

## John Cahir Succeeds E. W. Miller as College's Associate Dean for Resident Instruction

Dr. John Cahir, associate professor of meteorology, has been named associate dean for resident instruction in the College of Earth and Mineral Sciences, effective July 1.

He succeeds Dr. E. Willard Miller, professor of geography, who is retiring in June with emeritus rank after serving 35 years on the Penn State faculty.

Dr. Cahir, who received his B.S. in 1961 and his Ph.D. in 1971, both in meteorology from Penn State, joined the University faculty in 1965. He teaches courses in the areas of synoptic meteorology, climatology, and applications of satellites.

His research interests include application of minicomputer-based analysis methods to short-range weather forecasting, effects of cloudiness on the earth's radiation balance, and structure of small-scale circulations that produce cloud bands near fronts and jet streams.

In 1971, Dr. Cahir received the Wilson Teaching Award of the College of Earth and Mineral Sciences; in 1969, he was awarded the American Meteorological Society's Seal of Approval for Television Weather Forecasting; and last year, he received the Award for Outstanding Contributions to Applied Meteorology made annually by the National Weather Association.

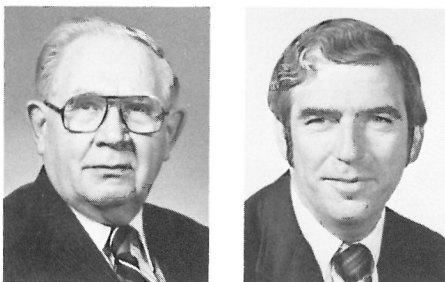
He serves as an editor of *Monthly Weather Review*, published by the American Meteorological Society, and, for the past two years, has served as chairman of the AMS Committee on Weather Forecasting and Analysis. He has also served on a National Academy of Science committee to evaluate the research program of the National Environmental Satellite Service, and a National Weather Association committee on automation.

He has been a member of Penn State's University Senate since 1973, serving on a number of its committees. He is the co-author of two books, *Principles of Climatology*, and *The Atmosphere*, and a number of articles, papers, and reports.

He has appeared regularly on WPSX-TV's State of the Weather/World program since its inception in 1966, and has been responsible for coordination of its meteorological aspects since 1971.

Dean Miller joined the University staff in 1945 as associate professor of geography and chief of the then Division of Geography. In 1949, he was made professor of geography, and, in 1953, was named head of the newly created Department of Geography, a position he held until 1963. In 1964, he became assistant dean for resident instruction in the college, and, in 1972, was made associate dean.

He has received a number of honors during



Dr. E. W. Miller, left, is retiring as associate dean for resident instruction in the college, and will be succeeded by Dr. John Cahir, right, associate professor of meteorology.

his long career. In 1945, he was awarded the Certificate of Merit from the Office of Strategic Services. In 1950, he received the Ray Hughes Whitbeck Award for the outstanding article in economic geography in the *Journal of Geography*. In 1975, the Governor of Pennsylvania presented him a Citation for Service to the Commonwealth, and the Secretary of the Pennsylvania Department of Commerce presented him the Secretary's Meritorious Services Award. In 1976, he received the Outstanding Science Award of the Pennsylvania Academy of Science and the Distinguished Service Award of the Pennsylvania Council for Geographic Education.

Dr. Miller is a Fellow of the American Association for the Advancement of Science, Explorers Club, American Geographical Society, and the National Council for Geographic Education, and is an honorary member of the Pennsylvania Academy of Science.

His first professional paper, "The Relationship of Structure to Petroleum Production in Eastern Venezuela," was published in 1939 in *Economic Geology*. Since then he has published more than 80 articles in such journals as *Economic Geography*, *The Scientific Monthly*, *Far Eastern Quarterly*, and *Canadian Geographer*.

He has presented more than 100 papers at professional meetings and is the author or co-author of 13 books including *The World's Nations* (with George F. Deasy and Phyllis R. Greiss); *A Geography of Manufacturing*; *A Geography of Industrial Location*; *A Socio-Economic Atlas of Pennsylvania*; *Manufacturing: A Study of Industrial Location*; *Industrial Location: A Bibliography* (with Ruby M. Miller); and *Economic, Political, and Regional Aspects of the World's Energy Problems: A Bibliography* (also with Mrs. Miller.)

Dr. Miller will continue his research at the University following his retirement. He and Mrs. Miller plan to spend part of this summer in China and Japan. During that trip, he will present a paper at the International Geographical Congress meetings in Tokyo.

1963, and an M.S. in nuclear engineering in 1965, an M.S. in physics in 1971, and a Ph.D. in physics in 1975 from the University of Arizona.

Dr. Deb Roy received his B.E. degree at Burdhan University in India in 1969 and his Ph.D. at the Indian Institute of Science, Bangalore, in 1974.

Dr. Messing received his B.S. in ceramic engineering at Alfred University in 1973 and his Ph.D. in materials science at the University of Florida in 1977. For the past two years, he worked as a research scientist at Battelle Memorial Institute, Columbus, Ohio.

### Elected UCAR Vice Chairman

Dr. John A. Dutton, professor of meteorology, was recently elected vice chairman of the University Corporation for Atmospheric Research (UCAR).

UCAR is a consortium of 48 North American universities and research institutions with active research programs in atmospheric science. Penn State was one of the 14 founding universities of the organization in the late 1950s.

Dr. Dutton has served on the UCAR board of trustees since 1975 and has been both secretary and treasurer of the corporation. He continues to serve as a member of the corporation's executive committee and the budget and program committees of the board of trustees, in addition to having other assignments involving management of the corporation and the center.

### Refractory Technology Short Course

Trends in refractory use and research will be reviewed by experts in this field during a short course entitled "Fundamentals of Refractory Technology," being offered June 30-July 3 as a continuing education service of the Department of Materials Science and Engineering.

Dr. Vladimir Stubican, professor of ceramic science and engineering, is director of the course which will cover such topics as mechanical properties of refractories, the application of refractories in the steel industry, slag attack on refractories, failure mechanisms of refractory concrete, and carbon and graphite as refractories.

Further information may be obtained from Dr. Stubican, 328 Steidle Building, University Park, Pa. 16802.

### Palynologists Incorrectly Listed

The report on the 12th annual meeting of the American Association of Stratigraphic Palynologists in the last issue of this bulletin had some omissions and errors. In addition to those correctly listed, Douglas J. Nichols, Ph.D., '70, was invited panelist in a featured roundtable (he is AASP newsletter editor); Arthur D. Cohen, Ph.D., '68, also presented a paper, as did Paul K. Strother, B.S., '75. Robert E. Dunay, Ph.D., '72, was chairman of a session.

### E&MS Short Courses

Folders describing the following continuing education offerings of the College of Earth and Mineral Sciences at Penn State's University Park Campus may be obtained by writing (Name of Program), Keller Bldg., University Park, PA 16802; or by phoning 814-865-7557.

**Fundamentals of Refractory Technology**, June 30-July 3.

**Mining Professional Engineering Exam Review**, July 7-11.

**Coal Cutting Technology**, July 14-16.

**Principles of Mine Accident Prevention and Safety Management**, August 4-6.

**Low-Voltage Trailing Cables—Splice Testing**, August 5-6.

**7th Annual Training Resources Applied to Mining Conference (TRAM VII)**, Morgantown, W. Va., August 17-20.

**Coal Mine Electrical Systems**, August 18-21.

**Application of Fracture Mechanics to the Failure of Ceramics and Glass**, August 18-22.

**Materials Transport in Mining**, August 25-27.

VOLUME 49 NO. 5 MAY/JUNE 1980

# EARTH AND MINERAL SCIENCES

THE PENNSYLVANIA STATE UNIVERSITY, COLLEGE OF EARTH AND MINERAL SCIENCES, UNIVERSITY PARK, PENNSYLVANIA

## Mineral Processing—Attacking the Problem of Declining Ore Quality

PETER T. LUCKIE, *Chairman, Mineral Processing Section*

Our nation is built upon a mineral-based economy. Consequently, we have a large industry involved in the extraction of minerals and their subsequent utilization or conversion.

A good example is the steel industry where iron ore is extracted—mined—from the earth and converted into various grades of steel. Over time, the quality, or grade, of the extracted minerals has declined while the need for higher and higher grades of minerals for utilization or conversion has increased. Bridging this ever widening gap between the quality of ores mined and the quality needed is an engineering discipline known as mineral processing.

The mineral processing engineer is responsible for upgrading the extracted mineral to a marketable product. As one might suspect, this involves the processing of particles. Particle process-

## Modeling Hydrothermal Ore Deposit Genesis

LAWRENCE M. CATHLES III

*Associate Professor of Geosciences*

Each year, the United States consumes about 30 billion dollars worth of mineral raw materials that are neither fuels nor common building materials such as stone or concrete. These valuable mineral materials are primarily metals that are supplied by various kinds of ore deposits.

Some of these deposits—such as iron—accumulated as sediments in ancient seas or lakes; some—such as bauxite—resulted from rock weathering; and still others—such as nickel and platinum group metals—were formed by the segregation of immiscible molten magmas. On a dollar basis, some 23 percent of all metals consumed each year by the United States are supplied by mineral deposits formed by a fourth mechanism—metal precipitation from hot aqueous solutions. Economic geologists refer to these as hydrothermal ore deposits—that is, they were deposited through the action of hot water.

