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ABSTRACT

The term "complex sulphide ores" generally refers to the relatively fine-grained, pyritic, polymetallic base-metal ores of volcanogenic origin. The metals of economic value in these ores are copper, zinc, lead, silver, gold, tin, cadmium, indium, selenium, and tellurium. The metals occur principally as constituents of the minerals chalcopyrite, sphalerite, galena, tetrahedrite, cassiterite, electrum, and many sulphosalts. The metal-bearing minerals are recovered by flotation in copper, lead, and zinc concentrates, which are then smelted and refined to recover the metals. Process mineralogy provides fundamental information for designing mineral beneficiation, extraction metallurgy, pyrometallurgy, and other plants for treating the ore, concentrates, and other products. Recent developments of equipment such as the automatic SEM-IPS-IAS image analysis system have made it possible to perform rapid quantitative analysis of mineralogical characteristics that affect processing. Previously, these analyses could only be determined qualitatively or not at all. The analyses have provided a better understanding of the behaviour of minerals and phases during processing, leading to improved metal recoveries at processing plants.

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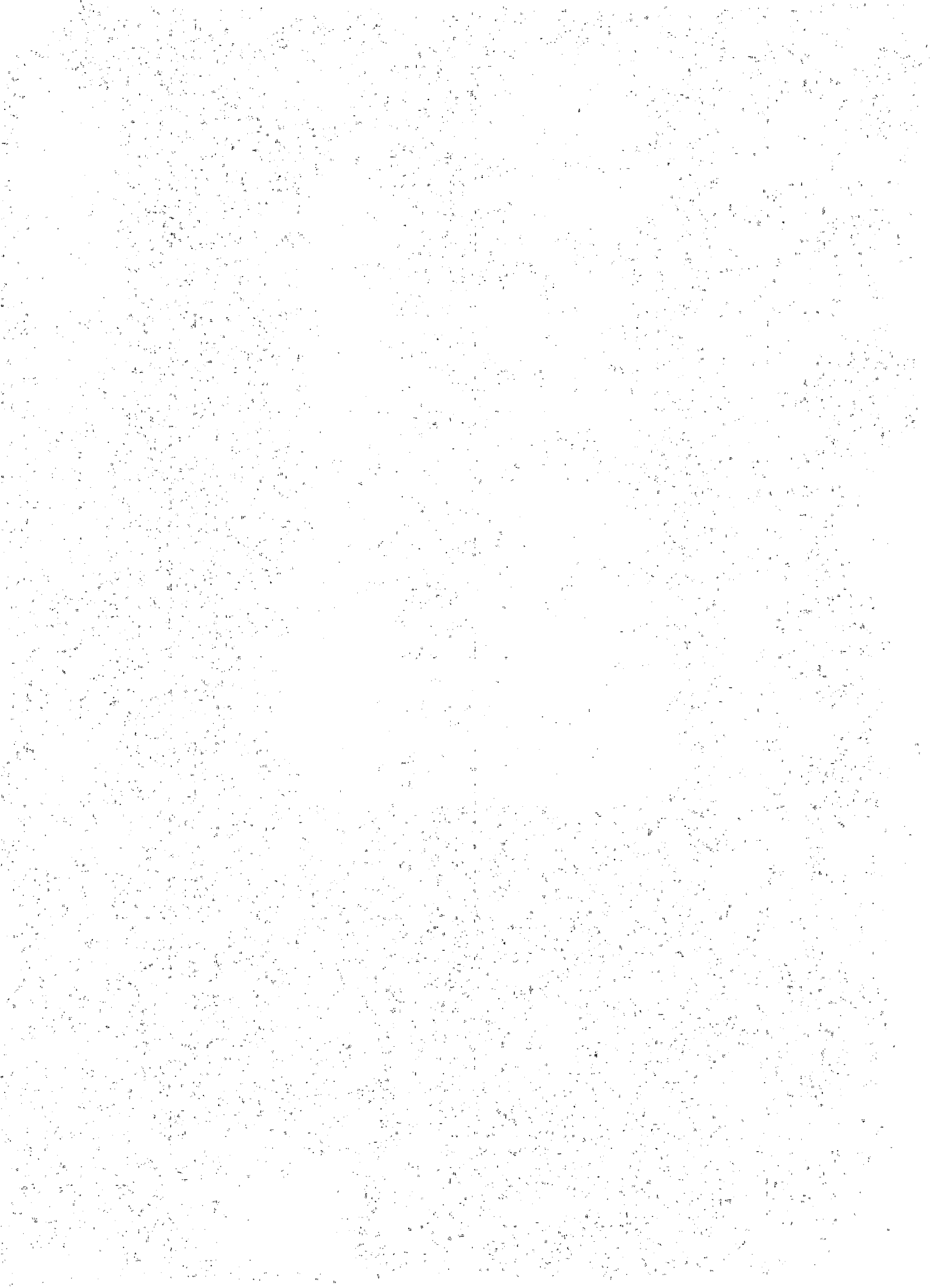
DÉVELOPPEMENTS RÉCENTS DANS LA MINÉRALOGIE INDUSTRIELLE DES MINERAIS SULFURÉS COMPLEXES

