite and retarded that of dolomite. Soap had no effect on magnesite but accelerated grinding of dolomite.

Rehbinder and Khodakov (4017) performed the most complete studies on wet grinding fluids for minerals. They ground quartz in a laboratory vibration mill. The nitrogen gas adsorption method was used to determine the surface area. At 80% fluid content the influence of water dominated that of the other fluids. After 32 min, the specific surface on milling was  $73 \text{ m}^2/\text{g}$  in water,  $9.3 \text{ m}^2/\text{g}$  in benzene,  $13.3 \text{ m}^2/\text{g}$  in acetone, and  $5.9 \text{ m}^2/\text{g}$  in air. The heat of wetting of these fluids was not much different. If the samples ground in benzene, acetone, or alcohol are further ground in water, the surface increases in 30 sec to the value it would have if milled for the same time in water. This rapid increase indicates that fine particles though formed were agglomerated.

These results strongly suggest that additives in wet grinding are effective as dispersing agents and not as agents to weaken the material, even though such weakening has been demonstrated in the breakage of single particles. The conclusion might be different if data were available for coarse grinding, in which agglomerates are less important. In fine grinding, however, the conclusion suggests that surfactants should be the most effective grinding aids, because they are the most effective dispersants.

There has been no scientific way to choose grinding aids suitable for a given feed material. Rosen (9823) begins to relate surfactant chemical structure and properties such as

surface tension reduction, micelle formation, foaming, wetting and dispersion of solids. Changes are influenced by the length and branching of the hydrophobic group, the nature of the hydrophilic group and its position in the molecule, and the presence of ionic charge.

Silicone grinding aids are also used in wet grinding. 0.05 to 0.1% polysiloxane increases the rate of wet ball milling of ultraporcelain and talc to a product below 10  $\mu\text{m}$ , according to Piven and Naloichenko (8550). According to Zaika and Piven (9259) the ball milling of an alumina slip at 72 to 74% solids content is increased by a silicone dispersing agent, which probably acts by decreasing the viscosity of the slip.

### 2.7.3 Dry Milling

There are a large number of reports of the effect of additives on dry ball milling. These include the effect of atmospheres saturated with organic vapors as well as the effect of small amounts of liquids and solids. Tanaka (4171) suggested that the aid must be volatile so that it can form a monomolecular layer on the particles, but nonvolatile graphite is effective for cement grinding. Sweitzer and Craig (1751) reported that 0.32 wt. % of carbon decreased the grinding time by 28%. Its action was due to reduction in ball coating. The carbon was also observed to improve dry flow properties. A patent (6254) advocates a phenolic compound for cement grinding.

Plant test data are reported on a number of grinding aids, which either increase cement production or increase fineness of the product, or both. Triethanolamine increases cement clinker production by 4%, according to Agareva (7010). Beke (7153) finds that it increases fineness from 600 to 11,000  $\text{cm}^2/\text{g}$ , and it differs in effectiveness for different cement minerals. Diethylene glycol is tested by Iwabuchi et al. (7866-7), who find that it reduces the water needed to make concrete with the

cement. Scheibe (8762) discusses the use of grinding aids, including triethanolamine and various glycols, as well as organic salts, longer-chained alcohols, xanthogenates, carboxylic acids, phosphoric acids, and various amines. Compounds with C<sub>17</sub> or C<sub>18</sub> chains are particularly effective. The last three types are nearly universal aids for cement, quartzite, and limestone.

Serafin (8824-7) and Dodson (7458) patent a series of organic acetates, amines, amides to increase grinding efficiency and resistance to pack setting of cement. Amounts from 0.005 to 0.4 wt. % are used.

A comparative test by Opoczky (8468) on grinding cement 1 to 90 hr in a laboratory ball mill shows that triethanolamine is effective in preventing ball coating, but not agglomeration of particles. Ball coating impairs productivity of grinding, while agglomeration impairs cement quality. Experience with glycol and amine cement grinding aids in Germany, summarized by Schneider (8773), shows that throughput is increased 25 to 50%, classifiers achieve sharper separation, and cement is more readily conveyed. Likewise, grinding aids are favored in Russia, and Sidocenko et al. (8858) report that triethanolamine has the best effect. Plant tests with three mills on cement containing 13% slag showed that the optimum dose was 0.020 to 0.025% additive; this gave the best fineness, increase of strength, and increase of mill throughput. Organosilicones are also being tried in Europe. Zadak and Zezulka (9256-7) report on their effect in clinker grinding. In a 15- $\phi$  batch mill Mel'nik et al. (8285) find that 0.01 to 0.05% decreases grinding time by 70%. Quality is not affected in this case. An extensive investigation of the effect of organic vapors on grinding of cement clinker in ball mills is reported by Seebach (8816).

There are a number of extensive investigations of the effect of vapors as grinding aids. Rumpf (4077, 1954-5) charges such

experiments with not representing either wet or dry grinding, but something in between. Therefore factors that influence surface condensation of these vapors are important, whereas they may not be important in purely wet or dry grinding. No one has apparently used vapors, except steam, as grinding aids on a commercial scale, although volatile solids are used. Still, these data may reveal something about the action of grinding aids in general.

Rehbinder and Khodakov (4017) found that the fluids that worked best in wet grinding also worked best as additives in dry grinding. The effect of water is a maximum at 1.2% addition, and then it decreases to a minimum between 4 and 30%. At 50%, it approaches wet milling.

Goette and Wagner (4727) found that water and organic vapors improve dry grinding of chalk, glass, and sand when one monolayer was absorbed, but the effect decreased with larger amounts. Goette (3641) studied dry milling of cement clinker, glass, quartz, marble, and anthracite in various atmospheres and in ionized air. He measured surface area by permeability, and he also measured oxygen content of the mill vessel. The experiments were done in a laboratory ball mill. Both nonpolar vapors (petroleum ether, hexane, benzene, carbon tetrachloride) and polar vapors (water, nitromethane, acetone) gave significant increases in surface produced. The heat of adsorption correlates with this effect (different from Rehbinder's finding). With inorganic feeds, the largest effect was observed in air, and a significant decrease occurred on adding vapors. Fat coal behaved in the opposite manner. The oxygen content of the air decreased 0.75% during the first phase of the process; oxygen apparently reacted with the new surface.

Larger amounts of acetone and benzene (up to 5%) were added in some experiments with coal. The maximum increase occurred at

2 to 3%. These quantities were related to adsorbed films on surfaces and their influence on adhesion of particles to make agglomerates. Capillary adhesion is a means by which a liquid film can bind particles together, and it has a maximum with a certain film thickness.

Goette and Ziegler (4729) found effects of various vapors, which in a vibratory mill showed a dependence on milling time.

Bond and Agthe (3091) studied the effect of ball coating in dry grinding, and their observations correlate with the independent work of others quoted above. They say that most materials coat balls if they are ground fine enough, and softer materials coat at larger sizes than harder materials.

Rapid cooling of cement clinker appears to reduce coating. Carbon introduced as a grinding aid reduces coating. The presence of a considerable amount of coarse particles inhibits coating, especially those above 35 mesh. Small amounts of moisture increase coating of many substances, especially hygroscopic ones, but dry materials may also coat. Very smooth media are not coated, but when they become scratched they coat. Large and small balls in the same charge coat the same.

Bond (3091) suggested that static electricity, adsorption of vapors and impurities, and mechanical tamping may promote coating. Coatings had a laminated, concentric structure that was most dense near the ball. The finest particles formed the first layer on the ball and were wedged into fine scratches. This first layer had a higher gypsum content than the rest of the clinker. A clinker grinding test without added gypsum gave slightly less coating. Addition of soft zinc oxide increased the coating. Addition of 0.88% water decreased the coating substantially. It is suggested that in this case water hydrates the finest cement particles so that they agglomerate with one another rather than adhering to the balls. In another test, a

water compound and a lignin compound were used. The balls were only slightly coated, and the cement was more finely ground. It was also suggested that harder ball alloys may wear smoother and thus coat less.

Berry (1561) reported a 30 to 40% improvement in cement clinker grinding production by 0.016% additions of Vinsol resin, cod oil, beef tallow, aluminum stearate, glycerol, and a lignin preparation. These were obviously selected for cheapness rather than for best effect.

Therefore dry grinding experiments attribute the effect of grinding aids to coating phenomena, although single-particle experiments show that additive vapors can affect strength. No data were found on the effect of additives in dry grinding when no coating occurred anyway. The results of this literature study suggest that further experiments would be worthwhile to answer the questions raised.

## 2.8 New Mills and Exotic Methods

Occasionally a new type of mill or a novel principle is presented. Most of these have a slim chance to replace the older types of mills. Only once in 15 years does an important new development in mills succeed. Perhaps one or two of the ideas mentioned here will eventually succeed.

### 2.8.1 Tensile Breakage

Bond (7236) reviews attempts to induce breakage without wastefully applying pressure and concludes that inherent practical limitations have been found for the following methods: spinning particles, resonant vibration, electrohydraulic crushing, induction heating, sudden release of gas pressure, and chisel effect breakers. He suggests that research to improve the efficiency of comminution start with the fundamental mechanisms of fracture as it depends on the physical structure of rocks.

Bergstrom (7174) reports a serious attempt to test the oft-repeated suggestion that comminution could more effectively be achieved by applying tension than compression. He devises or culls from the literature methods to set particles spinning to destruction. Finally, tensile failure is achieved by spinning a disk, as in the failure of a grinding wheel. The energy input is low, but the fragments are large. In fact, the new surface versus energy plots on a straight line extrapolated from published results of compression experiments, indicating that tensile comminution is not more efficient. Nevertheless, Maruna Enterprises Ltd. (9404) has patented a tensile comminution device based on rotation, claiming that it gives improved mineral grain cleavage.