Hydrothermal ore deposits have presumably been studied

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After copper is leached from its ore, the copper in solution is removed by contact with shredded "tin" cans. Here the shredded cans are being added to large open vats at a Kennecott Copper Corporation plant. (Kennecott photo)

ing engineering is a very necessary operation, not only to create raw materials and energy, but also to remove environmental

*Continued on next page*

## Combustion of Alternative Natural and Synthetic Fuels

JAMES J. REUTHER, *Assistant Professor of Fuel Science*

For strategical, economical, and national security reasons, but not necessarily environmental or technical ones, the United States is expected to place a heavier reliance on the utilization of coal, its most abundant and available fossil fuel, in order to meet short- and long-term energy demands.

Simultaneous to the recognition of an "energy crisis" during the last decade came the enactment of regulations for combustion-generated air pollutants. Because of these dual developments, considerable fuels and combustion research in the 1980s will focus on the discovery of ways to utilize domestic coal in an ecologically and technologically acceptable manner. When burning coal directly, it is often impossible to satisfy both ecological and technological criteria simultaneously.

A comprehensive and systematic study in progress at the College's Fuels and Combustion Laboratory is attempting to achieve a better understanding of how the compositional properties of natural and synthetic, fossil and non-fossil fuels relate to their combustion behaviors. The fundamental data resulting

*Continued on page 57*

## College News Notes

### Three New Faculty Members Named

Three new faculty members joined the staff of the College of Earth and Mineral Sciences recently. They are: Dr. Craig F. Bohren, assistant professor of meteorology; Dr. Tarasankar Deb Roy, assistant professor of metallurgy; and Dr. Gary L. Messing, assistant professor of ceramic science and engineering.

Dr. Bohren received a B.S. in mechanical engineering from San Jose State University in



## Bridging the Gap—

*Continued from first page*

pollutants. This does not mean that mineral processing is a new discipline, but rather that its impact is expanding rapidly.

Mineral processing traces its origins back to medieval and early Renaissance practices. As Gaudin pointed out in *Principles of Mineral Dressing*, “information concerning the operations of the past is not so full as might be wished. . . largely because educated Athenians and Romans alike would not lower themselves to such ‘common’ duties as are implied in technological description or discussion.” Consequently, most of the descriptions of very early practices in mining and mineral processing appear in *De Re Metallica* by Georgius Agricola, published in 1556. This book, which details the state of the art in Europe at the time of the Renaissance, was translated from Latin to English by Herbert Hoover (later to become president of the United States) and his wife, and published in 1912 by *The Mining Magazine*, London. In 1950, a new edition was issued by Dover Publications, Inc., New York, N.Y.

In his introduction to Chapter VIII in *De Re Metallica*, Agricola says, “First of all, I will explain the methods of preparing the ores; for since Nature usually creates metals in an impure state, mixed with earth, stones, and solidified juices, it is



*The concentration of valuable minerals as practiced during the 1500s is shown in this woodcut. Workers, including a woman on the left, are placing the ore on a screen, then jiggling the screen under water in a tub to wash away the undesirable “gangue,” leaving the desired ore. The process is directly comparable to modern jigging methods. (Reproduced with permission from De Re Metallica, published by Dover Publications, Inc., New York, N.Y., 1950)*

necessary to separate most of these impurities from the ores as far as can be, before they are smelted, and therefore I will now describe the methods by which the ores are sorted, broken with hammers, burnt, crushed with stamps, ground into powder, sifted, washed, roasted, and calcined.”

Agricola’s book is profusely illustrated with drawings showing in great detail the various steps in mining and mineral processing as it was done more than four centuries ago. One of these illustrations is reproduced on this page.

Hand-sorting—picking out the valuable lumps of ore from the worthless lumps—must be the oldest of all mineral processing unit operations. This technique is sometimes practiced today, except that now the large worthless lumps are picked out so that they will not damage any of the processing equipment. Old remains indicate that the washing of ore to remove fine particles was practiced centuries before the Christian era.

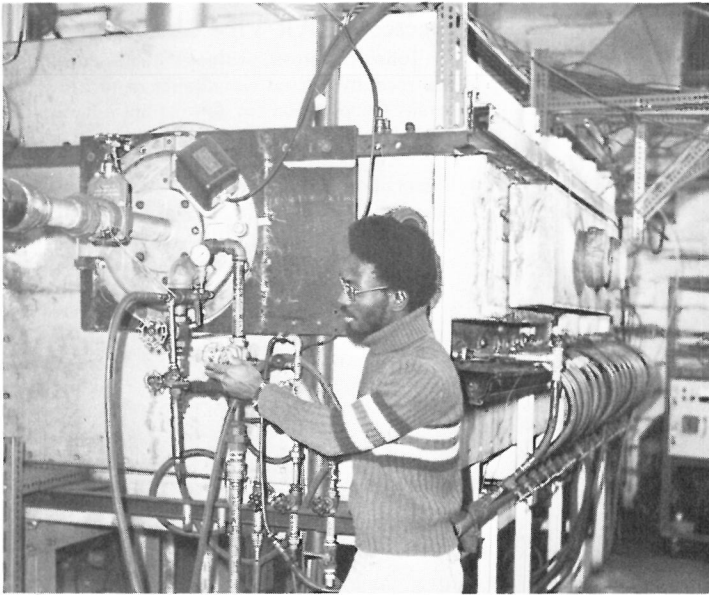
Size reduction to break worthless material from valuable material was also practiced at an early date, and washing was extended to gravity concentrating. In the ruins of the Athenian silver mines in Attica were found stone tables, set at an

angle, that were used to concentrate heavy particles. In the Harz mountains of Germany, jigging particles placed on a screen that was submerged in water developed into the jigging process of today in which heavy particles migrate to the bottom of a bed.

From medieval and early Renaissance times to the present, the importance of being able to process fine particles has become increasingly evident. Particle properties other than specific gravity have been explored to bring about separations, for instance, those caused by magnetism and surface chemistry. Perhaps the easiest way to explain what mineral processing is all about is to examine the evolution in our country of the processing of a mineral of which everyone is currently very much aware—gold.

### Gold as an Example of Mineral Processing

The first producers of gold had a rather easy job of it in that gold nuggets could be found in stream beds and simply picked up. In this case, nature had already extracted the mineral from its ore and done the processing of it. All that remained was the hand-sorting of the desired mineral from the sands of the stream bed.



**Left:** Olayinka Ogunsola, graduate student in fuel science, monitors the controls of the Fuels and Combustion Laboratory’s hot-wall furnace. This apparatus simulates industrial process furnace combustion conditions and is being used to evaluate coal liquids as replacements for petroleum-based fuels. **Right:** Dr. K. C. Yiin, research



associate in fuel science, operates a computer that analyzes data from low-pressure syngas flame studies. Mr. Ogunsola is standing by the low-pressure chamber in the background.

fuels appear to have innate clean-burning compositions. However, further inspection reveals that potential environmental advantages of firing these alternatives may be offset by technological problems—cleaner-burning substitute fuels may not have ignition and burnout characteristics as favorable as those of the dirty fuels they are replacing.

Coal conversion technology, with its manifold process variations, can either reconstitute, liquefy, or gasify coal. Reconstituted solid coal (SRC-I) has lower sulfur and ash than the parent coal, but also has more nitrogen and is more difficult to burn than the feedstock coal. The nitrogen-concentration problem exists, too, in the production of coal liquids, which also have higher aromaticities than petroleum-derived liquids, making them more prone to produce smoke upon rich combustion. This situation creates a dilemma. NOX production can be controlled by performing combustion in two stages, with the first stage operating fuel-rich. Hence, staged combustion of nitrogen-rich fuels having high aromaticities may result in increased smoke production while achieving the desired NOX reduction; one pollutant is traded for another.

Coal-derived syngases, though low in pollutant precursor concentrations, contain inert gases (CO<sub>2</sub> and H<sub>2</sub>O) along with combustible gases (CH<sub>4</sub>, H<sub>2</sub>, and CO). Carbon dioxide and water are known flame extinguishants, and their presence in syngas makes this fuel burn less readily.

### Fuels and Combustion Lab Research

Clearly, advanced concepts are needed if the nation is to extract energy from coal in

a clean and efficient manner. One advanced concept being explored is the combustion of blends of different fuels. A hybrid mixture of a clean, but difficult to burn fuel and a dirty, but easy to burn fuel may possess overall combustion characteristics that are superior to any single fuel because of synergistic effects.

The approach taken in research at the Penn State Fuels and Combustion Laboratory is to burn, probe, and analyze a variety of fuels under standardized, well-controlled, well-defined conditions in the combustors shown in the pictures accompanying this article. The goal is to achieve a better understanding of the fundamental process of combustion. Once this is properly understood, ways to burn available fuels in an environmentally and technologically acceptable manner can be

developed.

The research discussed here is currently funded by the Department of Energy, the Petroleum Research Foundation of the American Chemical Society, the Penn State Cooperative Program in Coal Research, and the Penn State Faculty Research Fund.

### The Author

Dr. James J. Reuther obtained a B.A. in chemistry from the State University College of Oneonta, New York, in 1973, an M.A. in combustion and flame from the State University of New York at Binghamton in 1976, and a Ph.D. in fuel science from Penn State in 1979. He was appointed assistant professor of fuel science at Penn State in 1978.

In addition to directing conventional and alternative fuel combustion research at the Fuels and Combustion Laboratory, Dr. Reuther is conducting research in the chemical and physical inhibition of flames by solid, liquid, and gaseous agents, in visible chemiluminescent metal atom oxidation reactions, and in soot formation from fuel-rich hydrocarbon flames.