W. Petruk* et P.R. Mainwaring**

RÉSUMÉ

Le terme de "minerais sulfurés complexes" désigne généralement les minerais contenant plusieurs métaux communs, pyriteux, à grains relativement fins, d'origine volcanique. Dans ces minerais, les métaux ayant une valeur commerciale sont le cuivre, le zinc, le plomb, l'argent, l'or, l'étain, le cadmium, l'indium, le sélénium et le tellurium. On rencontre principalement ces métaux comme composants des minéraux suivants: chalcopyrite, sphalérite, galène, tétraédrite, cassitérite, électrum, et de nombreux sulfosels. On récupère par flottation les minerais métallifères sous forme de concentrés de cuivre, de plomb et de zinc, que l'on soumet ensuite à la fusion et au raffinage, pour en extraire les métaux. L'étude minéralogique des procédés nous fournit l'information fondamentale qui nous permet de concevoir les procédés d'enrichissement du minerai, les procédés métallurgiques d'extraction, les procédés pyrométallurgiques, ainsi que d'autres types d'installations pour traiter le minerai, les concentrés et d'autres produits. La mise au point de nouveaux appareils, comme un système d'analyse automatique des images SEM-IPS-IAS nous permet maintenant d'effectuer une rapide analyse quantitative des caractéristiques minéralogiques influant sur ces procédés de traitement. Autrefois, on pouvait tout au plus déterminer qualitativement ces analyses. Celles-ci nous ont permis de mieux comprendre le comportement des minéraux et des phases minérales durant le traitement, et donc permis d'atteindre un meilleur taux d'extraction des métaux dans les installations de traitement.

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INTRODUCTION

The term "complex sulphide ores" is assumed to refer to fine-grained, pyritic, polymetallic base-metal ores of volcanogenic origin. The metals of economic value in such ores are copper, zinc, lead, and silver. In addition, small-to-significant amounts of gold occur in some orebodies, and recoverable amounts of tin in a few. Furthermore, most orebodies contain minor amounts of arsenic and trace amounts of indium, antimony, bismuth, selenium, tellurium, mercury, cadmium, manganese, and cobalt. The major elements -- copper, zinc, and lead -- occur largely as constituents of the minerals chalcopyrite, sphalerite, and galena, respectively; the precious metals and trace elements occur either as major constituents of a large number of trace minerals, or as trace elements in the major metal-bearing minerals, or both.

Processing involves mineral beneficiation of the ores to concentrate the minerals, and pyrometallurgical treatments of the concentrates to recover the metals. Mineral beneficiation involves grinding to liberate the minerals and concentrating to produce copper, lead, zinc, and, occasionally, tin concentrates. The silver and gold are recovered in the copper and lead concentrates.

The copper concentrate is generally smelted and refined, with the silver, gold, selenium, and tellurium recovered as by-products. The lead concentrate is also smelted; the contained silver, bismuth, and copper are recovered in the lead bullion. The zinc concentrate is roasted, leached, refined, remelted, and cast into zinc bars; impurities such as cadmium, silver, and copper are occasionally recovered, whereas the indium, manganese, and other elements generally are not.

To obtain optimum metal recoveries, it is necessary to know the characteristics of the material as it progresses through the mill, the concentrator, the smelter, and the refinery. Chemical assays can be obtained readily for the material at each point, but the assays only indicate the mineral or phase quantities without providing information on the characteristics of the minerals and phases. Information on mineral or phase characteristics is needed in designing a plant for optimum metal recovery, and in maintaining it at that level of recovery. Because complete mineralogical

investigation is time-consuming, it should be performed only during development of an orebody, during feasibility studies and plant design, and when recovery or grade problems occur. Mineralogical studies in connection with processing have not been used widely in the past, although they have been performed for many years at some institutes (1-3). In the last decade, however, such investigations have been used more often, with greater emphasis on the types of studies that should be conducted for solving processing problems. An appropriate mineralogical investigation of complex sulphide ores would, therefore, define the mineral and phase properties that have a bearing on grinding and floating the ore minerals, and on smelting and refining the concentrates. Many of the mineral and phase properties can be determined with an optical microscope, but others cannot. In the last two decades, a wide variety of instruments for performing mineralogical and phase studies have been developed, and studies related to processing utilize these instruments increasingly.

ORE CHARACTERISTICS THAT AFFECT MINERAL PROCESSING

Several-score minerals are known to occur in complex sulphide ores, but only about 16 metallic minerals, 6 silicate minerals, and 3 carbonate minerals are present in most orebodies of this type (Table 1). The main metallic minerals are pyrite, chalcopyrite, sphalerite, galena, pyrrhotite, arsenopyrite, tetrahedrite, boulangerite, and cassiterite.

Table 1-Common minerals in complex ores

Metallic minerals	Silicates	Carbonates
pyrite	quartz	ankerite
chalcopyrite	feldspar	dolomite
sphalerite	clay minerals	calcite
galena	chlorite	
pyrrhotite	muscovite	
arsenopyrite	biotite	
tetrahedrite		
tennantite		
freibergite		
magnetite		
boulangerite		
bornite		
covellite		
chalcocite		
cassiterite		
stannite		
pyrargyrite		
electrum		

1
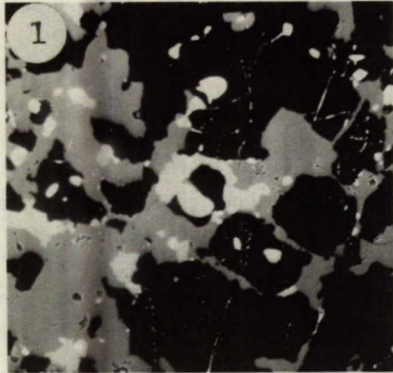
Fig. 1 - SEM-BSE photograph showing large chalcopyrite grains and narrow chalcopyrite veinlets (grey) in pyrite (black). The white areas are sphalerite
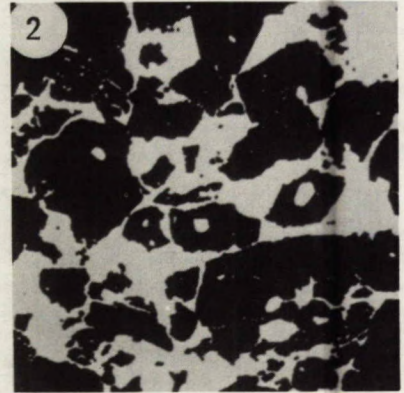
Fig. 2 - Display on CRT screen of image analyzer showing image of chalcopyrite in ore. The black represents all other minerals. The chalcopyrite image was isolated from a SEM-BSE image that displayed all minerals
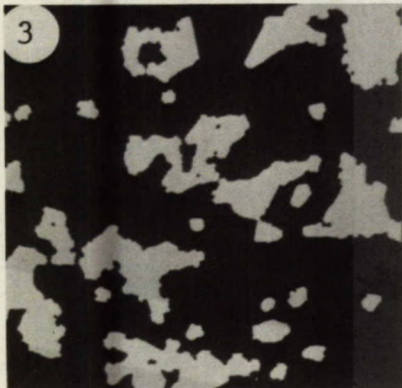
Fig. 3 - Same as Fig. 2, but only large chalcopyrite grains are isolated