#### 2.8.2 Selective Crushing

A goal that is often mentioned, but that has eluded practical application, is the selective crushing of an ore component in the presence of gangue. Selective crushing would permit a size separation, or at least would decrease the cost of grinding. Laskowski et al. (9704) now suggest a brute-force way of selectively crushing copper ore with a rubber squeezer. The sandstone gangue is preferentially crushed, and is removed by flotation.

Ores are ground to liberate valuable mineral fractions, which may then be separated by flotation or magnetic means. Wiegel and Li (9202) propose a model whereby random breakage of an assumed grain geometry produces a relation between the mineral concentration in a locked particle and the frequency of occurrence of such a particle. Predicted results are compared with measured liberation performance in industrial milling of taconite iron ore, and good agreement is achieved. The agreement raises the question whether selective breakage along grain boundaries occurs as often as has been assumed in the past.

### 2.8.3 Thermal Effects

Daellenbach et al. (9550) investigate improvement of taconite grindability by pretreatment. Roasting in a reducing atmosphere has the most effect, but quench cooling from the quartz crystal transition temperature is also effective. The work index is decreased to 13% for grinding to -48 mesh, but only to 60% for -400 mesh. Calculations carried out by Devore (7433) suggest that stresses arising from differential thermal contraction of coexisting mineral crystals are sufficient to cause brittle rupture of rocks subjected to temperature changes, and this may explain some of the results of Daellenbach.

Thermal expansion is also the cause of surface spalling by an exotic method — the use of giant laser pulses — according to Bristow et al. (7267). Complicated light absorption processes are involved when a laser impinges on glass, according to Davit (7417).

Pieces of rock can be broken by thermal shock caused by absorption of RF energy. Matthaei (8265-6) describes a Yagi antenna for focussing the energy on the piece, and also describes characteristics of the rock needed to absorb the energy. Results of tests with limestone are presented. Pickarski (8539) describes similar experiments, fracturing asbestos ore with RF currents.

Sarapuu (8744-5) demonstrates electrical heating to break rock in several iron ore mines in Missouri and Minnesota. Heating is due to electrical contact resistance and internal resistance and performance depends on electrical conductivity of the rock. Equipment is commercially available. Multi-point electrodes and electrified drill bits are used. Electric power consumption is 1 to 2 kwh/ton rock.

#### 2.8.4 Electrohydraulic Crushing

Electrohydraulic crushing is an exotic method that has not yet been found practical. The method applies a spark under water in the presence of pieces to be broken. Yigit, Johnson, and Maroudas (9247) measure the shape and size distribution of aggregate crushed in this way. Ohme (8454) reports an extensive investigation to try to make the method practical. The most severe experimental problem was obtaining a suitable electrical insulator for the electrodes, but a suitable one is found. Brass is most suitable for the electrodes themselves. Shock waves or friction cause comminution of grains; cavitation appears to play a minor role. Performance is rated in terms of kwh per unit of new surface formed. It is best when the water has a low conductivity, and the material to be crushed completely surrounds the spark. Product particle sizes are mostly below 0.06 mm, and fineness increases with sparking time. The energy consumption is still 10 times that of conventional methods.

Further studies of the power consumed in electrohydraulic crushing are reported by Carley-Macaulay et al. (7323). Yigit et al. (4887, 9248) continue their studies of electrohydraulic crushing with a study of selective breakage of heterogeneous materials by this method.

A test installation for crushing quartz without contamination by wear is described by Belopitow et al. (7162). A report by Kutter (8084) investigates the potential of this effect.

#### 2.8.5 Special Tumbling Mills

A tumbling mill with an elastic wall is described by Generlich (7605). As it turns on a roller the mill deforms, causing a stirring action of the media.

Eigner (7505-6) gives a detailed account of the design and testing of a tumbling mill of square cross-section with rounded corners. A spiral lifter bar arrangement tends to segregate

balls according to size, and this rather than the shape may be responsible for the claimed improved output per unit power of 30%.

Plank (8557) describes slanting liner plates which are supposed to cause large balls in a ball mill to go to the feed end and the smaller ones to the discharge end. If the grist in the mill is not well mixed, then this old idea would put the largest balls where they could act on the largest particles, and this would increase the grinding rate. Plank (8557) postulates effects which may help or hinder such classification; however, no data has been published to prove that such liners actually cause ball classification.

The German patent literature is reviewed by Lohn (8356-7). Subjects covered include stone crushers, mills drying with hot gases, and a jet mill.

Planiol (8553-5) advocates comminution of particles by projecting them against hard targets in vacuum. Important economy of energy, increasing rapidly with desired fineness, is claimed.

Planiol's (8556) impact grinder operating under vacuum is described in an English article. A rotor in this device throws particles of ore against a metal ring. Data tabulated in the article indicate less power consumption than a ball mill.

#### 2.8.6 Plasmas

Ultrafine powders can be prepared in high-temperature plasmas. Particles below 1  $\mu\text{m}$  and larger particles with unusual surface structures are formed according to Waldie (9138). Energy costs are discussed. The review of Okuda (8460) mentions a number of exotic methods as well as traditional grinding equipment.

### 3. ALPHABETICAL LIST OF SUBJECT INDEX TOPICS

Three-letter codes identify topics used on the computer listed subject index, Section 9. See also Sections 4 and 5.

ABR	Abrasives, diamonds
ADS	Adsorption, Bet
AFR	Africa
AGL	Agglomeration, caking
AID	Aids, additives
ANN	Annular mill
ASA	Asia
ASB	Asbestos
ATM	Atmosphere
ATR	Attrition
AUS	Australia
AUT	Autogenous
B	Breakage function
BAL	Balls
BAT	Batch
BML	Ball, pebble, tube mill
BND	Bending
BOK	Book
BRT	Britain
BTL	Brittle
CLC	Calculation of performance
CAL	Calorimetry
CRB	Carbon, graphite
CMT	Cement
CRM	Ceramics, clay
CRL	Cereal
CHF	Charge of feed
CMF	Chemical effects
CMS	Chemicals, salts
CIR	Circuit, closed
CLS	Classifiers
CWM	Classification within mill
CLW	Clearance of working part
COL	Coal and coke
CLM	Colloid mill
CBS	Combination of stresses
CMM	Components of mills
CPC	Compaction, crushing bed
CPM	Compartment in mill
CMW	Composition in working part
CRP	Compression
CNC	Concentration of solids
CNM	Conceptual models
CON	Cone crusher

CST	Construction feature other
CNT	Contact phenomena, Hertz
CTN	Continuous
CTR	Control
COU	Counter, sensing zone
CRK	Crack propagation, Griffith
CRU	Crushing, coarse
CRY	Crystal structure
CYC	Cyclones
DAT	Data
DED	Dead load of mill
DNW	Density balls, working part
DNM	Density of material ground
DIM	Dimensional analysis
DST	Distribution of residence time
DSC	Disc mill
DSD	Discharge devices
DSP	Dispersing, dispersion
DRY	Dry
DNG	Drying
DUR	Duration, contact time
ECN	Economics
ELS	Elastic
ELC	Electrical effect, conductance
ENG	Energy, power
EXP	Explosive shattering
EXF	External feed mechanism
EUR	Europe other
FRT	Fertilizers
FLA	Flaws
FLO	Flow of fluid
FLP	Fluid properties
FOD	Foodstuffs
FRC	Fracture mechanics
FRL	French
FRI	Friction
GEO	Geometry
GLS	Glass, amorphous
GDY	Grindability
GYR	Gyratory crusher
GRL	German
GER	Germany, Austria
HAM	Hammers
HDW	Hardness balls, working part
HDM	Hardness of material ground
HAZ	Hazards
HVY	Heavy media
HET	Heterogeneous, grainy, grains
HIS	History
HOR	Horizontal axis of motion

IPM Impact mill  
 IPT Impact  
 INC Incorrectly applied  
 IDC Inertia drag classifier  
 INI Initial rate  
 IFM Internal feed mechanism  
 INT Internal action in mill  
 JAW Jaw crusher  
 JET Jet without anvil  
 JWA Jet with anvil  
 JIG Jigging, tabling  
 JPL Japanese  
 K Selection, rate function  
 KIN Kinetics of milling  
 LAB Laboratory experiment  
 LCS Lab crush experiment, single particle experiment  
 LGM Length of mill  
 LSC Light scattering  
 LMS Limestone  
 LGR Limit of grinding  
 LIN Liners, lifters  
 LDB Loading of balls  
 MAG Magnetic effects  
 MTG Materials ground, feeds  
 MAT Mathematics, statistics  
 MTX Matrix  
 MEC Mechanical  
 MET Metal  
 MTR Methods of research  
 MIC Microscopes  
 MIL Mills and grinding  
 MKN Milling cutter, knives  
 MNL Minerals, nonmetallic  
 MNG Mining effect on feed  
 MXR Mixer  
 MXG Mixing  
 MOD Moduli  
 MST Moisture  
 MTW Motion balls, working part  
 MTP Motion of particles  
 NIP Nip angle  
 NOV Novel technique  
 NUC Nucleation of flaws  
 NUM Numerical analysis, computer  
 OPR Operating problems  
 OPT Optimum operating conditions  
 OTL Other language  
 OCP Ores, copper  
 OGD Ores, gold  
 OIR Ores, iron

