

Information Circular 8778

10

Occurrence and Recovery of Certain Minor Metals in the Smelting-Refining of Copper

By John G. Parker



UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary
BUREAU OF MINES

ib

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

This publication has been cataloged as follows:

Parker, John G

Occurrence and recovery of certain minor metals in the smelting-refining of copper / by John G. Parker. [Washington] : U.S. Dept. of the Interior, Bureau of Mines, 1978.

79 p. ; ill., 27 cm. (Information circular • Bureau of Mines ; 8778)

Bibliography: p. 71-79.

1. Copper • Metallurgy. 2. Copper • Byproducts. 3. Scrap metals. I. United States. Bureau of Mines. II. Title. III. Series: United States. Bureau of Mines. Information circular • Bureau of Mines ; 8778.

TN23.U71 no. 8778 622.06173

U.S. Dept. of the Int. Library

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock No. 024-004-01930-1
Catalog No. I 28.27: 8778

ic ~~12~~

CONTENTS

	<u>Page</u>
Abstract.....	1
Introduction.....	1
Acknowledgments.....	2
Minor metal production associated with copper production.....	2
Generalizations on materials flow in copper smelting.....	6
Presmelting processing.....	6
Copper smelting procedures.....	6
Data acquisition.....	7
Domestic copper smelters and refineries.....	7
Smelter feed materials.....	11
Distribution of domestic and foreign concentrates.....	12
Domestic sources of copper concentrates, 1971-74.....	13
Arizona.....	13
California.....	19
Colorado.....	19
Idaho.....	19
Michigan.....	19
Missouri.....	20
Montana.....	20
Nevada.....	20
New Mexico.....	21
Oklahoma.....	21
Tennessee.....	22
Utah.....	22
Foreign sources of copper concentrates, 1971-74.....	23
Canada.....	23
British Columbia.....	23
New Brunswick.....	23
Northwest Territories.....	23
Peru.....	23
Philippines.....	24
Published assay data on smelter materials, 1971-74.....	24
Solicited assay data, 1971-74.....	24
Arsenic in concentrates.....	25
Selenium in concentrates.....	25
Tellurium in concentrates.....	25
Gold in concentrates.....	26
Silver in concentrates.....	26
Platinum and palladium in concentrates.....	26
Byproduct metals in precipitates.....	26
Arsenic, 1971-73.....	27
Arsenic in concentrates, precipitates, and other feed to type 1 plants.....	27
Arsenic in roaster calcines.....	29
Minor metals in dust and fume.....	29
Arsenic in dust and fume.....	30
Minor metals in reverberatory smelting furnace feed.....	30
Arsenic in reverberatory furnace feed.....	31

CONTENTS--Continued

	<u>Page</u>
Minor metals in reverberatory furnace products.....	31
Arsenic in reverberatory furnace products.....	32
Minor metals in converter feed.....	32
Arsenic in converter feed.....	33
Minor metals in converter products.....	34
Arsenic in converter products.....	35
Selenium, 1971-73.....	35
Selenium in concentrates, precipitates, and other feed to type 1 plants.....	35
Selenium in roaster calcines.....	36
Selenium in dust and fume.....	36
Selenium in reverberatory furnace feed.....	36
Selenium in reverberatory furnace products.....	37
Selenium in converter feed.....	38
Selenium in converter products.....	38
Tellurium, 1971-73.....	39
Tellurium in concentrates, precipitates, and other feed to type 1 plants.....	39
Tellurium in roaster calcines.....	40
Tellurium in dust and fume.....	40
Tellurium in reverberatory furnace feed.....	41
Tellurium in reverberatory furnace products.....	41
Tellurium in converter feed.....	42
Tellurium in converter products.....	43
Gold, 1971-73.....	43
Gold in concentrates, precipitates, and other feed to type 1 plants.	43
Gold in roaster calcines, dust, and fume.....	44
Gold in reverberatory furnace feed.....	45
Gold in reverberatory furnace products.....	45
Gold in converter feed.....	46
Gold in converter products.....	47
Silver, 1971-73.....	48
Silver in concentrates, precipitates, and other feed to type 1 plants.....	48
Silver in roaster calcines, dust, and fume.....	49
Silver in reverberatory furnace feed.....	49
Silver in reverberatory furnace products.....	50
Silver in converter feed.....	50
Silver in converter products.....	52
Platinum, 1971-73.....	52
Platinum in concentrates, precipitates, and other feed to type 1 plants.....	52
Platinum in roaster calcines, dust, and fume.....	52
Platinum in reverberatory furnace feed and products.....	52
Platinum in converter feed and products.....	53
Palladium, 1971-73.....	54
Palladium in concentrates, precipitates, and other feed to type 1 plants.....	54