## Alumni Are Urged to Return Questionnaires for New Directory to Be Published in Fall

Gathering up-to-date information on alumni of the College of Earth and Mineral Sciences for the college’s new alumni directory to be printed this fall got under way in March with the mailing of questionnaires to all college alumni.

A second set of questionnaires went to all alumni in mid-May. If you are an alumnus of the college and have not yet returned one of these two questionnaires, please return one at once. There is no need to return more than one.

If an alumnus does not wish his name listed in the directory, he should so indicate on the questionnaire and return it.

The directory will list both home and business addresses for more than 7,500 graduates of the college. Names of deceased alumni and those for whom no addresses are available will not be included.

Compilation, printing, and marketing of the directory is being done by Bernard C. Harris Company, Inc., White Plains, N.Y., under contract with the university, and at very little expense to the college.

The college will not benefit financially from the sale of the directory, but both the college and the University will derive substantial benefit from the comprehensive updating of alumni records that will result from the Harris efforts.

Beginning in late summer, Harris personnel will telephone all alumni to verify the information received or solicit information if it has not been sent in. During this phone call, the alumnus will also be invited to purchase a copy of the directory. Only enough directories to fill the prepublication orders will be printed and circulation will be carefully restricted to alumni.

49th Year of Publication

## EARTH AND MINERAL SCIENCES

(ISSN 0026-4539)

Robert Stefanko, *Editorial Director*

Mary S. Neilly, *Editor*

THE COLLEGE OF EARTH AND MINERAL SCIENCES OF THE PENNSYLVANIA STATE UNIVERSITY

... dedicated to resident instruction, research, and continuing education in disciplines related to the earth and its environments, and the exploration, discovery, utilization, control, and conservation of the natural environment and the materials found therein.

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Earth Sciences; Geosciences—*Geochemistry and Mineralogy, Geology, Geophysics, Biogeology, General, Geography*; Materials Science and Engineering—*Ceramic Science and Engineering, Fuel Science, Metallurgy, Polymer Science, Solid State Science, Metallurgical Engineering Technology*; Meteorology; Mineral Economics; Mineral Engineering—*Geomechanics, Mineral Engineering Management, Mineral Processing, Mining Engineering, Mining Technology, Petroleum and Natural Gas Engineering*.

Published bimonthly September/October through July/August by Earth and Mineral Sciences Continuing Education, 110 Mineral Sciences Building, University Park, Pennsylvania 16802. Second-class postage paid at State College, Pennsylvania 16801. Subscriptions available without cost upon request. POSTMASTER: Send address changes to *Earth and Mineral Sciences*, 110 Mineral Sciences Building, University Park, Pennsylvania 16802 U.Ed. 80-730



TABLE I. TYPICAL COMPOSITION OF SELECTED CONVENTIONAL AND ALTERNATIVE FUELS												
A. SOLID AND LIQUID FUELS												
Fuel (Phase)	Ultimate Analysis					Proximate Analysis				Aromatic Carbon (%)	Heating Value (Btu/lb)	H/C Ratio
	C	H	N	S	O	Ash	Volatiles	Fixed Carbon	Moisture			
	(dry, wt %)					(dry, wt %)						
SOLID												
Coal												
Bituminous*	80.5	5.0	1.50	1.3	5.9	5.8	29.6	64.6	6.7	84	14,430	0.75
Anthracite	84.2	2.8	0.80	0.6	2.2	9.4	3.4	84.2	4.5	92	13,810	0.40
Reconstituted Coal												
SRC-I	86.1	5.8	1.80	0.7	5.2	0.4	60.1	37.3	2.2	90	15,300	0.80
Gasifier Char	77.7	2.1	1.60	0.6	6.2	11.8	10.7	75.4	2.1	--	12,030	0.32
Biomass												
Wood	51.6	6.4	0.20	0.1	41.3	0.6	81.5	17.5	30.0	--	9,010	1.49
LIQUID												
Petroleum Crudes												
Middle East	86.7	11.9	0.18	0.7	0.4	0.01	--	--	--	--	19,070	1.65
Texas	86.0	9.7	0.46	3.5	0.1	0.23	--	--	--	--	17,800	1.36
Alaska	86.0	11.2	0.51	1.6	0.6	0.03	--	--	--	--	18,470	1.56
Refined Fuel Oils												
No. 2*	86.3	13.3	0.03	0.2	0.1	nil	--	--	--	19	19,600	1.85
No. 6	86.6	12.5	0.22	0.2	0.5	0.02	--	--	--	40	19,110	1.73
Coal Liquid Crudes												
SRC-II	89.1	7.7	0.69	0.3	2.2	0.01	--	--	--	70	17,070	1.04
H-Coal	88.9	9.2	0.39	0.1	1.5	0.01	--	--	--	43	18,080	1.23
Donor Solvent	89.6	9.9	0.08	0.1	0.3	0.01	--	--	--	53	17,500	1.33
Alternative Crudes												
Shale Oil	84.9	11.7	1.75	0.7	0.8	0.05	--	--	--	26	18,970	1.65
Tar Sands	84.5	10.7	0.80	2.4	1.6	0.01	--	--	--	19	18,400	1.52
B. GASEOUS FUELS												
Fuel	Relative Composition								Heating Value (Btu/ft <sup>3</sup> )	H/C Ratio		
	Combustible Components					Noncombustible Components						
Natural Gases *												
Texas	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	H <sub>2</sub>	CO	NH <sub>3</sub>	H <sub>2</sub> S	CO <sub>2</sub>	N <sub>2</sub>	H <sub>2</sub> O	970	3.95	
Ohio	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	H <sub>2</sub>	CO	NH <sub>3</sub>	H <sub>2</sub> S	CO <sub>2</sub>	N <sub>2</sub>	H <sub>2</sub> O	1130	3.70	
Coal-Derived Syngases												
High-Btu Gas	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	H <sub>2</sub>	CO	NH <sub>3</sub>	H <sub>2</sub> S	CO <sub>2</sub>	N <sub>2</sub>	H <sub>2</sub> O	900-1000	4.02	
Medium-Btu Gas	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	H <sub>2</sub>	CO	NH <sub>3</sub>	H <sub>2</sub> S	CO <sub>2</sub>	N <sub>2</sub>	H <sub>2</sub> O	250-350	1.48	
Low-Btu Gas	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	H <sub>2</sub>	CO	NH <sub>3</sub>	H <sub>2</sub> S	CO <sub>2</sub>	N <sub>2</sub>	H <sub>2</sub> O	100-200	1.40	
*Conventional Fuel High--51-95%; medium--16-50%; low--6-15%; trace--5% or less (volume).												

Combustion characteristics obviously play a crucial role in fuel selection. To some extent, the physical (ignition, burn-out rates) and chemical (air-pollution emissions) combustion behavior of a fuel can be anticipated by its composition. The atomic hydrogen-to-atomic carbon ratio (H/C) is an informative parameter since it can be used to characterize a fuel's ease of burning.

Ease of burning can be expressed by three interrelated phenomena: ignition, reaction, and completion. As the H/C ratio decreases, the ease of burning deteriorates—ignition becomes more difficult, reaction slows, burnout is delayed. Fuel-flame behavior according to the H/C ratio also indicates, in part, the reason why natural gas and petroleum liquids have been preferred over coal as fuels, since H/C ratios of about 4, 1.2, and 0.8 delineate the gaseous, liquid, and solid

phases of fossil fuels, respectively. This preference for readily combustible fuel is primarily why natural gases and oils have recently become endangered fossil fuel species.

Coal: A Solution

With continued extensive use of petroleum and natural gas no longer possible, combustors will have to be retrofit to fire coal. The coal conventionally used is bituminous because it is easier to burn than coals of other ranks. The ease of ignition and burnout of a powdered fuel is, to a great extent, a function of its volatile matter and fixed carbon content. Broadly speaking, the higher the percentage of volatile matter and the lower the percentage of fixed carbon, the more readily the coal will ignite and burn out.

Bituminous coal usage, however, is not a panacea for the current energy-

availability crisis. First, not all combustors can be retrofit to fire coal; because of size limitations, some combustors can only burn oil or gas, which generate shorter flames than coal. Second, because of stringent environmental performance standards, fuels must not only be easy to burn but also *clean* to burn. An evaluation of a fuel's combustion-generated air-pollution potential can be made by inspection of its chemical composition: the higher the percentage of nitrogen (N), sulfur (S), and ash, and the lower the H/C ratio (or, correspondingly, the higher the aromaticity), the greater the tendency for the combustion of that fuel to result in higher nitrogen oxide (NOX), sulfur oxide (SOX), particulate (ROX) and smoke pollution, respectively.

The bituminous coal composition given in Table I is a good estimate of the average composition of all known reserves of coal of this rank. With these high precursor-to-pollutant concentrations, none of the known reserves of bituminous coal, when fired directly, can simultaneously comply with NOX and SOX emission standards, and none with NOX standards alone, unless expensive air-pollution control techniques are implemented.

Alternative Energy Scenarios

The latter situation has caused several alternative coal-utilization strategies to be developed. These include: a) a switch to solid fuels that are naturally cleaner burning, e.g., anthracite coal, wood; b) a switch to alternative sources of liquid fuels, e.g., tar sands, oil shales; or c) the removal of the elemental precursors to pollutants, e.g., the synthesis of solid (SRC-I), liquid (SRC-II), and gaseous (syngas) coal derivatives.