OLZ	Ores, lead, zinc, pyritic
ONK	Ores, nickel
OVR	Ores, various
OFD	Other feed component present
OTM	Other type of mill
PAN	Pan, muller
PSA	Particle size analysis
PAT	Patent
PER	Permeability
PHR	Pharmaceuticals
PTG	Photography
PIG	Pigment, paint
PIL	Pilot scale experiment
PLA	Plant scale experiment
PLN	Planetary or other ball mill
PLS	Plastic properties
PLY	Polymers
POR	Portable
PWD	Powder behavior
PTR	Power transmission, drive
PRC	Practice, industrial
PRE	Pretreatment of feed
PRO	Process with grinding step
PRD	Production rate, efficiency
PZO	Pre-1920
QTZ	Quartz, sand
QUA	Quality of product
RAD	Radioactive techniques
RAK	Rake, screw classifiers
RAT	Rate of stressing
RXL	Recrystallize, amorphotize
RSR	Research results
RES	Resistance of materials
REV	Review article
RNG	Ring roll, ring ball mill
ROD	Rod mill
ROL	Roll mill
RUS	Russia
RSL	Russian
SAM	Sampling
SCN	Scandinavia
SEM	Scanning electron microscope
SED	Sedimentation, elutriation
SEL	Selective grinding
SEQ	Sequential mill units
SHW	Shape balls, working part
SHM	Shape of mill
SHP	Shape of particles
SHR	Shear
SHO	Shock waves

SIM	Simulation, grinding equation
SRD	Shredding, shredder
SIV	Sieve
SGL	LCX-single particle experiment
SZD	Size distribution law
SZE	Size-energy law
SZW	Size of balls, working part
SZM	Size of mill, diameter
SZF	Size of feed
SZP	Size of product
SON	Sonic, ultrasonic
SPD	Speed
STM	Stamp mill
STD	Standard
STR	Stirred ball mill
STN	Stone, aggregate
SRC	Surface chemical reaction
SRF	Surface
TRN	Transient
TBO	Triboluminescence
TMP	Temperature
TEN	Tension, tensile stress
TRA	Tracer experiment
TRL	Translated, English
TTH	Toothed, fluted part
USA	United States
VAR	Variables
VRT	Vertical axis of motion
VIB	Vibratory
WAS	Wastes, trash
WAR	Wear, abrasion
WET	Wet
WOD	Wood, pulp, peat
WRK	Working part
WST	Western hemisphere other
XRY	X-ray
1PC	1-point contact
2PC	2-point contact
20	1920's
30	1930's
40	1940's
50	1950's
60	1960's
70	1970's

4. INDEX TOPICS GROUPED UNDER SUBJECT AREAS

Mills

ANN Annular  
AUT Autogenous  
BAL Ball, pebble, tube  
CLM Colloid  
CON Cone crusher  
CRU Crushing, coarse  
DSC Disc  
DSP Dispersion  
EXP Explosive shattering  
GYR Gyratory crusher  
IPM Impact mill, hammer mill  
JAW Jaw crusher  
JET Jet without anvil  
JWA Jet with anvil  
MIL Mills and grinding  
MKN Milling cutter, knife  
MXR Mixer  
NOV Novel  
OTM Other type  
PAN Pan mill, muller  
PLN Planetary or other ball mill  
POR Portable  
RNG Ring roll, ball race  
ROD Rod  
ROL Roll crusher  
SRD Shredder  
SON Sonic, ultrasonic  
STM Stamp  
STR Stirred ball  
VIB Vibratory

Applications

CTR Control  
DSP Dispersion  
DNG Drying  
ECN Economics  
GDY Grindability  
HIS History  
INC Incorrectly applied  
HAZ Hazards  
LGR Limit of grinding  
OPR Operating problems  
OPT Optimization, best operating conditions

PAT	Patent
PRC	Practice
PRO	Process with grinding step
PRD	Production rate, efficiency
PWD	Powder behavior
QUA	Quality of product
REV	Review article
SEL	Selective grinding
STD	Standards

### Mill Components and Characteristics

BAL	Ball
CLW	Clearance of working part
CMM	Component of mill
CMW	Composition of working part
CPM	Compartment in mill
CST	Construction feature other
DNW	Density of working part, balls
DSD	Discharge device
EXF	External feed mechanism
HAM	Hammers
HDW	Hardness of working part
HOR	Horizontal axis of motion
LGM	Length of mill
LIN	Liners, lifters
LDB	Loading of balls
MEC	Mechanical
MET	Metal
MTW	Motion of working part, balls
PTR	Power transmission, drive
SEQ	Sequential mill units
SHW	Shape of balls, working part
SHM	Shape of mill
SZM	Size of mill, diameter
SZW	Size of balls, working part
TTH	Toothed, fluted part
VRT	Vertical axis of motion
WRK	Working part of mill

### Action within Mills

AGL	Agglomeration, caking
ATM	Atmosphere, vapors
ATR	Attrition
CMF	Chemical effects
CWM	Classification within mill
CRY	Crystal structure
DSP	Dispersing
IFM	Internal feed mechanism
INT	Internal action in device
MXG	Mixing
MTW	Motion of working parts, balls
QUA	Quality of product
RXL	Recrystallize, amorphotize
SEL	Selective grinding, differential grinding, release of component
SRC	Surface chemical reaction
SRF	Surface
WAR	Wear

### Materials Ground, Feeds

ABR	Abrasives, diamonds
ASB	Asbestos
CRB	Carbon, graphite
CMT	Cement
CRM	Ceramics, clay
CRY	Crystal structure
CRL	Cereal
CMS	Chemicals, salts, sulfur
COL	Coal, coke
DNM	Density of material ground
FRT	Fertilizers, phosphates
FOD	Foodstuffs
GLS	Glass, amorphous
HDM	Hardness of material ground
HET	Herogeneous, grainy
LMS	Limestone
MTG	Material ground
MET	Metal
MNG	Mining effect on feed
MNL	Minerals, nonmetallic

#### Ores

OCP	Copper
OGD	Gold
OIR	Iron

OLZ	Lead, zinc
ONK	Nickel
OVR	Various
OFD	Other feed component present
PHR	Pharmaceuticals
PLY	Polymers
PIG	Pigment
PRE	Pretreatment of feed
RAD	Radioactive ores
QTZ	Quartz, sand
RES	Resistance of materials
SEL	Selective grinding, release of component
SHP	Shape of particles
SZF	Size of feed
STN	Stone, aggregate
WAS	Wastes, trash
WOD	Wood, pulp, peat

### Variables

AID	Aids, additives
ATM	Atmosphere, vapors
CHF	Charge of feed
CLW	Clearance of working part
CMW	Composition of working part
CNC	Concentration of solids, slurry density
DED	Dead load of mill
DNW	Density of balls, working part
DNM	Density of material ground
DRY	Dry
DUR	Duration, contact time
DST	Distribution of residence time
ELC	Electrical effect, conductivity
ENG	Energy, power
FLO	Flow of fluid
FLP	Fluid properties
FRI	Friction
GDY	Grindability
HDW	Hardness of balls, working part
HDM	Hardness of material ground
LGM	Length of mill
LGR	Limit of grinding (product size)
LDB	Loading of balls
MAG	Magnetic effects
MTG	Materials ground
MNG	Mining effect on feed
MST	Moisture
PRE	Pretreatment of feed

PRD	Production rate
SZW	Size of balls, working part
SZE	Size energy law
SZF	Size of feed
SZM	Size of mill, diameter
SZP	Size of product
SON	Sonic, ultrasonic
SPD	Speed
TMP	Temperature
VAR	Variables
WAR	Wear
WET	Wet

Experimental (See also under fracture)

BAT	Batch
CAL	Calorimetry
CTN	Continuous
DAT	Data
INI	Initial rate
KIN	Kinetics of milling
LCX	Lab crush experiment, single particle experiment
LAB	Laboratory scale
MTR	Method of research
PIL	Pilot scale
PLA	Plant scale
PTG	Photography
RAD	Radioactive technique
RSR	Results of original research
SAM	Sampling
TRA	Tracer technique
TBO	Triboluminescence

Models

B	Breakage function
CLC	Calculation of performance
CNM	Conceptual models (physical)
DIM	Dimensional analysis
GEO	Geometry
IFM	Internal feed mechanism
MAT	Mathematics, statistics, equation solving
MTX	Matrix mathematics
MTW	Motion of balls, working part
MTP	Motion of particles

NUM Numerical analysis, computer  
 NIP Nip angle  
 PRD Production rate  
 K Selection, rate function  
 SZE Size energy law  
 SIM Simulation, equation of grinding based on  
     population balance  
 TRN Transient

Fracture, Breakage Phenomena

1PC 1-point contact  
 2PC 2-point contact  
 BND Bending  
 BTL Brittle  
 CBS Combination of stresses  
 CPC Compaction, crushing of a bed  
 CPR Compression  
 CNT Contact phenomena, Hertz  
 CRK Crack propagation, Griffith  
 ELS Elastic  
 FLA Flaws  
 FRC Fracture mechanics  
 FRI Friction  
 IPT Impact  
 MOD Moduli  
 NUC Nucleation of flaws  
 PLS Plastic properties  
 RAT Rate of stressing  
 RES Resistance of materials  
 BTL Brittle  
 ELS Elastic  
 MOD Moduli  
 PLS Plastic  
 SHR Shear  
 LCX Single particle, lab crushing experiment  
 1PC 1-point contact  
 2PC 2-point contact  
 SHO Shock waves  
     (Stresses)  
 BND Bending  
 CBS Combination of  
 CPR Compression  
 FRI Friction  
 IPT Impact  
 RAT Rate of stressing  
 SHR Shear  
 TEN Tension, tensile  
 SRF Surface  
 TEN Tension, tensile stress

### Classifiers

CLS	Classifier
CWM	Classifier within mill
CIR	Circuit, closed
CTR	Control
CYC	Cyclone
HVY	Heavy media
IDC	Inertia drag classifier
JIG	Jigging, tabling
RAK	Rake, screw
SED	Sedimentation, elutriation
SIV	Sieve
TRN	Transient behavior
MAS	Mechanical air separator

### Particle Size Analysis

ADS	Adsorption, surface, BET
COU	Counter
LSC	Light, optics, scattering
MIC	Microscopes
MTP	Motion of particles
PER	Permeability
SAM	Sampling
SEM	Scanning electron microscope
SED	Sedimentation, elutriation
SHP	Shape of particles
SIV	Sieve
SZD	Size distribution law
SON	Sonic, ultrasonic
SRF	Surface
XRY	X-ray

### Decade Published

P20	Pre-1920
20	1920's
30	1930's
40	1940's
50	1950's
60	1960's
70	1970's

Language

FRL French  
GRL German  
JPL Japanese  
RSL Russian  
OTL Other language  
TRL Translated, English

Region Where Work Was Done

AFR Africa  
ASA Asia  
AUS Australia  
BRT Britain  
EUR Europe, other  
GER Germany, Austria  
RUS Russia  
SCN Scandinavia  
USA United States  
WST Western hemisphere, other

5. THESAURUS FOR ADDITIONAL SUBJECT TOPICS

The following are cross-references to additional subject index topics.