Fig. 4 - Same as Fig. 2, but only veinlets are isolated
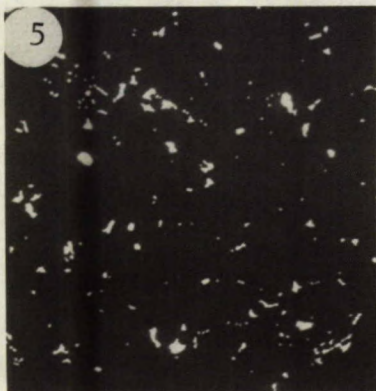
Fig. 5 - Same as Fig. 2, but only minute chalcopyrite grains are isolated
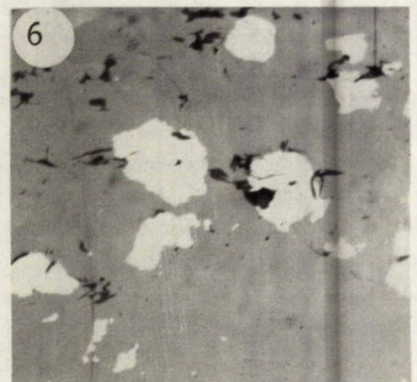
Fig. 6 - Massive sphalerite (grey) with pyrite inclusions (white)

CHALCOPYRITE

The chalcopyrite occurs as large grains in pyrite, pyrrhotite and/or sphalerite; as networks of veinlets in pyrite; and as minute inclusions in pyrite (Fig. 1). In the process of ore dressing, the large grains are liberated during grinding and recovered in the copper concentrate. Size distributions of the chalcopyrite grains in the ore will provide the necessary information to predict the required grind and the expected liberation at the appropriate grind. The size distributions are best performed by obtaining an image of the material with an image analyzer, and by isolating the image of the mineral in question (Fig. 2). The image of the large chalcopyrite grains can be isolated further from the image of the chalcopyrite veinlets with a Kontron image analyzer (Fig. 3), thus enabling the isolated portions of the large chalcopyrite grains to be analyzed. Grain sizes can be determined either by chord or areal analysis. From the size analysis, it is possible to calculate the liberation that would be obtained in each screened fraction of the ground ore by using King's liberation model (4) for chord size analysis, Klimpel's liberation model (5) for areal analysis, or empirical models that have been tested (6,7). Some of the chalcopyrite that occurs as veinlets in pyrite will break free during grinding, whereas some will adhere to the pyrite. In the latter case, the chalcopyrite will coat the pyrite particles and cause them to behave like chalcopyrite. The detrimental effect of chalcopyrite veinlets in pyrite on the grade of the copper concentrate, as well as on metal recoveries, depends on the proportion of chalcopyrite occurring as veinlets and on the widths of the veinlets. The image of the chalcopyrite veinlets can be separated from images of other forms of chalcopyrite with the Kontron image analyzer and analyzed separately (Fig. 4). The analysis will determine the quantity and the veinlet widths of the chalcopyrite occurring in this form. The minute chalcopyrite inclusions in pyrite (Fig. 5) are so small that they likely cannot be liberated and recovered. The quantity and size distributions of the chalcopyrite grains occurring in this manner should, however, be determined to characterize the non-recoverable chalcopyrite.

The chalcopyrite in complex sulphide ores can contain trace-to-several thousand ppm silver and a few ppm selenium and tellurium. The silver is generally recovered from the chalcopyrite during the metallurgical process as a valuable by-product, whereas the selenium and tellurium may either be recovered or may remain as an impurity in the copper. Selenium in copper reduces the quality of the copper; therefore, it is important to determine the mode of occurrence and quantity of the element.

SPHALERITE

The sphalerite occurs as sphalerite layers and as disseminated grains in pyrite (Fig. 6 and 7). The layered sphalerite is massive, but the masses contain many inclusions of pyrite, chalcopyrite, galena, tetrahedrite, and cassiterite, as well as the clusters of minute, rounded and elongated chalcopyrite grains commonly referred to as "the chalcopyrite disease" (Fig. 8). When performing size analysis to predict liberations of the massive sphalerite, it is necessary to determine inter-inclusion sizes of the sphalerite (see Fig. 6). This can only be done by chord size analysis. By contrast, size distributions of the sphalerite inclusions in the massive pyrite (see Fig. 7) can be performed by either areal or chord size analysis.

The sphalerite contains minor-to-trace amounts of silver, cadmium, manganese, indium, and many other elements. The average minor-to-trace element content of the elements in the sphalerite can be determined by analyzing a statistically valid number of grains with a microprobe, with an ion microprobe, or with a micro-PIXE.

GALENA

The galena occurs as irregular grains in sphalerite and pyrite, and as minute inclusions in pyrite (Fig. 9 and 10). Because the mineral is generally fine-grained, much of it is not liberated when the ore has been ground for liberating the sphalerite and chalcopyrite. Image analysis studies should be performed to determine the quantity of the minute galena inclusions in pyrite, the quantity of large galena inclusions in pyrite, and the quantity of galena associated with sphalerite and chalcopyrite. The minute inclusions in pyrite are nonrecoverable, whereas the large galena inclusions in pyrite are recoverable, but they may respond differently to processing than the galena in chalcopyrite and sphalerite. Galena contains significant amounts of silver and bismuth in solid solution. In complex sulphide ores studied to date by the author, about one-third of the silver in the complex sulphide ores occurs in solid solution in galena.