CONTENTS--Continued

	<u>Page</u>
Palladium in roaster calcines, dust, and fume.....	54
Palladium in reverberatory furnace feed and products.....	54
Palladium in converter feed and products.....	55
Generalizations on the refining of copper, materials flow, and minor metals contents.....	57
Domestic copper refineries.....	59
Minor metals in refinery feed, 1971-74.....	61
Arsenic in blister, anode, and other refinery feed.....	62
Selenium in blister, anode, and other refinery feed.....	63
Tellurium in blister, anode, and other refinery feed.....	64
Gold in blister, anode, and other refinery feed.....	64
Silver in blister, anode, and other refinery feed.....	65
Platinum-group metals in blister, anode, and other refinery feed....	65
Minor metals in refinery products, 1971-74.....	65
Arsenic.....	66
Selenium.....	66
Tellurium.....	66
Gold.....	66
Silver.....	67
Platinum-group metals.....	67
Newer technology.....	67
Conclusions and recommendations.....	69
Bibliography.....	71

ILLUSTRATIONS

1. Copper smelting and refining, showing principal byproduct metals....	5
2. Locations of domestic copper smelters and refineries operating, 1971-74.....	10
3. Generalized flowsheet for copper processing.....	12
4. Copper mines of Arizona and New Mexico operating, 1971-74.....	15
5. Roasting.....	28
6. Reverberatory smelting.....	31
7. Converting.....	34
8. Fire refining of copper.....	62
9. Electrolytic refining of copper.....	63

TABLES

1. Domestic copper smelters and refineries operating, 1971-74.....	8
2. Arizona: Fifteen leading copper-producing mines operating, 1971-74..	14
3. Arsenic in type 1 plants operating, 1971-73--roaster feed.....	27
4. Arsenic in type 1 plants operating, 1971-73--reverberatory furnace feed and products.....	29
5. Arsenic in type 2 plants operating, 1971-73--reverberatory furnace feed and products.....	30
6. Arsenic in type 1 plants operating, 1971-73--converter feed and products.....	32

TABLES--Continued

	<u>Page</u>
7. Arsenic in type 2 plants operating, 1971-73--converter feed and products.....	33
8. Selenium in type 1 plants operating, 1971-73--roaster feed.....	35
9. Selenium in type 1 plants operating, 1971-73--reverberatory furnace feed and products.....	36
10. Selenium in type 2 plants operating, 1971-73--reverberatory furnace feed and products.....	37
11. Selenium in type 1 plants operating, 1971-73--converter feed and products.....	38
12. Selenium in type 2 plants operating, 1971-73--converter feed and products.....	39
13. Tellurium in type 1 plants operating, 1971-73--roaster feed.....	40
14. Tellurium in type 1 plants operating, 1971-73--reverberatory furnace feed and products.....	41
15. Tellurium in type 2 plants operating, 1971-73--reverberatory furnace feed and products.....	42
16. Tellurium in type 1 plants operating, 1971-73--converter feed and products.....	42
17. Tellurium in type 2 plants operating, 1971-73--converter feed and products.....	43
18. Gold in type 1 plants operating, 1971-73--roaster feed.....	44
19. Gold in type 1 plants operating, 1971-73--reverberatory furnace feed and products.....	45
20. Gold in type 2 plants operating, 1971-73--reverberatory furnace feed and products.....	46
21. Gold in type 1 plants operating, 1971-73--converter feed and products.....	46
22. Gold in type 2 plants operating, 1971-73--converter feed and products.....	47
23. Silver in type 1 plants operating, 1971-73--roaster feed.....	48
24. Silver in type 1 plants operating, 1971-73--reverberatory furnace feed and products.....	49
25. Silver in type 2 plants operating, 1971-73--reverberatory furnace feed and products.....	50
26. Silver in type 1 plants operating, 1971-73--converter feed and products.....	51
27. Silver in type 2 plants operating, 1971-73--converter feed and products.....	51
28. Platinum in type 2 plants operating, 1971-73--reverberatory furnace feed products.....	52
29. Platinum in type 1 plants operating, 1971-73--converter feed and products.....	53
30. Platinum in type 2 plants operating, 1971-73--converter feed and products.....	53
31. Palladium in type 1 plants operating, 1971-73--roaster feed.....	54
32. Palladium in type 1 plants operating, 1971-73--reverberatory furnace feed and products.....	55