Abrasion	Use	Wear (of mill) or attrition (of feed)
Adsorption from liquid		Surface chemical reaction
Aerofall		Autogenous and ball mill
Aggregate (meaning gravel)		Stone
Amplitude		Motion of working part
Bauer mill	Use	Disk mill
Blaine		Permeability
Bond law		Size energy law
Bowl mill		Ring roll
Capacity	Use	Production rate
Cascade mill		Autogenous and ball mill
Circulating load		Charge of feed and continuous or circuit
Clinker		Cement
Conductivity		Electrical effect
Conical mill		Ball mill
Consistency		Concentration
Contact time		Duration
Crystal defects		Flaws and crystal structure
Cylinder mill		Ball mill
Differential grinding	Use	Selective grinding
Dyes		Pigments

Edge runner	Use	Pan mill
Efficiency		Production rate and energy
Electron diffraction		X-ray
Electron microscope		Microscope
Elutriator		Sedimentation
Enamel		Ceramics
Entoleter		Impact mill
Explosion hazard		Hazard
Feldspar	Use	Minerals
Fluid energy		Jet
Fluid shear mill		Colloid mill
Fracture characteristics		Grindability Fracture mechanics Resistance of material Crystal structure Hardness
Gas absorption	Use	Absorption
Grain, wheat, etc.		Cereal
Grainy, grains		Heterogeneous
Granulation		Compaction or mills
Grizzly		Sieve
Gypsum		Minerals
Hammer mill	Use	Impact mill
Hardinge mill		Ball mill
Haultain infrasizer		Sedimentation
Hydrocyclone		Cyclone and wet
Hydrometer		Sedimentation
Ink	Use	Pigment
Kick law	Use	Size energy law
Kinematics		Motion of particles or motion of balls

Laboratory crushing experiment		Related terms: Impact Compression Rate of stressing Shear Bending
Loesche mill	Use	Ring roll
Lopulco mill		Ring roll
Mean diameter of particle	Use	Size of product or size law
Micronizer		Jet without anvil
Muller		Pan mill
Nephelometry	Use	Light scattering
Paint	Use	Pigment
Peat		Wood
Pebble mill		Ball mill
Pin mill		Impact mill
Prall mill		Impact mill
Pressure on rolls		Clearance
Product quality		Quality
Pug mill		Mixer
Recirculation rate	Use	Charge of feed, circuit
Reduction ratio		Size of feed and product
Refractories		Ceramics
Release of component		Selective grinding
Reynolds number		Flow of fluid
Rittinger law		Size energy law
Roller classifier		Sedimentation

Salts	Use	Chemicals
Sand		Quartz
Settlers		Sedimentation
Simons crusher		Cone crusher
Size distribution of mill product		Size of product Size law only if this is specifically involved
Slag		Cement
Solidifying		Pretreatment; temperature
Stone mill		Attrition mill or colloid mill
Sugar		Food
Sulfur		Chemicals
Symposium		Book
Thickener	Use	Sedimentation and classifier
Time		Duration or distribution of residence time
Tinting strength		Light scattering
Triaxial stresses		Combination of stresses
Tube mill		Ball mill
Turbidimeter		Light scattering
Ultrasonic	Use	Sonic
Vitreous layer	Use	Glass
Vibration ball mill		Ball mill and vibratory

## 6. LIST OF JOURNAL NAMES AND ABBREVIATIONS

The following journals appear in the bibliography references, and are abbreviated as indicated.

Aachener Bl. Aufbereiten-Verkoken-Brikettieren  
(Aachener Blaetter fuer Aufbereiten-Verkoken-Brikettieren)

Acta Chem. Scand.  
(Acta Chemica Scandinavica)

Acta Pharm. Suecica (Engl.)

Acta Physiol. Latinoam. (Span.)  
(Acta Physiologica Latinoamericana)

Acta Polytech. Scand.  
(Acta Polytechnica Scandinavica)

Acta Polytech. Scand. Phys. Nucl. Ser.  
(Acta Polytechnica Scandinavica, Physics including Nucleonics Series).

Acta Tech. Acad. Sci. Hung.  
(Acta Technica Academiae Scientiarum Hungaricae)

Advan. Chem. Ser.  
(Advances in Chemistry Series)

Agri. Eng.  
(Agricultural Engineering)

A.I.Ch.E. J.  
(American Institute of Chemical Engineers Journal)

Alyum. Splavy (Russ.)  
(Alyuminievye Splavy, Sbornik Statei)

Am. Ceram. Soc. Bull.  
(American Ceramic Society Bulletin)

Am. Ind. Hyg. Assoc. J.  
(American Industrial Hygiene Association Journal)

Am. J. Phys.  
(American Journal of Physics)

Am. Mineralogist  
(American Mineralogist)

Am. Soc. Mech. Engrs.  
(American Society of Mechanical Engineers)

Am. Soc. Testing Mater. Spec. Tech. Publ.  
(American Society for Testing and Materials, Special Technical  
Publication)

Anal. Chem.  
(Analytical Chemistry)

Anal. Chim. Acta  
(Analytica Chimica Acta)

Analyst

Animal Produc.  
(Animal Production)

Ann. Entomol. Soc. Am.  
(Annals of the Entomological Society of America)

Ann. Mines  
(Annales des Mines)

Ann. N. Y. Acad. Sci.  
(Annals of the New York Academy of Sciences)

Ann. Phys (Paris) (Fr.)  
(Annales de Physique (Paris))

Ann. Rev. Fluid Mech.  
(Annual Review of Fluid Mechanics)

Ann. Travaux Publics Belg. (Fr.)

APPITA  
(Journal of the Australian Pulp and Paper Industry)

Appl. Opt.  
(Applied Optics)

Appl. Spectry.  
(Applied Spectroscopy)

Arch. Eisenhuettenw.  
(Archiv fuer das Eisenhuettenwesen)

Arch. Environ. Health  
(Archives of Environmental Health)

Arch. Pharm.  
(Archiv der Pharmazie und Berichte der Deutschen Pharmazeutischen  
Gesellschaft)

Arch. Pharm. Chemi (Dan.)  
(Archiv for Pharmaci og Chemi)

Asahi Garasu Kenkyu Hokoku (Japan.)

Aufbereitungs-Technik (Ger.)

Australasian Inst. Mining Met. Proc.  
(Australasian Institute of Mining & Metallurgy Proceedings)

Australian Min.

Autom. Welding (USSR) (Engl. Trans.)  
(Automatic Welding)

Avtomob. Prom.  
(Avtomobil'naya Promyshlennost)

Ball Bearing J. S.K.F.  
(Ball Bearing Journal)

Banyasz. Kut. Intez. Kozlem. (Hung.)  
(Banyaszati Kutato Intezet Kozlemenyei)

Battelle Res. Outlook  
(Battelle Research Outlook)

Batterien

Ber. Bunsenges. Phys. Chem. (Ger.)  
(Berichte der Bunsengesellschaft Physicalische Chemie)

Ber. Deut. Keram. Ges.  
(Berichte der Deutschen Keramischen Gesellschaft e.V.)

Bergakademie

Bergbauwissenschaften

Beton Zhelezabeton (Russ.)

Biometrische Zeitschrift

Braunkohle

Brennstoff-Waerme-Kraft

Brick Clay Record

Brit. Ceram. Soc. J.  
(British Ceramic Society Journal)

Brit. Chem. Eng.  
(British Chemical Engineering)

Brit. Foundryman  
(British Foundryman)

Brit. J. Appl. Phys.  
(British Journal of Applied Physics)

Brown Boveri Rev.  
(Brown Boveri Review)

Bulgarian Standards Inst.  
(Bulgarian Standards Institute)

Bull. Am. Phys. Soc.  
(Bulletin of the American Physical Society)

Bull. Brit. Coal Utilization Res. Assoc.  
(Bulletin of the British Coal Utilization Research Association)

Bull. Chem. Soc. Jap. (Engl.)  
(Bulletin of the Chemical Society of Japan)

Bull. Inst. Mining Met.  
(Bulletin of the Institution of Mining and Metallurgy)

Bull. Japan. Soc. Precision Eng.  
(Bulletin of the Japanese Society of Precision Engineering)

Bull. Powder Advisory Centre  
(Bulletin of the Powder Advisory Centre)

Bull. Soc. Franc. Ceram.  
(Bulletin de la Societe Francaise de Ceramique)

Bumazhn. Prom. (Russ.)  
(Bumazhnaya Promyshlennost)

Can. Inst. Mining Met. Bull.  
(Canadian Institute of Mining and Metallurgical Bulletin)

Can. J. Chem.  
(Canadian Journal of Chemistry)

Can. J. Chem. Eng.  
(Canadian Journal of Chemical Engineering)

Can. J. Soil Sci.  
(Canadian Journal of Soil Science)

Can. Mining J.  
(Canadian Mining Journal)

Can. Mining Met. Bull.  
(Canadian Mining and Metallurgical Bulletin)

Can. Pit Quarry  
(Canadian Pit & Quarry)

Carbon

Cement, Lime Gravel

Cement-Wapno-Gips

Cem., Vapno, Azbestochem., Sadra (Czech.)