Fig. 7 – Disseminated sphalerite (grey) in massive pyrite (white)
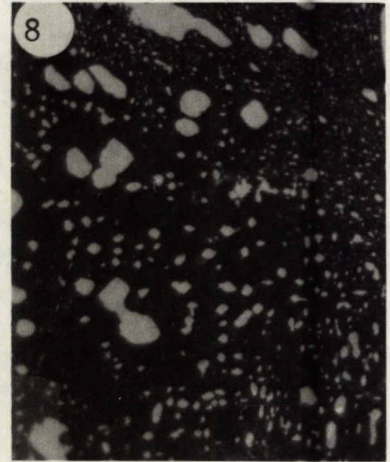

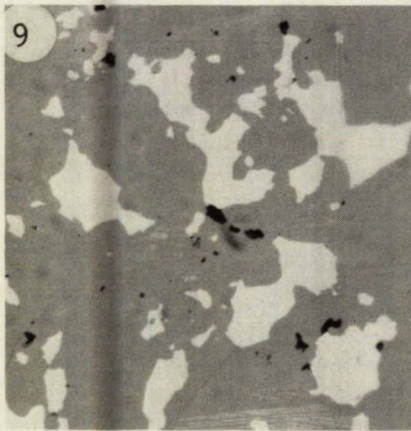Fig. 8 – Minute rounded grains and lamellae of chalcopyrite (white) in sphalerite (grey)

Fig. 9 – Galena inclusions (white) in sphalerite (grey)

Fig. 10 – Minute galena inclusions (encircled) in pyrite. The grey is sphalerite

TETRAHEDRITE-TENNANTITE-FREIBERGITE AND BOULANGERITE

Minerals of the tetrahedrite-tennantite-freibergite solid-solution are referred to in this paper as tetrahedrite. Tetrahedrite and boulangerite are minor minerals in complex sulphide ores. They can be mistaken easily for each other during a cursory examination with an optical microscope because both have the same colour in white light, although boulangerite is anisotropic and tetrahedrite is isotropic. The tetrahedrite commonly contains silver, with amounts varying from 0 to 35 wt %. The average silver content of the tetrahedrite can be determined by analyzing a statistically valid number of grains with an electron microprobe, or with a scanning electron microscope (SEM) equipped with a quantitative energy dispersive X-ray analyzer (EDXA).

SILVER AND BISMUTH SULPHOSALTS

In some orebodies, portions of the silver and bismuth occur in a wide variety of sulphosalt minerals. These minerals are generally present as very minute grains and many tend to be lost to the concentrator tailings.

GOLD

Gold generally occurs as minute grains of electrum or gold-silver-mercury-bearing phases. The grains commonly occur as minute inclusions in pyrite and as stringers of minute grains along healed fractures in pyrite, as well as along pyrite-chalcopyrite grain boundaries. It has been observed that when the quantity of gold in an ore is very low (< 1 ppm), the gold is lost to tailings along with the pyrite (8). This suggests that the gold occurs either at very low concentrations as solid solution in the pyrite, or as very minute inclusions in pyrite.

CASSITERITE AND STANNITE

The tin in complex sulphide ores occurs largely as minute grains of cassiterite, and to a minor extent, as stannite. The cassiterite commonly occurs as minute inclusions in sphalerite, whereas the stannite is generally associated with chalcopyrite.

MINERALOGICAL AND IMAGE ANALYSIS STUDIES OF THE ORES

A complete mineralogical study of an ore with respect to mineral dressing entails defining the host mineral for each element and predicting the grind required for liberating the minerals. Defining the host mineral involves identifying the minerals, determining the mineral compositions, determining trace element contents, and determining the quantities of each mineral. To predict the grind, size analysis is required.

MINERAL IDENTITIES AND COMPOSITIONS

The minerals are generally identified with an optical microscope, by X-ray diffraction, or with a scanning electron microscope (SEM). Mineral compositions are determined with a microprobe, or with an SEM equipped with an energy dispersive X-ray analyzer (EDXA). Methods of analysis with these instruments are well established and do not need to be discussed here.

TRACE ELEMENT CONTENTS

Trace element contents in minerals can be determined with a microprobe, if the concentrations are above 200 to 300 ppm, and with an ion microprobe or micro-PIXE, if the values are between about 200 ppm and 5 ppm. If the values are lower than 5 ppm, they can only be determined by preparing a monomineralic concentrate and analyzing the concentrate with chemical-instrumental methods such as plasma analysis. Trace elements of importance in complex sulphide ores are silver in galena, silver in chalcopyrite, silver in sphalerite, gold in pyrite (?), bismuth in galena, selenium and tellurium in chalcopyrite, and tin in pyrite (9). The trace element contents in minerals vary considerably from spot to spot in a grain, and from grain to grain in an ore. Consequently, many spots from many different grains may need to be analyzed to obtain a value that is near the average trace element content in a mineral. The quantities of trace elements in the minerals of complex sulphide ores vary from 1 to several thousand ppm, but are commonly 1 to several hundred ppm.