Table II shows a comparison between the combustion characteristics of conventional and alternative fuels. On first inspection, several natural and synthetic

TABLE II. COMPARISON OF CONVENTIONAL AND ALTERNATIVE FUEL COMBUSTION CHARACTERISTICS						
Fuel (Phase)	Ignition	Burnout	NOX	SOX	ROX	Smoke
<u>SOLID</u>						
Bituminous Coal	- - - - -	- - - - -	Reference	- - - - -	- - - - -	- - - - -
Anthracite Coal	D	D	L	L	H	H
SRC I	E	D	H	L	L	L
Gasifier Char	D	E	H	L	H	H
Wood	E	E	L	L	L	L
<u>LIQUID</u>						
Petroleum Fuels	- - - - -	- - - - -	Reference	- - - - -	- - - - -	- - - - -
Coal Liquids	S	S	H	L	L	H
Shale Oil	S	S	H	H	H	S
Tar Sands	S	S	H	H	S	S
<u>GAS</u>						
Natural Gas	- - - - -	- - - - -	Reference	- - - - -	- - - - -	- - - - -
High-Btu Syngas	S	S	H	S	-	S
Medium-Btu Syngas	D	D	H	S	-	H
Low-Btu Syngas	D	D	H	H	-	H
D - more difficult; E - easier; S - similar; L - lower potential; H - higher potential						

However, it was not long before these types of nuggets were depleted, and the gold producer had to find other sources. Closer examination of the stream-bed sands revealed small pieces of gold mixed in with the larger quantity of stream-bed material. In this case, nature had extracted the mineral, but had not processed it.

By carefully panning the bed material, that is, washing it with a swirling action that removed the bed sand, leaving behind the heavier gold particles, the old prospector could obtain gold dust. When the quantity of gold particles in the stream-bed material was too small to make panning worthwhile, this process was replaced by another known as sluicing. A wooden trough—the sluice—was constructed and a flowing stream of water was directed into it. The materials in the water stratified into layers due to their different specific gravities so that the heavier particles were trapped behind riffles in the bottom of the sluice. In this wooden trough, the prospector had basically reproduced the action of nature that had concentrated the gold particles in the stream in the first place. The sluice was operated for a time and then the gold particles were removed. Although such concentrating of an ore is only one phase of mineral processing, it is the heart of the operation.

Eventually, the sources of gold that could be recovered by sluicing declined, and then the prospector went underground to extract veins of gold-bearing rock. Some of these veins produced gold nuggets that were obtained simply through crushing the rock and then picking them out. This process—the liberation of a mineral from the gangue (worthless) material associated with it by fracturing the ore—is another of the mineral processing unit operations.

Other prospectors found gold-bearing rock containing small particles of gold. In this case, they crushed the rock to liberate

the gold particles and then sluiced the crushed ore the same way they had sluiced stream-bed materials to concentrate and separate the gold particles.

Eventually, the ore declined in gold content to such an extent that all that was left existed as only flakes in a quartz matrix. Then it was necessary to go to still higher technology to obtain the valuable metal, and amalgamation was one of the methods used. The gold ore pulp, that is, a mixture of fine particles and water, was passed over surfaces coated with mercury, and the gold particles dissolved in the mercury. The process would be stopped periodically and the amalgam of gold and mercury was recovered. The mercury was then distilled from the gold and reused.

Another popular method of gold recovery was—and still is—cyanidation. In this process, the gold is dissolved with cyanide and the liquor separated from the solid impurities. Then the gold is precipitated from the cyanide solution by the addition of zinc dust. The zinc is retorted from the gold and reused while the gold is sold to mints for final purification. Today, substantial quantities of gold and silver are obtained as by-products of the smelting of nonferrous metals such as copper and lead.

Although the final product may not be as exciting as gold, a scenario much the same as the one just outlined for gold applies for many of our other base metals and other minerals that are much more important than gold in our everyday lives. This means that the demand for mineral processing engineers continues to increase as solutions to the problems of concentrating low-grade ores into high-grade concentrates are sought.

The Steps in Mineral Processing

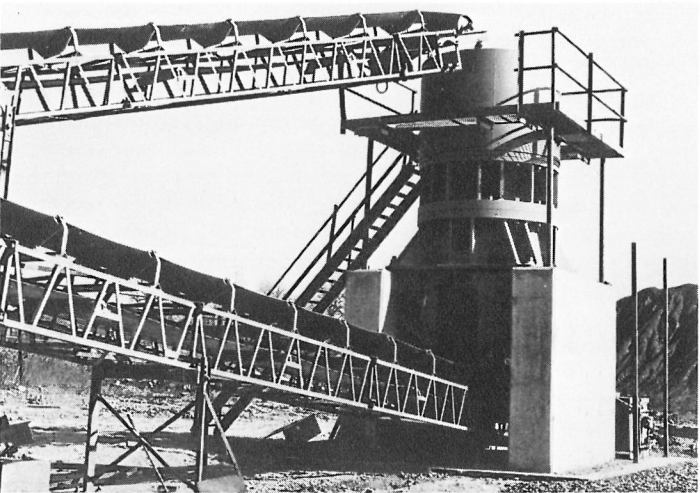
The procedures employed in mineral processing can be condensed into four steps: characterization, liberation, sorting, and

disposal.

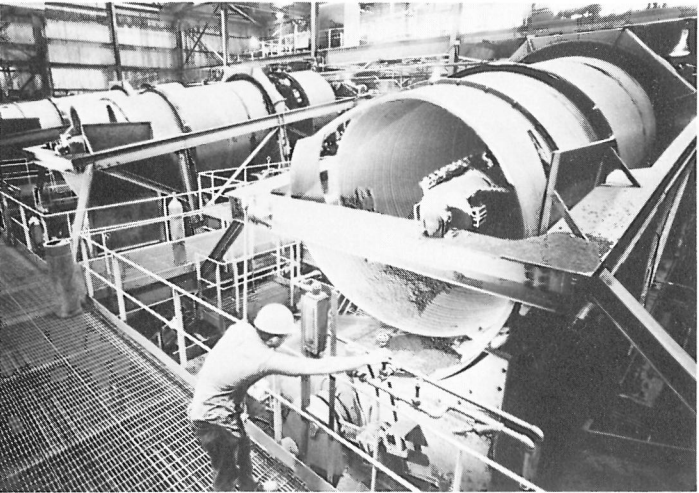
*Characterization* is the examination of the ore to determine its makeup and the amount of mineral and gangue material in it. Many times, there are several desirable minerals in an ore, making the concentrating more challenging.

*Liberation* involves the creation of particles whose content of the desirable mineral is very high and of other particles with a high content of undesirable gangue. Creating only two types of particles would be the ideal situation, but, in reality, particles of various concentrations of the desirable mineral are created. Liberation is achieved by size reduction—crushing and grinding of run-of-mine ore, sometimes reducing it down to particles of 50 microns or less in size.

*Sorting* is the separation of the liberated ore into concentrate—material containing particles with a high concentration of the desirable mineral—and tailings—material containing particles with a very low concentration of the desirable mineral. During the process, material known as middlings which contains intermediate concentrates of the desirable mineral, can be produced. The sorting is done physically by utilizing differences in such particle characteristics as size, shape, specific gravity, and magnetic susceptibility. When physical differences cannot be successfully exploited, chemicals are used to alter the surface properties of the particles either to create size differences by attracting some particles into agglomerates while dispersing others, or to create particles which are hydrophobic (water-hating) or hydrophilic (water-loving). Or the mineral is dissolved, making it possible then to perform a separation by liquid/liquid extraction where the dissolved mineral species preferentially enters liquid B, leaving the impurities in liquid A because the two liquids will not mix. Sometimes the dissolved species is removed by ion-exchange



This gyratory crusher, left, is one of several types used to reduce the size of ores. On the right are pelletizers that agglomerate very fine iron concentrate particles into spheres



which, after firing, are not only convenient to transport and handle, but provide a more efficient gas/solid interaction in the blast furnace. (Kennedy Van Saun photos)



methods in which the mineral ion displaces another ion in a resin material.

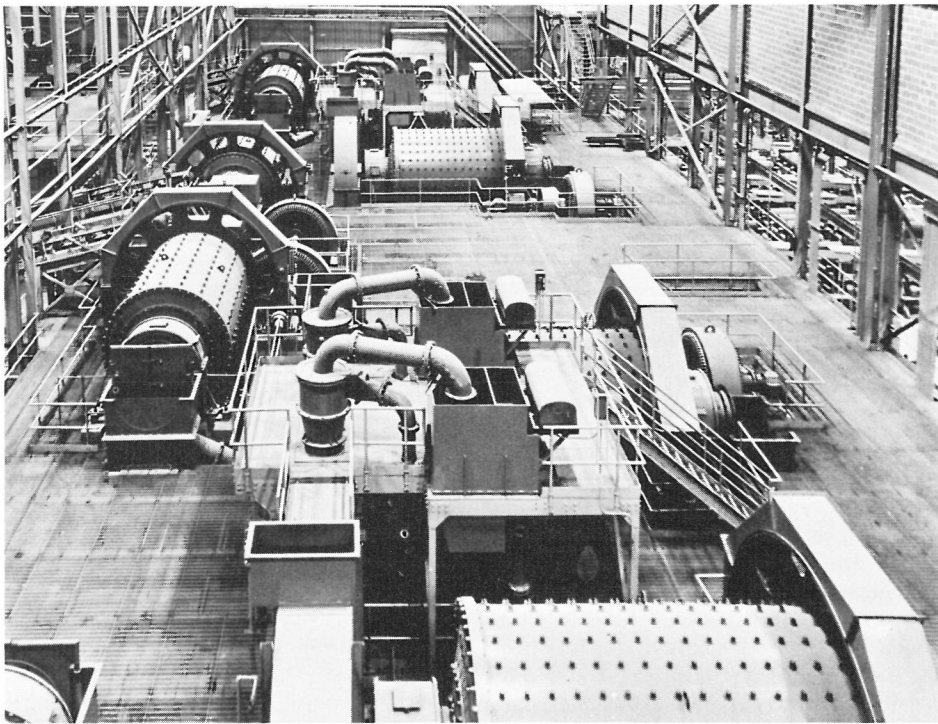
*Disposal* is the process of cleaning up the various solid and liquid streams created while producing the mineral concentrates. Solids are separated from the liquids which are then recycled, all in an environmentally acceptable manner. This involves solid/fluid separations, water treatment, agglomeration, and other operations.