Ceram. Age  
(Ceramic Age)

Ceram. Bull.  
(Ceramic Bulletin)

Ceramics

Ceram. Ind.  
(Ceramic Industry)

Ceram. Informaz. (Ital.)

Cereal Chem.  
(Cereal Chemistry)

Cereal Sci.  
(Cereal Science Today)

Chem. Age (London)  
(Chemical Age)

Chem. Age India  
(Chemical Age of India)

Chem. Anal. (Warsaw) (Pol.)  
(Chemia Analityczna)

Chem.-Anlagen Verfahren (Ger.)

Chem. Eng.  
(Chemical Engineering)

Chem. Eng. News  
(Chemical & Engineering News)

Chem. Eng. Progr.  
(Chemical Engineering Progress)

Chem. Eng. Sci.  
(Chemical Engineering Science)

Chemiker Ztg. (Ger.)  
(Chemiker Zeitung)

Chem. Ind. (London)  
(Chemistry & Industry)

Chem.-Ing.-Tech. (Ger.)  
(Chemie-Ingenieur-Technik)

Chem. Pharm. Bull. (Tokyo) (Engl.)  
(Chemical & Pharmaceutical Bulletin)

Chem. Process. (Chicago)  
(Chemical Processing)

Chem. Process Eng.  
(Chemical & Process Engineering)

Chem. Process Eng. (Bombay)  
(Chemical & Process Engineering)

Chem. Prumysl (Czech.)  
(Chemicky Prumysl)

Chem. Soc. Japan, Ind. Chem.

Chem. Tech. (Berlin)  
(Chemische Technik)

Chem. Week  
(Chemical Week)

Chim. Ind. (Milan) (Ital.)  
(Chimica e l'Industria)

Chim. Ind. (Paris) (Fr.)  
(Chimie & Industrie)

Civil Eng. (N.Y.)  
(Civil Engineering (New York))

Claycraft

Claycraft Struct. Ceram.

Clays Clay Minerals  
(Clays and Clay Minerals, Proceedings of the National Conference  
on Clays and Clay Minerals)

Coal Age

Coke Chem. (USSR) (Engl. Trans.)  
(Coke and Chemistry)

Colloid J. (USSR) (Engl. Trans.)  
(Colloid Journal)

Compt. Rend.  
(Comptes Rendus)

Contemp. Phys.  
(Contemporary Physics)

Contrib. Geol.  
(Contributions to Geology)

Contrib. Mineral. Petrol.

Control Instr.  
(Control Instrumentation)

Cost Eng.  
(Cost Engineering)

Denpun Kogyo Gakkaishi (Japan.)

Deut. Edelstahlwerke-Tech. Ber. (Engl.)

Dissertation Abstr.  
(Dissertation Abstracts)

Dokl. Akad. Nauk. SSSR (Russ.)  
(Doklady Akademii Nauk SSSR)

Dokl. Soil (USSR) (Russ.)

Double Liaison

Drug Cosmetic Ind.  
(Drug & Cosmetic Industry)

Edgar Allen News

Eesti NSV Tead. Akad. Toim., Fuus, Mat. (Russ.)  
(Eesti NSV Teaduste Akadeemia Toimetised, Tehnilliste ja  
Fuusikalis-Matemaatiliste Teaduste Seeria)

Elec. Eng. Japan  
(Electrical Engineering)

Electron. News Eng.

Elektrotehnika (Bucharest) (Rom.)

Elektrichestvo (Russ.)

Energia Atomtech. (Hung.)  
(Energia es Atomtechnika)

Energietechnik (Ger.)

Eng. Contract Rec.

Eng. Fracture Mech.

Eng. Geol.  
(Engineering Geology)

Engineering

Eng. Mining J.  
(Engineering and Mining Journal)

Epitoanyag

Ernaehrungsforschung

Erzmetall

Euro-Ceram. (Ger.)  
(Euro-Ceramic)

Exp. Mech.  
(Experimental Mechanics)

Farbe Lack  
(Farbe und Lack)

Feedstuffs

Fette Seifen Anstrichmittel (Ger.)

Fiz.-Khim. Mekhan. Dispersnykh Struktur, Akad. Nauk SSSR,  
Sb. Statei (Russ.)

Fiz.-Khim. Mekh. Mater. (Russ.)

Fiz.-Tekhn. Probl. Razrabolki Polezn. Iskop., Akad. Nauk SSSR,  
Sibersk. Atd. (Russ.)

Foerdern u. Heben (Ger.)  
(Foerdern und Heben)

Food Manuf.  
(Food Manufacture)

Food Technol.  
(Food Technology)

Fortschr. Verfahrenstech. (Ger.)  
(Fortschritte der Verfahrenstechnik)

Freiberger Forschungsh.  
(Freiberger Forschungshefte)

French Standards Assoc. (Fr.)  
(French Standards Association)

Fresenius' Z. Anal. Chem. (Ger.)  
(Fresenius' Zeitschrift fuer Analytische Chemie)

Fuel

Geochim. Cosmochim. Acta  
(Geochimica et Cosmochimica Acta)

Geol. Met., Bol. (Sao Paulo) (Span.)  
(Geologia e Metalurgia, Boletim)

Geol. Polez. Iskop. Zaboikol. (Russ.)

Geol. Soc. Am. Bull.  
(Geological Society of America Bulletin)

Geotechnique

German Standards Committee (Ger.)

Glas-Email-Keramo-Tech.  
(Glas-Email-Keramo-Technik)

Glass Ceram. (USSR) (Engl. Trans.)  
(Glass Ceramics)

Glass Ind.  
(Glass Industry)

Glass Technol.  
(Glass Technology)

Glastech. Ber. (Ger.)  
(Glastechnische Berichte)

Glueckauf (Ger.)

Gorn. Zh. (Russ.)  
(Gornyi Zhurnal)

Grinding Finishing

IEEE Trans. Parts  
(Institute of Electrical and Electronic Engineers Transactions)

Ill. State Geol. Surv. Ind. Miner. Notes  
(Illinois State Geological Survey, Industrial Mineral Notes)

Ind. Diamond Rev.  
(Industrial Diamond Review)

Ind. Eng. Chem.  
(Industrial and Engineering Chemistry)

Ind. Eng. Chem. Fundamentals  
(Industrial and Engineering Chemistry, Fundamentals)

Ind. Eng. Chem. Process Design Develop.  
(Industrial Engineering Chemistry, Process Design and Development)

Ind. Eng. Chem. Prod. Res. Develop.  
(Industrial and Engineering Chemistry, Product Research and Development)

Ind. Handling  
(Industrial Handling)

Indian Chem. Engr.  
(Indian Chemical Engineer)

Indian Concrete J.  
(Indian Concrete Journal)

Indian J. Tech.  
(Indian Journal of Technology)

Ind. Lab. USSR (Engl. Trans.)  
(Industrial Laboratory)

Instr. Prac.  
(Instrument Practice)

Inter. J. Rock Mech. Mining Sci.  
(International Journal of Rock Mechanics and Mining Sciences)

Intern. Chem. Eng. (Engl.)  
(International Chemical Engineering)

Intern. J. Appl. Radiation Isotopes  
(International Journal of Applied Radiation and Isotopes)

Intern. J. Eng. Sci.  
(International Journal of Engineering Science)

Intern. J. Fracture Mech.  
(International Journal of Fracture Mechanics)

Intern. J. Powder Met.  
(International Journal of Powder Metallurgy)

Inzh.-Fiz. Zh. Akad. Nauk Belorussk. SSR (Russ.)  
(Inzhenerno-Fizicheskii Zhurnal, Akademiya Nauk Belorusskoi SSR)

Iron Age

Israel J. Technol.  
(Israel Journal of Technology)

Izv. Dnepropetrovsk. Gorn. Inst.  
(Izvestiya Dnepropetrovskogo Gornogo Instituta)

Izv. vuzov, Gornyi Zhurnal, Sverdlovsk (Russ.)