MINERAL QUANTITIES AND SIZE DISTRIBUTIONS

Mineral quantities, size distributions, and mineral liberations can be determined with an image analyzer. Analytical techniques for performing the analysis are now established, but a major problem exists in automatically discriminating the minerals that occur in complex sulphide ores. This is particularly true when an optical microscope is used to produce an image. In this case, the reflectance value of individual minerals is so close to the values of other minerals that the individuals cannot be differentiated well enough to analyze them automatically. Some of the problematical mineral groups are chalcopyrite-pyrrhotite-galena, pyrite-arsenopyrite, sphalerite-magnetite, etc. The problem can be overcome partly by interfacing the image analyzer with a scanning electron microscope, and using the backscattered electron image that differentiates each mineral on the basis of its average atomic number. Even this technique does not differentiate all minerals. This problem was circumvented by Professor Jones (10) at the Royal School of Mines, and overcome by Reid (11) at CSIRO and by the authors (12) at CANMET. Professor Jones uses a Cameca microprobe equipped with four wavelength spectrometers. He moves the stage at one-micron intervals under a fixed beam to identify the minerals at each spot, on the basis of four elements. The trade-off with this technique is that only linear analysis is performed. The QEM*SEM at CSIRO and SEM-IPS-IAS image analysis system at CANMET use a SEM and a microprobe, respectively, to produce a backscattered electron (BSE) image. The image is sent to an image analyzer, and the phases are discriminated on the basis of their grey level. If there are mineral pairs that cannot be discriminated in this way, the minerals are identified by steering the electron beam of the microprobe to scan each particle automatically and to identify it with the EDXA on the basis of its composition. When the particles have been identified, the quantities, size distributions, and mineral liberations can be determined readily with the image analyzer.

AUTOMATED SEM-IPS-IAS

The automated SEM-IPS-IAS image analysis system at CANMET has not yet been described in the literature; therefore, a brief description is given here. The system consists of a microprobe with two wavelength spectrometers, a Tracor Northern EDXA 2000, and a SEM-IPS image analyzer. The units are interfaced with two-way communications between them. The image analyzer has a 256-K memory buffer and a 10-M byte hard disc storage. Furthermore, it can store up to 14 images. The image is produced with the microprobe and displayed on the CRT screen of the microprobe. Particles having different grey levels are identified off-line with the EDXA. The image is then collected by the image analyzer. Each mineral that can be discriminated on the basis of its grey level is stored in a separate image memory. Free and unliberated grains of the mineral are stored in other image memories. Minerals that cannot be differentiated on the basis of their grey level are stored as a "family" of minerals in still another ("family") memory. Each particle in this "family" memory is scanned with the X-ray beam of the microprobe and identified by EDXA. The reason for scanning only those particles that cannot be identified on the basis of their grey level, rather than scanning all particles, is speed of analysis. The slowest step in image analysis is scanning the particles with electron beam. After the particles have been identified by EDXA, the image is analyzed to determine the physical properties of the particles.

ORE-DRESSING PLANT

Mineralogical studies that should be performed on products which are produced during processing of complex sulphide ores include identifying the minerals, determining mineral liberations, determining size distributions of the free and of the unliberated minerals, and classifying the particles according to the quantity of the mineral of interest that occurs in each particle. This information will pinpoint the reasons for specific problems in circuits and will provide the data for performing a mineral-metals balance. The mineral-metals balance can be used in many ways, one of which is evaluating the behaviour of free mineral grains in a circuit. Such an evaluation will assess whether a particular process is designed for treating a specific ore. For example, Table 2 shows that 97.7% of the free chalcopyrite and 73.3% of the unliberated chalcopyrite was recovered in the copper concentrate in a bench test of a complex sulphide ore. The free chalcopyrite represented 70%, and the unliberated chalcopyrite 30% of the chalcopyrite in the ore.
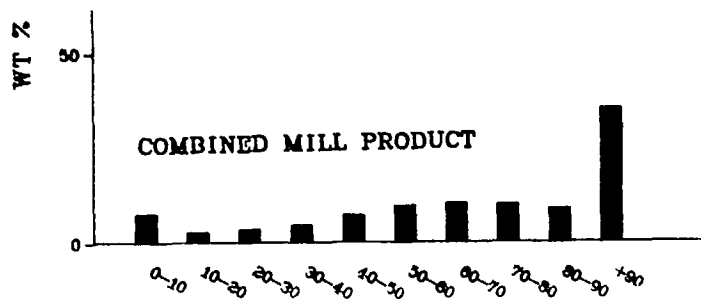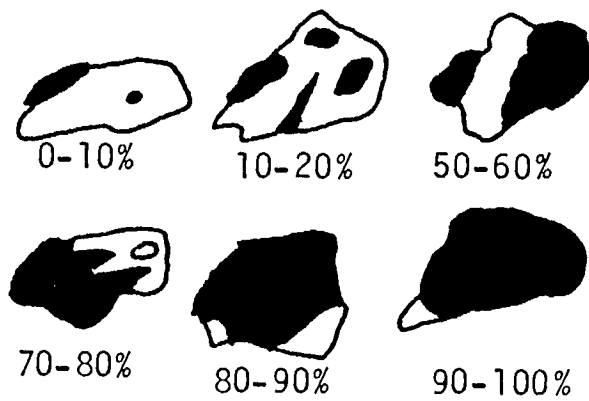
Fig. 11. Diagram showing types of particles that constitute each particle
class, and histogram showing quantities (in area %) of mineral of
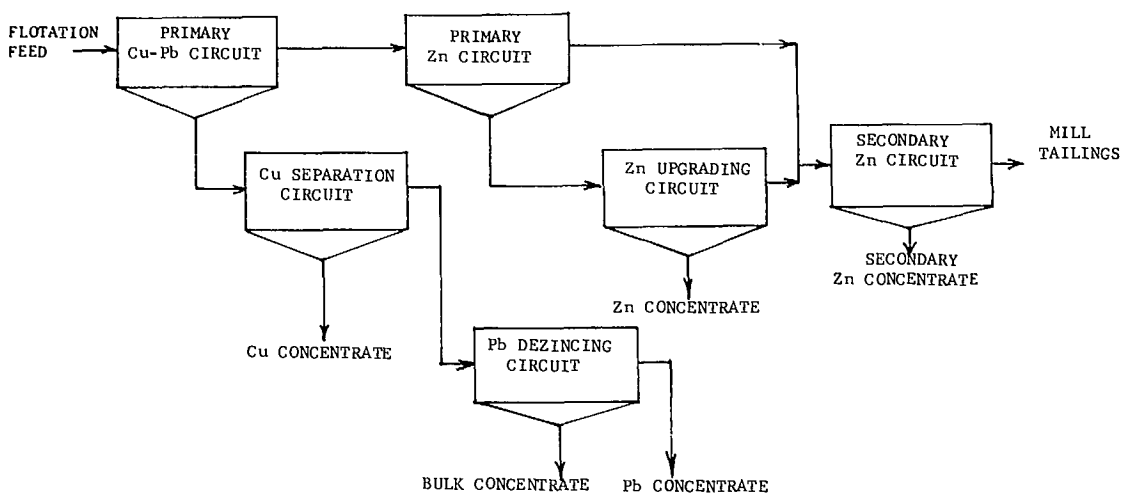interest that occurs in each particle class.