#### Where Mineral Processing Engineers Work

Mineral processing engineers work for companies that produce mineral products such as coal, iron, phosphate, copper, uranium, aluminum, titanium, and cement. Within such companies, these engineers are involved in planning, engineering, operations, and research. For example, consider the positions of several of our Penn State mineral processing alumni. Dale Augenstein (B.S. '69, M.S. '71, Ph.D. '74) is supervisor of operations for K & J Coal Co. Ed Martinez (M.S. '53) is a superintendent in the central research laboratory of ASARCO. Al Terchick (B.S. '60) supervises research for U.S. Steel; Dave Irons (B.S. '62, M.S. '66) supervises research for Bethlehem Steel; Elliott Spearin (B.S. '69, M.S. '71, Ph.D. '79) conducts research for Inland Steel.

Mineral processing engineers also work for firms that design, engineer, construct, and research the systems used to produce minerals, and for companies that manufacture the equipment or produce the supplies, such as chemicals, that are used to prepare and concentrate the ore. For example, Dick Wesner (M.S. '48), the first Penn State graduate in mineral processing, is president of Kennedy Van Saun Corporation. Jim Patterson (B.S. '58, M.S. '62) is with Long-Airdox Construction Company. Ken Harrison (B.S. '63) is with Heyl and Patterson Company. Dick Borio (B.S. '61, M.S. '70) manages research for Combustion Engineering; Sid Cohen (B.S. '55, M.S. '60) manages research for the Fuller Corporation; Booker Morey (B.S. '63, M.S. '66) directs research for Envirotech. Jim Kindig (M.S. '61, Ph.D. '66) is a vice-president of Hazen Research.

Mineral processing engineers are employed, too, in government and universities, conducting research, formulating policy, and engineering systems to clean up our environment because the techniques used to concentrate minerals can also be used to remove many pollutants from our atmosphere and streams. Dave Maneval (Ph.D. '61), formerly with the Appalachian Regional Commission, is now with the Office of Surface Mining. Jan Miller (B.S. '64) is a professor at University of Utah; Joe Leonard (M.S. '58) is dean of the College of Mineral and Energy



Rod and ball mills such as those shown here are used to reduce iron ore to fine sizes in order to liberate the valuable mineral which is then concentrated and agglomerated before being charged to a blast furnace. (Kennedy Van Saun photo)

Resources at West Virginia University; Bill Foremen (Ph.D. '65) is a professor at Virginia Polytechnic and State University.

Still other mineral processing graduates end up doing their own "thing." Sam Weir (M.S. '65) and his wife, Mary, are helping to improve the environment by buying, restoring, and selling old houses. Recently interviewed on the NBC Today Show, they have written a book about their experiences.

#### Mineral Processing at Penn State

Mineral Processing at Penn State first received recognition as a separate discipline in 1944 when, in an overall reorganization of the administrative structure of what was then the School of Mineral Industries, the Division of Mineral Preparation was established as one of six divisions in the Department of Mineral Engineering. However, courses in coal washing and ore dressing had been offered within the mining curriculum as early as the 1890s. In *The Report of the Pennsylvania State College* for 1894, in the section on mining engineering, there is a report on instruction offered in "The Mechanical Treatment of Ores." Students learned in part from working with operating models of a coal washer, an ore-dressing mill, and a coal breaker.

The first degree in mineral preparation was granted in 1948. Since then, more than 100 B.S., about 80 M.S. and over 25 Ph.D. degrees have been awarded.

In 1950, the division became the Department of Mineral Preparation within

the Division of Mineral Engineering, and, in 1962, its head, Dr. H. B. Charnbury, was appointed Pennsylvania's secretary of mines. Dr. H.L. Lovell became acting head, serving until 1968 when Dr. Frank F. Aplan was named head. In 1971, the department became the Mineral Processing Section within the Department of Material Sciences, and the undergraduate degree was dropped and replaced by an extractive metallurgy option within the metallurgy B.S. program. In 1978, the section became a part of the Department of Mineral Engineering, which is where it began more than three decades ago, and the undergraduate degree is now offered as an option in the mining engineering program. In 1979, the author of this article was named chairman of the section.

In addition to the usual engineering background courses in mathematics, chemistry, physics, mechanics, and computer science, the undergraduate in mineral processing also takes basic courses in mining and mineral processing and then studies operations analysis, electrical power, unit operations, physical and non-physical concentration, and design. Courses in particle characterization, hydrometallurgy, and pollution control may also be elected.

#### The Graduate Programs

At the graduate level, the mineral processing section offers programs leading to the M.S. and Ph.D. degrees. These courses of study are oriented toward specialized knowledge in the fundamental principles

steadily operate, but, at depths where porphyry ore shells are formed, transient cooling due to warming of the initially cool overlying rock strata is not sufficient to cause significant mineral precipitation. We are thus *forced* to look to other precipitation mechanisms. The most likely candidates are fluid condensation or boiling, and we are now directing our efforts toward gaining insights into these mechanisms through modeling.

#### Other Aspects of Hydrothermal Activity Investigated by Modeling

Other situations of interest to those studying ore deposits have also been investigated by computer modeling. Nearly continuous intrusive activity near the world's mid-ocean ridges creates new oceanic plates at the rate of 2 to 15 centimeters a year and causes substantial hydrothermal circulation. It is estimated by various techniques that the entire mass of water in the world's oceans is convectively circulated through the oceanic plate in 1 to 10 million years. For comparison it takes the discharge from rivers about 100,000 years to replace the mass of water in the oceans. Hydrothermal circulation near ocean ridges is, therefore, of potential importance to the global chemical balances that control the chemical composition of ocean water.

Massive sulfide ore deposits are associated with mid-ocean ridges and sea-floor spreading. Recently, a massive sulfide deposit has been found in the process of being formed near an ocean ridge off Baja California, 8,200 feet below the ocean's surface.<sup>3</sup>

There, pipe-like orifices projecting upward from the ocean floor resemble black-belching factory smokestacks. Solutions venting from the orifices appear as dark-colored smoke because of the precipitated zinc, iron, and copper sulfides entrained in them. Temperatures of these "plumes," it was determined, are more than 350°C. Spectacular pictures of this phenomenon appear in a recent issue of *National Geographic*.<sup>3</sup> Two of these pictures, taken by scientists from the Woods Hole Oceanographic Institute, are reprinted on page 56. Modeling studies have been useful in helping to define the kinds of hydrothermal circulation that can be expected in the ocean ridge environment.<sup>1</sup>

Large intrusives with unusual but still very low-grade radiogenic mineral content, such as the so-called "Conway Granite" in New Hampshire, can steadily maintain temperature contrasts of about 150°C between the central portion of the intrusive and the rock at an equivalent depth outside. Such a temperature anomaly persists essentially indefinitely, causing hydrothermal fluid circulation whenever tectonic forces fracture the intrusive and

its surroundings. It has been hypothesized that such hydrothermal circulation may periodically leach the parent intrusive and lead to the formation of daughter uranium vein deposits all of which are younger than the parent intrusive.<sup>5</sup> Such daughter vein deposits have been observed in several areas.

Modeling of the genesis of a large area of volcanogenic massive sulfides in northern Japan that are known as Kuroko deposits is being carried out here at Penn State as part of a project led by Dr. Hiroshi Ohmoto, professor of geochemistry. This project is described in a recent issue of this bulletin in which Dr. A. L. Guber, associate professor of geology, discusses one aspect of the research being done.<sup>6</sup>

#### Plans for Future Work

The most exciting activity for the future in our work is a tighter joining of chemistry and the fluid-flow models already developed. We have only just begun this process.

Ultimately, what we look forward to is a predictive physical/chemical model of the ore deposition process itself, including the chemical and isotopic alteration of the surrounding rock formations. Preliminary models of isotopic alteration have been made by other workers.

It is expected, too, that much will be learned from modeling geochemical alteration by hydrothermal fluids. Gravity and magnetic anomalies are useful in constraining geologic possibilities in large part because methods have been developed to predict what anomalies will be produced

by bodies of various types. A great deal more information will certainly be obtainable from the often very regularly zoned rock alteration and mineral patterns observed near and in hydrothermal ore deposits once the methodologies required to predict the alteration and mineral deposition processes are established. The first testing area for the methodologies developed here at Penn State will be the Kuroko deposits of Japan.