Izv. Vysshikh Uchebn. Zavedenii, Gorn. Zh. (Russ.)  
(Izvestiya Vysshikh Uchebnykh Zavedenii, Gornyi Zhurnal)

Izv. Vyssh. Ucheb. Zaved., Khim. Khim. Tekhnol. (Russ.)  
(Izvestiya Vysshykh Uchebnykh Zavedenii, Khimiya i Khimicheskaya  
Tekhnologiya)

J. Adhesion  
(Journal of Adhesion)

J. Air Pollution Control. Assoc.  
(Journal of the Air Pollution Control Association)

J. Am. Ceram. Soc.  
(Journal of the American Ceramic Society)

J. Am. Chem. Soc.  
(Journal of the American Chemical Society)

J. Am. Oil Chemists' Soc.  
(Journal of the American Oil Chemists' Society)

J. Animal Sci.  
(Journal of Animal Science)

Japan. J. Appl. Phys.  
(Japanese Journal of Applied Physics)

Japan. Soc. Precision Eng. Bull.  
(Japanese Society of Precision Engineering Bulletin)

J. Appl. Crystallography  
(Journal of Applied Crystallography)

J. Appl. Math. Mech. (USSR)  
(Journal of Applied Mathematics and Mechanics, USSR)

J. Appl. Phys.  
(Journal of Applied Physics)

J. Assoc. Offic. Anal. Chem.  
(Journal of the Association of Official Analytical Chemists)

J. Basic Eng.  
(Journal of Basic Engineering)

J. Biul. Wojsk. Akad. Tech.

J. Chem. Eng. Data  
(Journal of Chemical and Engineering Data)

J. Colloid Interface Sci.  
(Journal of Colloid and Interface Science)

J. Econ. Entomol.  
(Journal of Economic Entomology)

J. Electroanal. Chem. Interfacial Electrochem.  
(Journal of Electroanalytical Chemistry, Interfacial Electro-chemistry)

J. Eng. Ind.  
(Journal of Engineering for Industry)

Jernkontorets Ann. (Swed.)  
(Jernkontorets Annaler)

J. Franklin Inst.  
(Journal of the Franklin Institute)

J. fur Reine u. Angew. Mathematik

J. Geophys. Res.  
(Journal of Geophysical Research)

J. Glass Studies  
(Journal of Glass Studies)

J. Hyg. Epidemiol. Microbiol. Immunol. (Prague) (Engl.)  
(Journal of Hygiene, Epidemiology, Microbiology, and Immunology)

J. Inst. Fuel  
(Journal of the Institute of Fuel)

J. Inst. Petrol.  
(Journal of the Institute of Petroleum)

J. Mater. Sci.  
(Journal of Materials Science)

J. Mech. Eng.  
(Journal of Mechanical Engineering Science)

J. Metals  
(Journal of Metals)

J. Microscopy-Oxford  
(Journal of Microscopy-Oxford)

J. Oil Colour Chemists' Assoc.  
(Journal of the Oil and Colour Chemists' Association)

J. Opt. Soc. Am.  
(Journal of the Optical Society of America)

J. PCA Res. Dev. Lab.  
(Journal of the Portland Cement Association)

J. Pharm. Pharmacol.  
(Journal of Pharmacy and Pharmacology)

J. Pharm. Sci.  
(Journal of Pharmaceutical Sciences)

J. Phys. E.  
(Journal of Physics, Part E. Scientific Instruments)

J. Polymer Sci.  
(Journal of Polymer Science)

J. Prosthetic Dentistry)  
(Journal of Prosthetic Dentistry)

J. S. African Chem. Inst.  
(Journal of the South African Chemical Institute)

J. S. African Inst. Mining Met.  
(Journal of the South African Institute of Mining and Metallurgy)

J. Sci. Food Agr.  
(Journal of the Science of Food and Agriculture)

J. Sci. Ind. Res. (India)  
(Journal of Scientific and Industrial Research)

J. Sci. Instr.  
(Journal of Scientific Instruments)

J. Sedimen. Petrol.  
(Journal of Sedimentary Petrology)

J. Soc. Cosmetic Chem.  
(Journal of the Society of Cosmetic Chemists)

J. Soc. Mater. Sci. (Japan) (Japan.)  
(Journal of the Society of Material Science)

J. Spacecraft Rockets  
(Journal of Spacecraft and Rockets)

Kagaku To Kogyo (Osaka) or (Tokyo) (Japan.)

Kemiai Kozlem. (Hung.)  
(Kemiai Kozlemenyek)

Keram. Z.  
 (Keramische Zeitschrift)

Khimiko Farma. Zhur.  
 (Khimiko Farmatsevticheskii Zhurnal)

Khim. Neft. Mashinostr. (Russ.)  
 (Khimicheskoe i Neftyanoie Mashinostroenie)

Khim. Prom. (Moscow) (Russ.)  
 (Khimicheskaya Promyshlennost)

Khim. Tverd. Topl.

Kirk-Othmer Encycl. Chem. Technol.  
 (Kirk-Othmer Encyclopedia of Chemical Technology)

Kogyo Kagaku Zasshi (Japan.)

Koks i Khim. (Russ.)  
 (Koks i Khimiya)

Koks, Smola, Gaz (Pol.)

Kolloid-Z. (Ger.)  
 (Kolloid-Zeitschrift and Zeitschrift fur Polymer)

Konstr. Mater. Asn. Grafita

Korrosion

Kristall Technik.

Krupp Tech. Rev.

Kuei Suan Yen Hsueh Pao (Chin.)

Kunststoffstoffe

Lakokrasoch. Mater. Ikh. Primen.  
 (Lakokrasochnye Materialy i ikh Primenenie)

Lebensmittel Ind. (Ger.)  
 (Lebensmittel Industrie)

Liteinoe Proizv. (Russ.)  
 (Liteinoe Proizvodstvo)

Machine Design

Machine Production Eng.  
(Machine Production Engineering)

Magy. Kem. Lapja (Hung.)  
(Magyar Kemikusok Lapja)

Mashinenbau Tech.  
(Maschinenbau Technik)

Mater. Genet. Eksp. Mineral. (Novosibirsk: Nauka)

Materialpruefung (Ger.)

Mater. Res. Bull.  
(Materials Research Bulletin)

Mater. Res. Std.  
(Materials Research and Standards)

Mater. Sci. Eng.  
(Materials Science and Engineering)

Mech. Eng.  
(Mechanical Engineering)

Messtechnik

Metall

Metalloberflaeche (Ger.)

Metallurgia

Metalurgia-ABM (Port.)

Metal Mining Proc.

Metals Mater.

Mfg. Chemist  
(Manufacturing Chemist)

Mfg. Chemist Aerosol News  
(Manufacturing Chemist Aerosol News)

Microscope

Mikrochim. Acta (Engl.)  
(Mikrochimica Acta)

Mine Quarry Eng.  
(Mine & Quarry Engineering)

Minerals Process.  
(Minerals Processing)

Mines et Metallurgie

Mining Chem. Eng. Rev.  
(Mining & Chemical Engineering Review)

Mining Congr. J.  
(Mining Congress Journal)

Mining Eng.  
(Mining Engineering)

Mining Engr. (London)  
(Mining Engineer)

Mining J. (London)  
(Mining Journal)

Mines Mag. (London)  
(Mining Magazine)

Mining Met. Soc. of Am. Bull.  
(Mining Metallurgical Society of America Bulletin)

Mining Mineral Eng.  
(Mining and Mineral Engineering)

Mining World

Mitt. Ver. Grosskesselbesitzer  
(Mitteilungen der Vereinigung der Grosskesselbesitzer)

Mod. Develop. Powder Met.  
(Modern Developments in Powder Metallurgy)

Mod. Plastics  
(Modern Plastics)

Nature

Naturstein-Ind. M. Bautechn.

Naturwissenschaften

Neftepererab. Neftekhim. (Russ.)

Nenryo Kyokaishi (Japan.)

New Zealand J. Sci.  
(New Zealand Journal of Science)

Nucl. Appl.

Obogashch. Rud  
(Obogashchenie Rud)

Obzhigmagn. Obogashch. Okislennykh Zhelez. Rud Burykh Zelez.  
(Russ.)

Ogneupory (Russ.)

Oklahoma Geol. Notes  
(Oklahoma Geological Notes)

Optimizats. Parametrov. Rats. Ispol'z. Topliva Energoustanovkakh  
(Russ.)

Paint Manuf.  
(Paint Manufacture)

Paint Oil Colour J.  
(Paint, Oil & Colour Journal)

Paliva

Paperi Puu (Swed.)  
(Paperi ja Puu)

Paper Trade J.  
(Paper Trade Journal)

Papier

Parfum. Cosmet. Savons (Fr.)  
(Parfums, Cosmetiques, Savons)

P'ezoelek. Mater. Preobrozovateli

Pharm. Ind.  
(Pharmazeutische Industri)

Pharmazie

Pharm. Prax  
(Pharmazeutische Praxis, Beilage zur Zeitschrift)

Phil. Mag.  
(Philosophical Magazine)

Phys. Chem. Glasses  
(Physics and Chemistry of Glasses)

Phys. Fluids  
(Physics of Fluids)

Phys. Rev.  
(Physical Review)

Phys. Status Solidi  
(Physica Status Solidi)

Phys. Zeit

Pishch. Prom.

Pit Quarry  
(Pit and Quarry)

Planseeber. Pulvermet. (Engl.)  
(Planseeberichte fuer Pulvermetallurgie)

Plaste Kaut.  
(Plaste und Kautschuk)

Polymer Engr. Sci.  
(Polymer Engineering and Science)

Poroshkovaya Met.  
(Poroshkovaya Metallurgiya, Akademiya Nauk Ukrainskoi SSR)

Poultry Sci.  
(Poultry Science)

Powder Met.  
(Powder Metallurgy)

Powder Met. Bull  
(Powder Metallurgy Bulletin)

Powder Tech.  
(Powder Technology)

Process Biochemistry

Process Biochim.

Proc. Brit. Ceram. Soc.  
(Proceedings of the British Ceramic Society)

Proc. Nutr. Soc.  
(Proceedings of the Nutrition Society (England and Scotland))

Proc. Roy Soc. (London) Series A  
(Proceedings of the Royal Society (London))

Prod. Problems Pharmaceut.  
(Produits et Problemes Pharmaceutiques)

Przegląd Mechaniczny

Przem. Chem. (Pol.)  
(Przemysł Chemiczny)

Pulp Paper Mag. Can.  
(Pulp and Paper Magazine of Canada)

Quarry Manager's J.  
(Quarry Manager's Journal)

Radex Rundschau

Razrab. Mestorozhd. Polez. Iskop. (Kiev) (Russ.)

Rech. Aerosp.  
(Recherche Aerospatiale)

Refractories USSR (Engl. Trans.)