Fig. 12. Generalized flowsheet in concentrator for treating a complex
sulphide ore.

Table 2 —Recovery of free and unliberated chalcopyrite in bench test

Product	Free %	Unliberated %
Copper concentrate	68.3	22.2
1st Copper cleaner tail	0.0	0.8
2nd Copper cleaner tail	0.7	1.2
Zinc concentrate	0.9	1.2
Zinc cleaner tail	0.1	0.8
Final tail	0.0	3.8
Total in feed	70.0	30.0
Recovered in copper concentrate	97.7	73.3

The classification of the particles into those that contain different amounts of the mineral of interest provides a method for defining the characteristics of the minerals in a product, and for predicting how the product will behave during processing. An established classification is 10 classes of particles, with particles in each class containing different amounts of the mineral of interest. This classification is 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90, and 90-100% by area of the mineral of interest in each particle. In general, it is considered that free grains are of the 90-100% class (Fig. 11). It has been found, by analyzing many mill products, that grains containing more than 70% by area of the mineral of interest tend to be recovered in the concentrate, whereas small grains with less than 30% by area of the mineral of interest tend to be lost to the tailings. Intermediate grains could go either way. If the intermediate grains are large, they could be liberated by regrinding.

GRINDING CIRCUIT

When the ore has been ground, it should be analyzed to confirm that the mineral liberations predicted during the mineralogical study were in fact achieved, and to determine what proportions of the minerals of interest are in particles that are recoverable and nonrecoverable. Material from the grinding circuit should also be studied to evaluate the performance of rod mills, ball mills, and cyclones (13), and to determine how the minerals break during grinding. Mineralogical and image analyses related to grinding include determining mineral liberations, classifying the particles, performing size analyses of the free and unliberated grains, and determining the shapes of the free and unliberated grains.

COPPER CIRCUIT

The copper circuit is the first circuit in most concentrators treating complex sulphide ores (Fig. 12). It usually contains banks of rougher, scavenger, and cleaner flotation cells. The rougher concentrate contains the copper- and lead-bearing minerals as well as some free sphalerite, some free pyrite, and some silicate and carbonate minerals. The relative quantity of free sphalerite is usually proportional to the relative quantity of non-copper-bearing minerals in the rougher concentrate. The rougher copper concentrate is generally cleaned several times. The scavenger concentrate is reground and returned to the feed. The scavenger tailing is generally fed to the zinc circuit, whereas the cleaner circuit tailing is fed to a lead circuit. The copper concentrate recovers chalcopyrite, bornite, tetrahedrite, stannite, small amounts of unliberated galena and pyrite, and the free electrum. The scavenger tailing, which is the copper circuit discharge, contains pyrite, sphalerite, pyrrhotite, boulangerite, and cassiterite; under some conditions, it also contains slow-floating minerals such as acanthite, silver-poor tetrahedrite, silver-bismuth sulpho-salts, and other minor metallic minerals as well as the silicates.

It has been found that the presence of about 0.01 wt %, or more, of covellite plus chalcocite in the ore affects flotation in such a manner that the chalcopyrite cannot be floated selectively from the sphalerite and galena. The problem can be partly overcome by adding sodium cyanide to the flotation circuit (14,15). The sphalerite, however, is depressed only when an excess of sodium cyanide has been added and free cyanide is present. The technique is, therefore, not economical when the ore contains more than 0.1 wt % copper due to covellite plus chalcocite.

Mineralogical and image analysis studies should be performed on the materials in the copper circuit to determine the quantities, size distributions, and liberation characteristics of the minerals of economic value, and to obtain a mineral-metal balance for the free chalcopyrite, galena, sphalerite, tetrahedrite, and gold.

LEAD CIRCUIT

The lead circuit feed in most plants is the copper cleaner circuit tailing. It contains most of the sphalerite and pyrite that were pulled into the copper rougher concentrate. The galena in complex sulphide ores is usually much finer grained than the sphalerite and chalcopyrite; thus, a high proportion of the galena in the copper rougher concentrate is in combined galena-sphalerite and galena-pyrite particles. Consequently, if high lead recoveries are looked for, the lead concentrate will have to be low-grade. Such a lead concentrate usually contains galena, sphalerite, pyrite, tetrahedrite, lead sulphosalts, and other minerals. Commonly, about one-third of the silver in the ore is recovered in the lead concentrate. A large proportion of the silver in the lead concentrate is in solid solution in galena, but some is also in tetrahedrite and some in other silver minerals.

Mineralogical and image analysis studies should be performed on the materials in the lead circuit to determine the quantities, size distributions, and liberation characteristics of the minerals of economic value, and to obtain a mineral-metal balance for the lead, silver, zinc, copper, bismuth, and gold. This involves image analysis and microprobe analysis. The mode of occurrence of gold in the lead concentrate is unknown.