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#### The Author

Dr. L. M. Cathles received his B.A. in physics and his Ph.D. in geophysics from Princeton University. Before joining the Penn State faculty in 1978, he worked for Kennecott Copper Corporation in Lexington, Massachusetts, where he did research on the genesis of ore deposits, the leaching of industrial sulfide waste heaps, and the in situ leaching of sulfide ore by passing leach solutions between drill holes. He has also done research on the viscosity of the earth's mantle, and has published a book on this topic. His current research involves the in situ leaching of uranium, desulfurization of coal by heap leaching, acid mine drainage, and modeling of ore deposit genesis.

## Combustion—

*Continued from first page*

from this research will provide information concerning the following technological questions: a) what fuel/combustor interchangeability problems will be experienced when conventional fuels are replaced by alternative, probably coal-derived ones; b) what environmental problems are associated with alternative fuel combustion; and c) what are the most effective retrofit and air-pollution control strategies for the various alternative fuels?

#### Fuel Versus Flame Properties

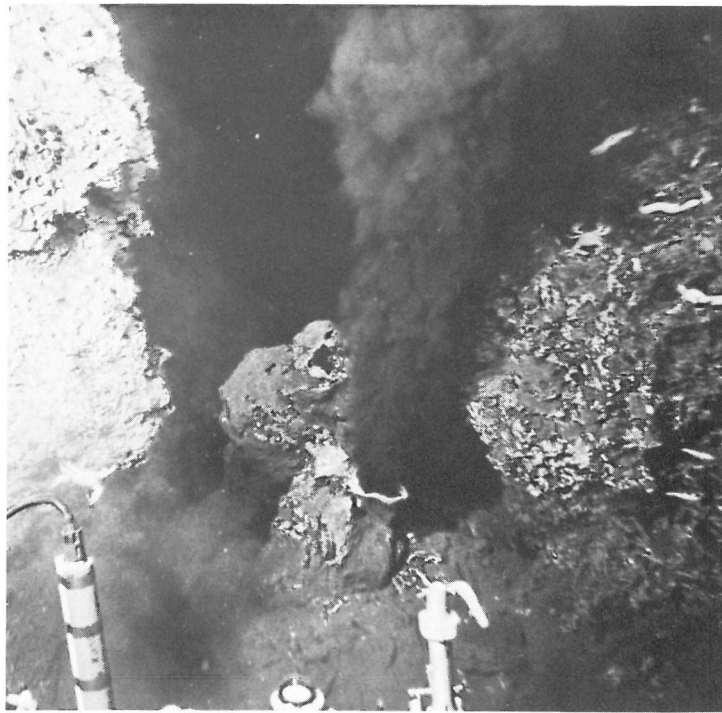
Table I lists typical compositions of selected conventional and alternative fuels, ranked according to phase. The data in this table represent averages and should be used for comparison purposes only since:

- a) natural fuels can vary over a spectrum of compositions, and
- b) synthetic fuels have final compositions that are difficult to forecast.

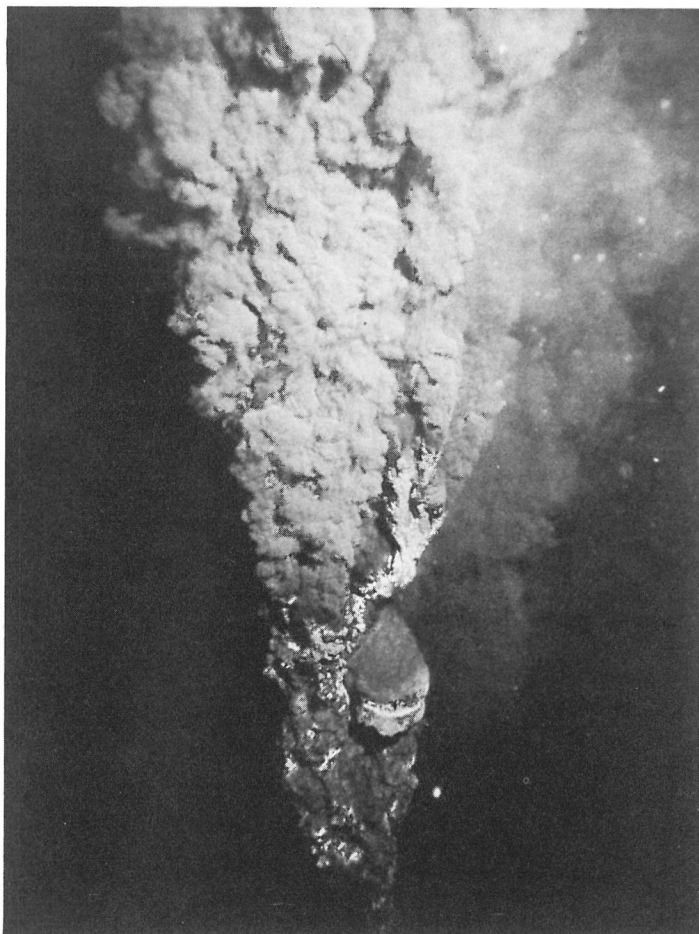


Dr. James J. Reuther, author of this article, checks readings on instruments that record information on solid fuel combustion tests using a plane flame furnace. The combustion behavior of anthracite coal, reconstituted coal, and biomass (wood) are being evaluated.





A process of ore formation was actually seen for the first time when "chimneys" spewing blackened, mineral-laden hot water onto the sea floor were discovered last year by scientists exploring at depths of more than 8,000 feet near an ocean ridge off Baja California. Sulfides of copper, iron, and zinc precipitated instantly as fine particles when the heated mineral solution hit the surrounding, much colder seawater, and formed mounds around what the scientists called "black smokers." Two of these hot, metal-rich plumes found deep in the sea are shown here in photos taken by Woods Hole Oceanographic Institute scientists. (Left photo by Dudley Foster; right photo by Robert Ballard.)



sured in terms of the grams of fluid that will pass through a one-centimeter-square unit area perpendicular to the flow direction in some unit of time. The maximum mass flux rate shown in the figure occurs about 5,000 years after intrusion and above the center of the intrusive. The rate of flow is 17 grams of fluid per square centimeter per year—hardly a very rapid circulation, but one which, nonetheless, has a major impact on the rate and manner of the cooling of the intrusive.

The diagrams also show contours of constant temperature (solid lines) and fluid pressure (dot-dash lines). The initial intrusive is shaded as is the zone in which the pore fluids consist of steam rather than water. Above the cross-sectional depiction of temperature, fluid pressure, and fluid circulation in each of the diagrams is a graph showing the surface heat flow in HFU (1 HFU equal  $1 \times 10^{-6}$  calories per square centimeter per second).

It can be seen from the diagrams that fluid circulation causes the heat anomaly initially associated with the intrusive to lift off it like a hot-air balloon and rise upward till it impinges on the surface of the earth. At this time, very high surface heat flows are produced. For a permeability of 0.25 mD, the heat anomaly is sensed at the surface after about 7,000 years, and, 7,750 years after intrusion, surface heat flow

reaches a maximum value of 170 HFU. If the intrusive cooled by conduction alone (i.e., if the permeability were zero), the maximum heat flow would be only 3.4 HFU (1.9 HFU greater than the normal value of 1.5 HFU) and would occur 65,000 years after intrusion. The cooling is much more rapid in the convective case than in the conductive case. Note that the steam-dominated reservoir (second shaded zone in the second and third diagrams) lasts for only a few thousand years and is substantially reduced in size by the time strong heat-flow anomalies are manifested at the surface. At this time, the temperature of the system as a whole is also substantially reduced. Of course, the time a steam reservoir exists could be increased if the intrusive were made bigger. Scaling relationships, verified by model calculations, show, however, that the time to cool to any specified state increases only linearly with intrusive size (not as the square of the size, as is the case in conductive cooling). As a consequence, it appears that intrusives of geologically reasonable size will cool in the order of tens of thousands of years. Such a conclusion has immediate implications for exploration for geothermal reservoirs.

#### Practical Implications of Modeling Results

To be exploitable with current technology, geothermal reservoirs must have per-

meabilities of at least a few millidarcies. With such permeabilities, intrusives will cool very rapidly and, consequently, modeling suggests intrusive activity must have occurred within the last few thousand years in order for an exploitable geothermal system to have survived till the present. Furthermore, the most economically attractive (i.e., steam-dominated or hot-test) systems are likely to be those that have yet to manifest spectacular surface, hot-spring activity. By the time such surface manifestations are produced, the geothermal system that could be exploited at depth has substantially cooled.

The diagrams on page 54 also give insight into how porphyry copper ore shells might be deposited. The total amount of fluid circulation produced by an intrusive in cooling is adequate (given reasonable values for the solubility of copper in saline hydrothermal solutions) to allow precipitation of ore shells of the size observed. However, the heat anomaly associated with the intrusive migrates upward too rapidly to allow an ore shell to form above the intrusive as a result of temperature drop in the circulating fluids.

The extent of upward migration of the heat anomaly is related to the mass of fluid circulated, so the problem is fundamental. Ore minerals can be precipitated as a result of temperature drop near the earth's surface where strong cooling mechanisms

of comminution, classification, physical and nonphysical concentration, hydro-metallurgy, flocculation, solid/liquid separations, and agglomeration.

A major aspect of the graduate program is research oriented toward analysis and modeling of grinding circuits, flotation, flocculation, and mixing/transport; colloidal behavior of particles in liquid media; solid-liquid interfaces; influence of point defects in the structures of material on its separation behavior; the rheology of particulate systems; sulfur and ash removal from coal; and treatment of process water.