Repub., Com. Nac. Energ. At., CNEA

Res. Develop.  
(Research/Development)

Rev. Construct. Material. Construct.  
(Revista Constructilor si a Materialelor de Constructii)

Rev. Gen. Elec. (Fr.)  
(Revue Generale de l'Electricite)

Rev. Ind. Minerale (Fr.)  
(Revue de la Industrie Minerale)

Rev. Mater. Construct. Trav. Publ.  
(Revue des Materiaux de Construction et de Travaux Publics)

Rev. Met. (Span.)  
(Revue de Metallurgie)

Rev. Minelor (Bucharest) (Rom.)  
 (Revista Minelor)

Rev. Sci. Instr.  
 (Review of Scientific Instruments)

Rev. Universelle Mines  
 (Revue Universelle des Mines)

Roads Streets  
 (Roads and Streets)

Rock Prod.  
 (Rock Products)

Rudarsko-Met. Zbornik  
 (Rudarsko-Metalurski Zbornik )

Rudodobiv. Met. (Bulg.)  
 (Rudodobiv i Metalurgiya (Sofia))

Rudy (Prague)

Russ. Eng. J. (Engl. Trans.)  
 (Russian Engineering Journal)

S. African Ind. Chemist  
 (South African Industrial Chemist)

S. African Mining Eng. J.  
 (South African Mining and Engineering Journal)

Sb. Nauch. Tr., Nauch.-Issled. Proekt. Inst. Obogashch. Aglom.  
 Rud Chern. Metal. (Russ.)  
 (Sbornik Nauchnykh Trudov, Nauchno-Issledovatel'skii i Proektnyi  
 Institut po Obogashcheniyu i Aglomeratsii Rud Chernykh Metallov)

Sb. Pr. Vyzk. Astavu Z D H E (Czech.)

Sb. Tr. Vses. Nauch.-Issled., Inst. Nov. Stroitel. Mater.  
 (Sbornik Trudov, Vsesoyuznyi Nauchno-Issledovatel'skii Institut  
 Novykh Stroitel'nykh Materialov)

Sb. Tr., Vses. Nauch.-Issled. Proekt. Inst. Titana (Russ.)

Science

Sediment. Geol.  
 (Sedimentary Geology)

Sekko To Sekkai (Japan.)  
 Semento Gijutsu Nempo (Japan.)  
 Seramikkusu (Japan.)  
 Shika Zairyo Kenkyusho Hokoku (Japan.)  
 Silicates Ind.  
 (Silicates Industriels)  
 Silikat Tech.  
 (Silikat Technik)  
 Silikaty (Czech.)  
 Soc. Dyers & Col. J.  
 Soviet J. Non-Ferrous Metals (Engl. Trans.)  
 (Soviet Journal of Non-Ferrous Metals)  
 Soviet Phys. Acoust. (Engl. Trans.)  
 (Soviet Physics-Acoustics)  
 Soviet Phys. Cryst. (Engl. Trans.)  
 (Soviet Physics-Crystallography)  
 Soviet Phys. Doklady (USSR) (Engl. Trans.)  
 (Soviet Physics "Doklady")  
 Soviet Phys.-Solid State (Engl. Trans.)  
 (Soviet Physics-Solid State)  
 Soviet Phys. Usp. (Engl. Trans.)  
 (Soviet Physics-USpekhi)  
 Soviet Powder Met. Metal Ceram. (Engl. Trans.)  
 Spektrosk. At. Mol.  
 Sprechsaal (Ger.)  
 (Sprechsaal fuer Keramik-Glas-Email Silikate)  
 Stahl Eisen  
 (Stahl und Eisen)  
 Stal (USSR) (Engl. Trans.)  
 Staub-Reinhalt.-Luft (Ger.)

Stavebnicky Casopis  
 Stavivo (Czech.)  
 Steel Coal  
 Stekbi Kerainika  
 Steklo i Keram.  
 (Steklo i Keramika)  
 Strasse Autobahn (Ger.)  
 Stud. Cercet. Met.  
 Süswaren (Ger.)  
 Svensk Papperstid.  
 (Svensk Papperstidning)  
 Szklo Ceram.  
 (Szklo i Ceramika)  
 Taikabutsu Kogyo (Japan.)  
 Tappi  
 (Journal of the Technical Association of the Pulp and Paper  
 Industry)  
 Tech. Mitt. Essen  
 (Technische Mitteilungen Essen)  
 Tech. Mitt. Krupp Werksberichte  
 (Technische Mitteilungen Krupp Werksberichte)  
 Tectonophys.  
 (Tectonophysics)  
 Tehnika (Belgrade) (Croat.)  
 Teploenergetika (Russ.)  
 Thermal Eng. USSR (Engl. Ed.)  
 Thermochemica Acta (Engl.)  
 Tonind. Ztg. Keram. Rundschau.  
 (Tonindustrie-Zeitung und Keramische Rundschau)

Trans. AIME  
(Transactions of the American Institute of Mining, Metallurgical,  
and Petroleum Engineers)

Trans. Am. Geophys. Union  
(Transactions of the American Geophysical Union)

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Trans. Inst. Mining Met.  
(Transactions of the Institution of Mining and Metallurgy)

Tr., Gos. Vses. Proekt. Nauch.-Issled. Inst. Tsem. Prom.  
Tsement (Leningrad)

Tsvet. Metal. (Russ.)  
(Tsvetnye Metally)

Tugoplavkie Karbidy (Russ.)

Uch. Zap., Mosk. Gor. Pedagog. Inst. (Russ.)  
(Uchenye Zapiski, Moskovskii Gorodskoi Pedagogicheskii Institut  
im. V. P. Potemkina)

Ugol'

Ver. Deut. Ing.-Bericht (Ger.)  
(Verein Deutscher Ingenieur-Bericht)

Ver. Deut. Ing. Forschungsheft  
(Verein Deutscher Ingenieure Forschungsheft)

Ver. Deut. Ing. Z.  
(Verein Deutscher Ingenieure Zeitschrift)

Verfahrenstechnik

Verres Refractaires  
(Verres et Refractaires)

Vop. Khim. Khim. Tekhnol.

Wear

Wehrtech. Monatsh. (Ger.)

Welding J. (N.Y.)  
(Welding Journal (New York))

Welding Prod. (USSR) (Engl. Trans.)  
(Welding Production)

Wiss. Mikroskopie

World Mining

Yakugaku Zasshi (Japan.)

Zairyo (Japan.)

Z. Angew. Phys. (Ger.)  
(Zeitschrift fuer Angewandte Physik, Herausgegeben unter  
Mitwirkung des Verbandes Deutscher Physikalischer Gesellschaften)

Z. Anorg. Allgem. Chem.  
(Zeitschrift fuer Anorganische und Allgemeine Chemie)

Z. Chem.  
(Zeitschrift fuer Chemie)

Zdrav. Tech. Vzduchotech. (Czech.)

Zement-Kalk-Gips (Ger.)

Z. Erzbergbau Metallhuettenw.  
(Zeitschrift fuer Erzbergbau und Metallhuettenwesen)

Zh. Fiz. Khim. (Russ.)  
(Zhurnal Fizicheskoi Khimii)

Z. Naturoforsch. (Ger.)  
(Zeitschrift fuer Naturforschung)

Z. Zuckerind. (Ger.)  
(Zeitschrift fuer die Zuckerindustrie)

detd.	determined
detg.	determining
detn.	determination
diam.	diameter
dil.	dilute
dild.	diulted
dilg.	diluting
diln.	dilution
dissoc.	dissociate(s)
dissocd.	dissociated
dissocg.	dissociating
dissocn.	dissociation
distd.	distilled
distg.	distilling
distn.	distillation
elec.	electric, electrical, electrically
e.m.f.	electromotive force
en	ethylenediamine (used in Werner complexes only)
equil.	equilibrium(s)
equiv.	equivalent
esp.	especially
est.	estimate (as a verb)
estd.	estimated
estg.	estimating
estn.	estimation
e.s.u.	electrostatic unit
Et	ethyl
e.v.	electron volt(s)
evap.	evaporate
evapd.	evaporated
evapg.	evaporating
evapn.	evaporation
examd.	examined
examg.	examining
examn.	examination
expt.	experiment(as a noun)
exptl.	experimental, experimentally
ext.	extract
extd.	extracted
extg.	extracting
extn.	extraction
f.	faraday, farad
f.p.	freezing point
g.	gram(s)
γ	microgram(s)
geol.	geological, geologically
ha.	hectare(s)
histol.	histological, histologically
hr.	hour
inorg.	inorganic
insol.	insoluble
iso-Bu, iso-Pr	isobutyl, isopropyl

Rev. Minelor (Bucharest) (Rom.)  
(Revista Minelor)

Rev. Sci. Instr.  
(Review of Scientific Instruments)

Rev. Universelle Mines  
(Revue Universelle des Mines)

Roads Streets  
(Roads and Streets)

Rock Prod.  
(Rock Products)

Rudarsko-Met. Zbornik  
(Rudarsko-Metalurski Zbornik )

Rudodobiv. Met. (Bulg.)  
(Rudodobiv i Metalurgiya (Sofia))

Rudy (Prague)

Russ. Eng. J. (Engl. Trans.)  
(Russian Engineering Journal)

S. African Ind. Chemist  
(South African Industrial Chemist)

S. African Mining Eng. J.  
(South African Mining and Engineering Journal)

Sb. Nauch. Tr., Nauch.-Issled. Proekt. Inst. Obogashch. Aglom.  
Rud Chern. Metal. (Russ.)  
(Sbornik Nauchnykh Trudov, Nauchno-Issledovatel'skii i Proektnyi  
Institut po Obogashcheniyu i Aglomeratsii Rud Chernykh Metallov)

Sb. Pr. Vyzk. Astavu Z D H E (Czech.)