ZINC CIRCUIT

The zinc circuit feed is the tailings from the copper and lead circuits. The zinc circuit usually has banks of rougher, scavenger, cleaner, and recleaner flotation cells, commonly in open circuit with a regrind mill. The feed contains about 90 to 95 wt % of the zinc in the ore and small amounts of copper, lead, silver, and gold. Some of the copper, lead, silver, and gold is recovered in the zinc concentrate, but some is lost to the final tailing. About 10 to 15% of the silver in complex sulphide ores is usually recovered in the zinc concentrate. It is, therefore, desirable to determine how much of the silver in the zinc concentrate occurs as discrete minerals and how much is in solid solution in sphalerite. Preliminary investigations suggest that the sphalerite from complex sulphide ores contains about 20 to 50 ppm silver in solid solution, and this commonly accounts for about 30 to 50% of the silver in the zinc concentrates. It has been observed (16) that about 25 to 40% of the silver in zinc concentrates is soluble in a cyanide solution, but the host mineral for this silver has not been definitely established. It has been interpreted that the soluble silver occurs in acanthite grains that are smaller than one micrometre in diameter (17). These acanthite grains may have been precipitated during the processing of the ore. Auger analysis (18) of the sphalerite surfaces may provide some answers to this observation. The sphalerite in the zinc concentrate contains some inclusions of galena and chalcopyrite.

It has been found that only about 10% of the chalcopyrite that occurs as minute rounded inclusions and lamellae in the sphalerite of the ore (see Fig. 8) is still present as minute inclusions in the sphalerite of the zinc concentrate (19). The chalcopyrite inclusions in the sphalerite of the ore are so minute that only a small percentage of them would be liberated if the sphalerite grains broke randomly. It is observed, however, that most of the chalcopyrite inclusions in the sphalerite of the ore are aligned, apparently along specific crystallographic planes. This suggests that during grinding, the sphalerite tends to break preferentially along these planes, and the chalcopyrite breaks away from the sphalerite.

A mineralogical and image analysis study was conducted on the zinc circuit of the ore of Brunswick Mining and Smelting Ltd. to determine whether the mineralogical characteristics would suggest a method for improving zinc recoveries. It was found that a significant proportion of the sphalerite in the scavenger and rougher concentrates was in unliberated grains that ranged from about 5 to 50 micrometres in diameter. It was calculated from image analysis data that reducing the size of the sphalerite-bearing particles by a factor of two Tyler sizes ($2x\sqrt{2}$) would liberate enough sphalerite to improve zinc recoveries by about 3% (16). The company conducted a series of grinding tests and found that, by improving the classification, they improved zinc recoveries by about 5% (20).

TIN CIRCUIT

The tailing from the zinc circuit is sometimes treated to recover the tin that is generally in the form of cassiterite. The cassiterite in the ore usually occurs in sphalerite as inclusions that are 2 to 25 micrometres in diameter. The

Interpretation for grains of this size distribution is that most would be unliberated if the sphalerite broke randomly during grinding. However, most of the cassiterite in the tailing is free. It is interpreted that during grinding, the minute grains of the cassiterite - a hard mineral - were liberated from the sphalerite, which is a much softer mineral. Tabling of fine-grained material is an art. Therefore, tin recoveries by tabling depend largely upon the operator's skills. Flotation of the free cassiterite may be a desirable alternative and is being investigated at CANMET.

COPPER SMELTING AND REFINING

The general procedure for treating a copper concentrate is to combine it with the residues from the zinc plant, then to roast it to drive off some of the sulphur and produce a matte grading 35 to 50 wt % copper. The matte is smelted and converted to copper. The copper is cast into anodes and the anodes are refined. The anode copper contains the precious metals, selenium, tellurium, and other trace elements as impurities. Many of the impurities drop to the bottom of the refining tanks as sludge, which is then treated to recover the precious metals and other elements. Mineralogical studies of the roaster and smelter products, of the anodes, of the sludge, and of the final copper will provide a basis for improving the efficiency of operation, for improving metal recovery, and for obtaining premium-grade copper and by-products.

LEAD SMELTER

The lead smelter usually consists of a sintering machine and a furnace. The sintering machine drives off the sulphur, producing lead silicates that can be smelted. The lead concentrate is mixed with silica, limestone, and fuel. It is then heated in the sintering machine where the lead is combined with silica and calcium to produce lead silicates and lead calcium silicates; the iron and zinc combine into iron-zinc ferrites. The sinter is smelted in the furnace. During smelting, the lead silicates and lead calcium silicates melt; the lead as well as minor copper, silver, tellurium, selenium, bismuth, and gold separate as metals and are drawn off in the lead bullion. The iron, zinc, calcium, and silicon occur in the slag as ferrites, wustite, and a zinc-calcium silicate. The arsenic, antimony, some of the zinc, and some of the lead are combined with sulphur; they are also in the slag as sulphides, arsenides, and sulphantimonides. Several dozen phases are produced during smelting in the blast furnace (21,22). Material produced in a blast furnace has been studied by charging a cage with sinter, lowering it to an appropriate level in the blast furnace, allowing it to equilibrate, withdrawing it and allowing it to cool, and studying the frozen products (23). The phases in blast furnace products can best be identified with an SEM equipped with a qualitative and quantitative EDXA. If poor lead recoveries are obtained in the smelter, the reason may become obvious by identifying the phases, and determining their quantities and their textures. If large quantities of impurities are in the lead bullion, the quantities and sizes of the phases in the lead bullion would have to be determined, which is best done with an image analyzer.