#### Primary Areas of Research

The mineral processing faculty members have solid backgrounds in both industrial and academic areas. In addition to offering instruction of high quality, they have evolved through the years a tradition of excellence in several research specialties that have achieved an international reputation for the section.

One of the areas of specialty is the application of the froth flotation concentrating process to the beneficiation of coal. This work was initiated by a former dean of the College of Earth and Mineral Sciences, the late Dr. D. R. Mitchell, and was expanded by Dr. R. E. Zimmerman, who served as chief of the then Division of Mineral Preparation from 1948 to 1950, and Dr. S. C. Sun, now professor emeritus of mineral processing.

The froth flotation work is now directed by Dr. F. F. Aplan, professor of metallurgy and mineral processing. The current

thrust of the work is toward improving the process for the rejection of pyritic sulfur from coal; developing procedures to recover additional Btu's from raw coal that are being lost to refuse; and using the process as an integral part of the water reclamation circuit in a coal preparation plant. These goals indicate that the process will have an ever-growing role in coal preparation.

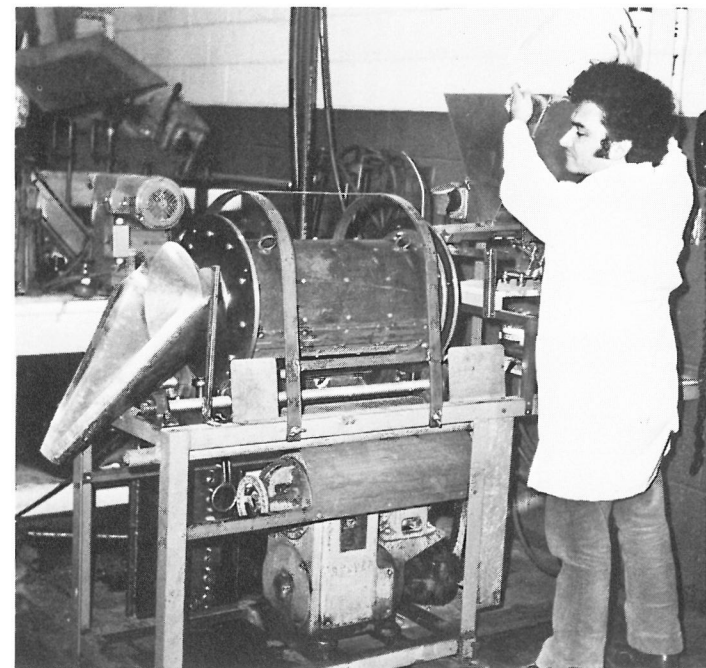
A second area in which the faculty has gained wide recognition for its work is comminution—the process of smashing ores, rock, coal, and cement to finer sizes. In 1957, Dr. L. G. Austin, professor of fuels and mineral engineering, started work on the unit operation size reduction. He applied the concepts of population balance—keeping track of the rate at which particles are created and destroyed, and reactor theory—defining movement of the solids through the size reduction device, which had been recently developed, to create a mathematical model for batch grinding.

Dr. Austin continued the development of this approach with Dr. R. P. Gardner, now professor of nuclear engineering at North Carolina State University, who received his Ph.D. at Penn State in 1961. Working with the author of this article and Dr. R. R. Klimpel, now scientist with Dow Chemical Company and adjunct professor of mineral processing at Penn State (where he received his Ph.D. in 1964), Dr. Austin extended the treatments to grinding circuits and developed methods for measuring rates of breakage in ball mills. This method of analysis and design of grinding

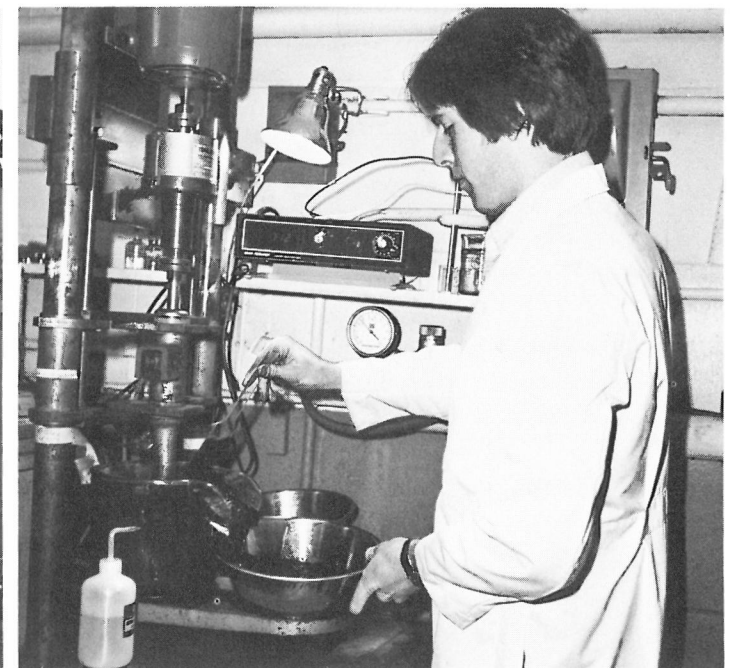
machines and circuits has been extended to several other types of grinding devices at Penn State. Because the cost of energy used in size reduction is increasing rapidly, and ores are becoming lower grade and thus requiring more size reduction, it is expected that the sophisticated computer design procedures developed here at Penn State will be adopted more and more by the designers and users of size reduction equipment in the next few years.

There is no question that acid drainage from coal mines is one of the most serious current water pollution problems in the coal mining areas of our country. Dr. Harold L. Lovell, professor of mineral engineering, has played a predominant role in the control and elimination of this problem during the past twenty years. Pragmatic methods of mine drainage treatment and the characterization of alternative unit operations in such systems have been developed through laboratory and full-scale plant design and operation by Dr. Lovell and his co-workers. The treatments developed—both chemical and biological—have provided insight into the origin of this severe environmental problem and, hence, its prevention.

As important as faculty, facilities, and research funding are to a successful academic program, they form only the foundation for the most important contribution to our society that the Mineral Processing Section can make. All efforts must be focused ultimately on the education and development of young engineers who will be equipped to solve the myriad



Grinding laboratory studies (left) are geared toward reducing the energy consumed during grinding and producing desired size distributions in ores. Here Zvi Rogovin, mineral preparation graduate student, works with a continuous ball mill. On the left, Richard Perry, another graduate student, collects froth containing the desired



mineral from a laboratory froth flotation mixer. In this flotation testing, he is examining various reagents and types of minerals in order to improve the recovery and grade of processed minerals.



of particle processing problems facing the mineral industries. As our mineral resources are depleted, efficient and economical mineral processing becomes of ever greater importance to the future wellbeing and security of our nation.

**Note:** The illustration on page 50 is reprinted by permission from Georgius Agricola's De Re Metallica, translated from the first Latin edition of 1556 by Herbert Clark Hoover and Lou Henry Hoover and published in 1950 by Dover Publications, Inc., New York, N.Y.

The Author

Dr. Peter T. Luckie joined the faculty of the Department of Mineral Engineering earlier this year as professor of mineral engineering and chairman of the Mineral Processing Section. He has three degrees from Penn State, having received his Ph.D. in mineral processing in 1972. He joined the Kennedy Van Saun Corporation, Danville, Pennsylvania, in that same year, and, in 1975, was made corporate director of research of Kennedy Van Saun's parent organization, McNally Pittsburgh Manufacturing Corporation. He had been serving as an adjunct associate professor of mineral processing at Penn State since 1976.

Ore Deposit Genesis—

Continued from first page

since the beginning of the bronze age, and efforts to explore for them have been guided—or misguided—from the start by concepts of how they were formed and the environments that they should, therefore, be found in. Because the concepts developed about such deposits have been based on observations, almost all have had elements of truth and were, therefore, “useful,” although concepts differing from those now in vogue often have had almost humorous aspects.

Recently, sophisticated laboratory-tested theories of mineral phase equilibria and stable isotope fractionation have been applied to observations of rock alteration and mineral precipitation in hydrothermal deposits, and much has been learned about the conditions of pressure and temperature under which the deposits formed. Penn State geochemists have been particularly active in this area and have made many important contributions.

In historical perspective, it is clear that it has often been difficult to shake old ideas of ore deposit genesis. Clear, indisputable disproof of someone's favorite theory is seldom found and, when it is, it is usually discovered by somebody else in an alien ore body. It has also proved difficult for scientists to view the ore formation process as a whole. Although there are notable exceptions, usually only the small part of the total mineralized system that happens to be economically exploitable is accessible for study at any one time, and only parts of this system are intensively studied scientifically.

The recent advent of high-speed digital computers and computer modeling tech-

niques has made possible study of the genesis—formation—particularly of hydrothermal ore deposits, as well as deposits of other types, in an entirely new way—by forward predictive computer modeling of the ore-forming process itself. This new approach requires simplification of some of the geological and scientific complexities and certainly will not

answer all our questions about ore genesis. It has, however, already yielded some interesting insights and promises to yield many more. It is particularly useful in forcing reconsideration of comfortable and usually unquestioned ideas, and suggesting new critical observations that might be made on the ore deposits. By its very nature, modeling requires considera-

tion of the ore-forming process as a whole and quantification of imponderables traditionally only vaguely defined. In this article, I would like to describe briefly how such modeling is done, some of the insights that have been gained thus far, and the directions for future work that appear the most exciting.