Sb. Tr. Vses. Nauch.-Issled., Inst. Nov. Stroitel. Mater.  
(Sbornik Trudov, Vsesoyuznyi Nauchno-Issledovatel'skii Institut  
Novykh Stroitel'nykh Materialov)

Sb. Tr., Vses. Nauch.-Issled. Proekt. Inst. Titana (Russ.)

Science

Sediment. Geol.  
(Sedimentary Geology)

Sekko To Sekkai (Japan.)  
 Semento Gijutsu Nempo (Japan.)  
 Seramikkusu (Japan.)  
 Shika Zairyo Kenkyusho Hokoku (Japan.)  
 Silicates Ind.  
 (Silicates Industriels)  
 Silikat Tech.  
 (Silikat Technik)  
 Silikaty (Czech.)  
 Soc. Dyers & Col. J.  
 Soviet J. Non-Ferrous Metals (Engl. Trans.)  
 (Soviet Journal of Non-Ferrous Metals)  
 Soviet Phys. Acoust. (Engl. Trans.)  
 (Soviet Physics-Acoustics)  
 Soviet Phys. Cryst. (Engl. Trans.)  
 (Soviet Physics-Crystallography)  
 Soviet Phys. Doklady (USSR) (Engl. Trans.)  
 (Soviet Physics "Doklady")  
 Soviet Phys.-Solid State (Engl. Trans.)  
 (Soviet Physics-Solid State)  
 Soviet Phys. Usp. (Engl. Trans.)  
 (Soviet Physics-Uspekhi)  
 Soviet Powder Met. Metal Ceram. (Engl. Trans.)  
 Spektrosk. At. Mol.  
 Sprechsaal (Ger.)  
 (Sprechsaal fuer Keramik-Glas-Email Silikate)  
 Stahl Eisen  
 (Stahl und Eisen)  
 Stal (USSR) (Engl. Trans.)  
 Staub-Reinhalt.-Luft (Ger.)

Stavebnicky Casopis  
 Stavivo (Czech.)  
 Steel Coal  
 Stekbi Kerainika  
 Steklo i Keram.  
 (Steklo i Keramika)  
 Strasse Autobahn (Ger.)  
 Stud. Cercet. Met.  
 Süswaren (Ger.)  
 Svensk Papperstid.  
 (Svensk Papperstidning)  
 Szklo Ceram.  
 (Szklo i Ceramika)  
 Taikabutsu Kogyo (Japan.)  
 Tappi  
 (Journal of the Technical Association of the Pulp and Paper  
 Industry)  
 Tech. Mitt. Essen  
 (Technische Mitteilungen Essen)  
 Tech. Mitt. Krupp Werksberichte  
 (Technische Mitteilungen Krupp Werksberichte)  
 Tectonophys.  
 (Tectonophysics)  
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(Zeitschrift fuer Naturforschung)

Z. Zuckerind. (Ger.)  
(Zeitschrift fuer die Zuckerindustrie)

## 7. ABBREVIATIONS

The following is a list of abbreviations that may occur in some of the abstracts:

A.	Angström unit(s)
abs.	absolute
abstr.	abstract
Ac	acetyl (CH <sub>3</sub> CO, not CH <sub>3</sub> COO)
a.c.	alternating current
addn.	addition
addnl.	additional
alc.	alcohol, alcoholic
alk.	alkaline (not alkali)
alky.	alkalinity (alkys. for alkalinities is not approved)
amp.	ampere(s)
amt.	amount (as a noun)
anal.	analytical (not analysis)
anhyd.	anhydrous
app.	apparatus
approx.	approximate (as an adjective), approximately
approxn.	approximation
aq.	aqueous
assoc.	associate(s)
assocd.	associated
assocg.	associating
assocn.	association
at.	atomic (not atom)
atm.	atmosphere(s), atmospheric
av.	average (except as a verb)
b.	(followed by a figure denoting temperature) boils at, boiling at (similarly b <sub>13</sub> , at 13 mm. pressure)

bacteriol.	bacteriological, bacteriologically
b.e.v.	billion electron volt(s)
biol.	biological, biologically
B.O.D.	biochemical oxygen demand
b.p.	boiling point
B.t.u.	British thermal unit(s)
Bu	butyl (normal)
Bz	benzoyl ( $C_6H_5CO$ , not $C_6H_5CH_2$ )
c-	centi- (as a prefix, e.g. cm.)
c.	curie(s)
cal.	calorie(s)
calc.	calculate
calcd.	calculated
calcg.	calculating
calcn.	calculation
cc.	cubic centimeter(s)
c.d.	current density
chem.	chemical (as an adjective), chemically (not chemistry)
clin.	clinical, clinically
coeff.	coefficient
com.	commercial
compd.	compound (as a noun)
compn.	composition
conc.	concentrate (as a verb)
concd.	concentrated
concg.	concentrating
concn.	concentration
cond.	conductivity
conds.	conductivities
const.	constant
contg.	containing
cor.	corrected
cp.	centipoise(s)
crit.	critical
cryst.	crystalline(not crystallize)
crystd.	crystallized
crystg.	crystallizing
crystn.	crystallization
d-	deci- (as a prefix, e.g. dl.)
d.	density ( $d_{13}$ specific gravity at 13° referred to water at 4°; $d_{20}^{20}$ , at 20° referred to water at the same temperature)
D.	debye unit
D.A.-B.	German Pharmacopeia (Deutsches Arzneibuch)
d.c.	direct current
decomp.	decompose(s)
decompd.	decomposed
decompg.	decomposing
decompn.	decomposition
deriv.	derivative
det.	determine

detd.	determined
detg.	determining
detn.	determination
diam.	diameter
dil.	dilute
dild.	diulted
dilg.	diluting
diln.	dilution
dissoc.	dissociate(s)
dissocd.	dissociated
dissocg.	dissociating
dissocn.	dissociation
distd.	distilled
distg.	distilling
distn.	distillation
elec.	electric, electrical, electrically
e.m.f.	electromotive force
en	ethylenediamine (used in Werner complexes only)
equil.	equilibrium(s)
equiv.	equivalent
esp.	especially
est.	estimate (as a verb)
estd.	estimated
estg.	estimating
estn.	estimation
e.s.u.	electrostatic unit
Et	ethyl
e.v.	electron volt(s)
evap.	evaporate
evapd.	evaporated
evapg.	evaporating
evapn.	evaporation
examd.	examined
examg.	examining
examn.	examination
expt.	experiment(as a noun)
exptl.	experimental, experimentally
ext.	extract
extd.	extracted
extg.	extracting
extn.	extraction
f.	faraday, farad
f.p.	freezing point
g.	gram(s)
γ	microgram(s)
geol.	geological, geologically
ha.	hectare(s)
histol.	histological, histologically
hr.	hour
inorg.	inorganic
insol.	insoluble
iso-Bu, iso-Pr	isobutyl, isopropyl

I.U.	International Unit
j.	joule
k-	kilo- (as a prefix, e.g. kg.)
kc.	kilocycle(s)
Kp	kilopfund; in German literature = 1000 g. force
l.	liter(s)
lab.	laboratory
L.D.	lethal dose
m-	milli- (as a prefix, e.g. mm.)
m.	meter(s); also (followed by a figure denoting temperature) melts at, melting at
m	molal (as applied to concn.)
M	molar (as applied to concn.)
ma.	milliamperes(s)
manuf.	manufacture
manufd.	manufactured
manufg.	manufacturing
math.	mathematical
max.	maximum(s)
Mc.	megacycle(s)
Me	methyl (not metal)
mech.	mechanical, mechanically
meq.	milliequivalent(s)
m.e.v.	million electron volt(s)
m.g.d.	million gallons per day
min.	minimum(s); also minute(s) (time unit only)
misc.	miscellaneous
mixt.	mixture
mol.	molecule, molecular (not mole)
m.p.	melting point
$\mu$	micron(s); also micro- (as a prefix, e.g. $\mu$ l.) ( $\mu$ g. is not approved)
n	index of refraction ( $n_D^{20}$ for 20° and sodium D light)
N	normal (as applied to concn.)
neg.	negative (as an adjective), negatively
n.m.	nuclear magneton(s)
no.	number
oe.	oersted(s)
org.	organic
oxidn.	oxidation
pathol.	pathological, pathologically
p.d.	potential difference
petr. ether	petroleum ether
Ph	phenyl
pharmacol.	pharmacological, pharmacologically
phys.	physical, physically
physiol.	physiological, physiologically
pos.	positive (as an adjective), positively
powd.	powdered (as an adjective)
p.p.m.	parts per million
ppt.	precipitate
pptd.	precipitated

pptg.	precipitating
pptn.	precipitation
Pr	propyl (normal)
prep.	prepare
prepd.	prepared
prepg.	preparing
prepn.	preparation
py	pyridine (used in Werner complexes only)
qual.	qualitative, qualitatively
quant.	quantitative, quantitatively
r.	röntgen
redn.	reduction
r.e.p.	röntgen equivalent physical
resp.	respective, respectively
r.p.m.	revolutions per min.
R.Q.	respiratory quotient
sapon.	saponification
sapond.	saponified
sapong.	saponifying
sat.	saturate
satd.	saturated
satg.	saturating
satn.	saturation
sec.	second(s) (time unit only)
sec	secondary (with alkyl groups only)
sep.	separate, separately
sepd.	separated
sepg.	separating
sepn.	separation
sol.	soluble
soln.	solution (as in a solvent)
soly.	solubility (solys. for solubilities is not approved)
sp.	specific (used only to qualify a physical constant)
sp. gr.	specific gravity
spp.	species
sq.	square
sym.	symmetrical, symmetrically
tech.	technical, technically
temp.	temperature
tert	tertiary (with alkyl groups only)
U.S.P.	United States Pharmacopeia
v.	volt(s)
vol.	volume (not volatile)
w.	watt(s)
wt.	weight