ZINC PLANT

The zinc concentrate is generally roasted to drive off the sulphur, and the resulting calcine is leached. A wide variety of residues are produced in the leaching plant, including a lead-silver residue, a copper cake, a copper cement, cadmium metal residue, and a jarosite residue if the jarosite process is used to remove the iron. The leach liquor is treated by electrolysis to precipitate the zinc as a zinc anode. The zinc anode is remelted to increase the purity of the zinc, which is cast into blocks. Mineralogical studies conducted on the phases in the calcine, and on the various leach residues, provide useful information for improving the operating efficiency of the zinc plant.

REFERENCES

1. Timm, W.B., and Haycock, M.H. "The mineragraphic laboratory"; Memorandum Series 58; Mines Branch, Department of Mines; Ottawa, Canada; 1933.

2. Kerr, P.F. "Reminisences in applied mineralogy"; in Process Mineralogy I, edited by D.M. Hausen and W.C. Park; pp. 3-22; AIME/ TMS; New York, N.Y.; 1981.

3. Hiemstra, S.A. "The role of applied mineralogy in ore beneficiation as illustrated by case histories"; Applied Mineralogy, edited by W.C. Park, D.M. Hausen, and R.D. Hagni; pp. 9-20; AIME/TMS; New York, N.Y.; 1984.

4. King, R.P. "A model for quantitative estimation of mineral liberation by grinding"; Int J Miner Process 6:207-220; 1979.

5. Klimpel, R.R. "Some practical approaches to analysing liberation from a binary system"; in Process Mineralogy III, edited by W. Petruk; pp. 65-81; AIME/SME; New York, N.Y.; 1984.

6. Petruk, W. "Application of quantitative mineralogical analysis of ores to ore dressing"; Canadian Institute of Mining and Metallurgy Bull 69:767:146-153; 1976.

7. Malvik, T. "An empirical model to establish the liberation properties of minerals"; 14 Int Mineral Processing Cong; Canadian Institute of Mining and Metallurgy; Montreal, Canada; preprint 8-2; 1982.

8. Chen, T.T., and Petruk, W. "Mineralogy and characteristics that affect recoveries of metals and trace elements from the ore at Heath Steele Mines, New Brunswick"; Canadian Institute of Mining and Metallurgy Bull 73: 823:167-179; 1980.

9. Cabri, L.J.; Campbell, J.L.; Laflamme, J.H.G.; Leigh, R.G.; Maxwell, J.A.; and Scott, J.D. "Proton-microprobe analysis of trace elements in sulphides from some massive sulphide deposits"; Can Mineral 23:2:133-148; 1985.

10. Jones, M.P. "Designing an X-ray image analyzer for measuring mineralogical data"; 14 Int Mineral Processing Cong; Canadian Institute of Mining and Metallurgy; Montreal, Canada; Preprint 8-4; 1982.

11. Miller, P.R.; Reid, A.F.; and Zuiderwyk, M.A. "QEM*SEM image analysis in the determination of model assays, mineral associations and mineral liberation"; 14 Int Mineral Processing Cong; Canadian Institute of Mining and Metallurgy; Montreal, Canada; preprint 8-3; 1982.

12. Mainwaring, P.R., and Petruk, W. "Automated electron microprobe image analysis: Application to mineral processing"; Particulate Science and Technology; (in press).

13. Petruk, W. "Image analysis studies to determine liberations of sphalerite, chalcopyrite, and galena during grinding of fine grained pyritic Zn-Pb-Cu-silver ores"; 14 Int Mineral Processing Cong; Bur. Recherches Geol. et Minieres; France; I, pp. 77-87; 1985.

14. McLean, D.C. "Upgrading of copper concentrates by chalcocite derimming of pyrite with cyanide"; in Process Mineralogy III, edited by W. Petruk; pp. 3-14; AIME/SME; New York, N.Y.; 1984.

15. Petruk, W. "Applied mineralogy in ore dressing of valcanogenic massive sulphide ores"; in Applied Mineralogy, edited by W.C. Park, D.M. Hausen, and R.D. Hagni; pp. 279-290; AIME/TMS; New York, N.Y.; 1984.

16. Petruk, W., and Schnarr, J.R. "An evaluation of the recovery of free and unliberated mineral grains, metals and trace elements in the concentrator of Brunswick Mining and Smelting Corp. Ltd."; Canadian Institute of Mining and Metallurgy Bull 74:833:132-159; 1981.

17. Boorman, R.S.; Petruk, W.; and Gilders, R. "Silver carriers in concentrates and tailings from Brunswick Mining and Smelting Corporation Limited"; in Process Mineralogy III, edited by W. Petruk; pp. 33-50; AIME/SME; New York, N.Y.; 1984.

18. Hagni, R.D. "The application of reflected and luminescence miroscopy and the auger microprobe to beneficiation problems"; 14 Int Mineral Processing Cong; Canadian Institute of Mining and Metallurgy; Montreal, Canada; preprint 8-7; 1982.

19. Petruk, W. "Predicting and measuring mineral liberations in ores and mill products, and effect of mineral textures and grinding methods on mineral liberations"; in Process Mineralogy VI, edited by R. Hagni; AIME/TMS; New York, N.Y.; (in press); 1986.

20. B.M.S. Engineers. Personal communication with metallurgical engineers of Brunswick Mining and Smelting Ltd.; 1985.

21. Petruk, W.; Owens, D.R.; Morris, D.R.; and Amero, B. "Mineralogy of phases in the lead blast furnace of Brunswick Mining and Smelting"; in Process Mineralogy III, edited by W. Petruk; pp. 183-199; AIME/SME; New York, N.Y.; 1984.

22. Petruk, W., and Morris, D.R. "Impurities in the lead concentrate of Brunswick Mining and Smelting and their behaviour in the lead blast furnace"; Canadian Institute of Mining and Metallurgy Bull 78:878:113-122; 1985.

23. Morris, D.R.; Amero, B.R.; Evans, P.G.; Petruk, W.; and Owens, D.R. "Reactions of sinter in a lead blast furnace"; AIME Metall Trans B 14B:617-623; 1983.