The Method of Modeling

The method of modeling is conceptually simple and exactly analagous to the kinds of numerical modeling of petroleum reservoirs described in the April 1979 issue of this bulletin by Drs. S.M. Farouq Ali and A.H.M. Totonji.<sup>1</sup> However, the modeling of ore deposits is in a much earlier stage of development than that of petroleum reservoirs, and, therefore, is not yet as sophisticated. Basically, differential equations describing conservation of mass (i.e., water and chemical species), momentum (fluid flow in porous media), and energy (heat balance) are written down and approximated as finite differences on a grid covering the rock domain to be investigated. The resulting algebraic equations are solved for specific initial and boundary conditions by matrix inversion. The result is a predictive model—predictive in the sense that, given initial and boundary conditions, the model predicts everything that happens next.

The great power of the numerical technique is that it allows many of the important geological complexities to be taken into account, and predicts automatically the logical consequences of a set of assumptions. For example, the true properties of water, including those that allow boiling and condensation, can be accounted for.<sup>2</sup> Also, variations in rock permeability that at least approach those occurring geologically—such as faults of high permeability in a rock formation of much lower permeability—can be easily modeled.

The modeling capability can be used to investigate (1) the time required for a hot igneous intrusion to cool by conduction and fluid convection, (2) the amount of hydrothermal circulation that will be driven by the intrusive as it cools, (3) the temperature of the fluids circulated as a function of time at any location, and (4) potentially, the manner in which minerals will be dissolved and reprecipitated as a result of the fluid circulation. These factors are all clearly related to the problem of what causes metals to accumulate in one location in high enough concentrations to become ore deposits.

Calculating the Cooling of an Igneous Intrusion

The diagrams on page 54 show, by way of example, calculations of the cooling of a hypothetical intrusive, 2.25 kilometers



Six people from the People's Republic of China who are currently studying and doing research with faculty members of the College of Earth and Mineral Sciences are shown here with Dr. C. L. Hosler, left, dean of the college. They are, left to right, Ta-Lin Chang, graduate student in meteorology; Yao Xi, visiting scientist at the University's Materials Research Laboratory; Jia Xiang Zhao, visiting scientist in fuel science; Jinchu Zhu, visiting research associate in the Department of Geosciences; Chiu-Shih Chen, assistant professor of meteorology; and Mrs. Yu-Fang Li, research assistant in meteorology.

Chinese Do Research, Study in College

Five members of faculties of Chinese educational institutions and a graduate student are currently studying and doing research with College of Earth and Mineral Sciences faculty members.

One of them, Jia Xiang Zhao, vice director of the nonmetallic department at Beijing (Peking) Institute of Materials and Technology, came to Penn State last fall and is working as a visiting scientist in fuel science in the Department of Materials Science and Engineering.

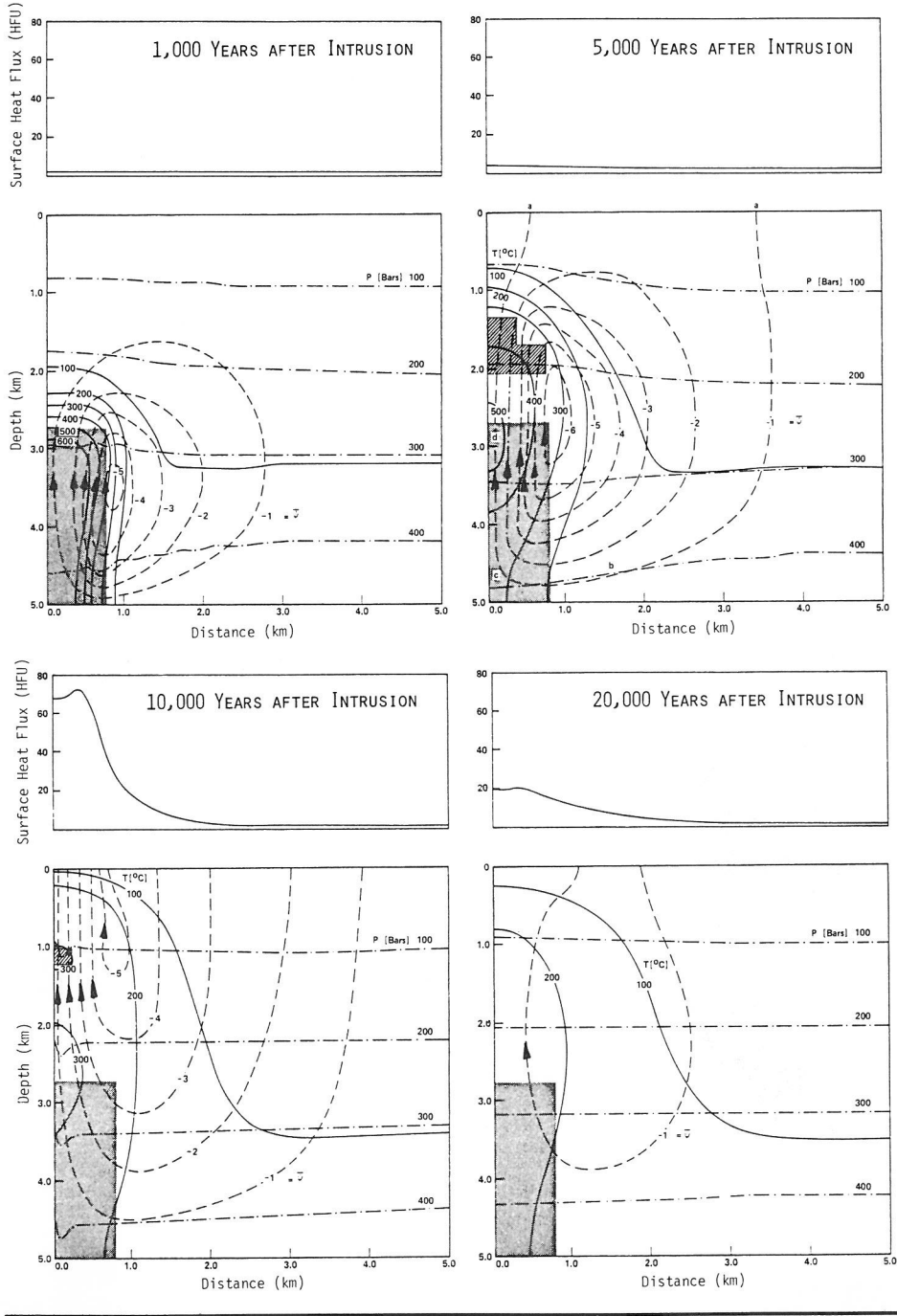
The others arrived on campus early this year. Three are working in the Department of Meteorology. They are: Mrs. Yu-Fang Li, a lecturer in meteorology at the University of Hangchow, who is a research assistant in meteorology here; Chiu-Shih Chen, an assistant professor of geophysics at Beijing University, who is

serving as an assistant professor of meteorology here; and Ta-Lin Chang, a graduate student in meteorology here.

Jinchu Zhu, a lecturer in geology at Nanjing University, is a visiting research associate in the Department of Geosciences here.

Yao Xi, a lecturer in electronic engineering at Xian Jiaotong University, is serving as a visiting scientist at Penn State's Materials Research Laboratory where he is working with Dr. Robert Newnham, professor of solid state science.

Mrs. Li is the second generation of her family to study at Penn State. Her father, Dr. Lai-Yong Li, received his Ph.D. in horticulture here in 1941. He is now professor and president emeritus of Fukien Agricultural College in Foochow.



The lower parts of these four diagrams show, in cross section, the calculated history of cooling of a hypothetical igneous intrusion 1,000, 5,000, 10,000, and 20,000 years after intrusion. The intrusive is emplaced suddenly at  $t = 0$ ; the temperature of intrusion is 700°C. The intrusive is indicated by the large shaded blocks in the lower left corners of the diagrams; the smaller, cross-hatched blocks in the second and third diagrams indicate the zones where the water in the pores of the rock formation will exist at least in part as steam. The curved dashed lines with arrows indicate the direction of fluid circulation; fluid pressure is shown by the dot-dash lines; and the temperature of the intrusive and its surroundings is shown by the solid lines. The permeability of the intrusive and its surroundings is 0.25 millidarcies. The upper part of each of the diagrams shows the total heat flow through the earth's surface above the area intruded. See the text for further discussion of these diagrams.

high and 1.5 kilometers wide (0.75 kilometers in half-width), and of infinite extent in the direction into or out of the page. The intrusive top is implaced 2.75 kilometers below the earth's surface, and the initial temperature of the intrusive is assumed to be 700°C. The domain into which the intrusive is implaced has, initially, a vertical heat flow typical of that encountered in continental regions— $1.5 \times 10^{-6}$  calories per square centimeter per second or 1.5 heat flow units (HFU)—or such as will produce a vertical temperature gradient of about 25°C per kilometer of depth.

The permeability of the intrusive and the rock it intrudes is assumed to be the same—0.25 millidarcies (mD). This permeability is much lower than that gener-

ally dealt with by groundwater hydrologists (1 to 1,000 darcies), or typical of hydrothermal systems currently being exploited for geothermal energy (20 to 100 mD), but is a value typical of the present permeability of rocks found near porphyry copper deposits. The ore in porphyry deposits is generally draped over the top of a “causative” porphyritic intrusive in a bowl-shaped shell about 200 meters thick. These ore shells are believed to have formed about 2.5 kilometers beneath the earth's surface.

Fluid circulation in the diagrams is indicated by the dashed lines with arrows. Where these lines are close together, the rate of fluid circulation is “fast”; where they are far apart, it is “slow.” By convention, the rate of fluid circulation is mea-