TABLES--Continued

	<u>Page</u>
33. Palladium in type 2 plants operating, 1971-73--reverberatory furnace feed and products.....	55
34. Palladium in type 1 plants operating, 1971-73--converter feed and products.....	56
35. Palladium in type 2 plants operating, 1971-73--converter feed and products.....	56

OCCURRENCE AND RECOVERY OF CERTAIN MINOR METALS IN THE SMELTING-REFINING OF COPPER

by

John G. Parker¹

ABSTRACT

Important quantities of gold, silver, platinum-group metals, selenium, tellurium, and arsenic are recovered in the processing of copper concentrates. The objective of this Bureau of Mines study was to determine the occurrence of these elements in copper ores and to trace their distribution during subsequent processing steps.

The study describes the important areas supplying concentrates, precipitates, and unrefined copper to the copper smelting and refining industry in a composite of the years 1971-74. The relative importance of these areas as a source of the respective byproducts is assessed.

The lack of certain quantitative and assay data, recycling of dusts and slags, and the addition of scrap to the feed often complicates calculations and estimations of the byproducts in the smelter-refinery throughputs.

Such volatile or low-boiling point elements as arsenic, selenium, and tellurium may be lost in gaseous and other emissions in various processing stages, or they may be concentrated in slags and residues for which samples were not available. The effects of antipollution legislation to improve control of sulfurous and other emissions that may affect recovery of certain byproducts was noted. A section on newer technology illustrating hydro-metallurgical techniques that may affect the recovery of minor metals is included.

INTRODUCTION

A 1973 study conducted by the Bureau of Mines provided an analysis of copper system byproducts (89).² The study examined the identification and classification of byproduct metals and the supply systems from which the byproducts were derived. Although the study achieved the intended objective,

¹Physical scientist, Intermountain Field Operations Center, Bureau of Mines, Denver, Colo.

²Underlined numbers in parentheses refer to items in the bibliography at the end of this report.

it also implied a need to assess the importance of domestic and foreign copper concentrates and other smelting and refining feed materials as the source of byproduct metals. Consequently, an attempt was made to collect and compile information on the sources of minor metals associated with the production of copper. Selected for study were arsenic, selenium, tellurium, gold, silver, and the platinum-group metals. A review of the literature indicated that published data alone would not be satisfactory and that it would be necessary to obtain analytical data, material flow, and other information directly from the copper producing companies. The lack of assay data on feed materials and products was partially compensated by acquisition of representative samples of the materials for Bureau of Mines analyses. Correspondence, telephone calls, and plant visits were required to obtain these data and samples. Some plants also provided copper processing flowsheets; others commented on flowsheets drawn by Bureau engineers from data supplied by the industry. Only one domestic copper company declined to participate in the study.

Initially, data were collected for 1971 but, as the work progressed, it was realized that information collected through 1974 would have to be used. In some cases, samples for 1971 were not available from the companies and it was necessary to use a composite of several years to accomplish the study.

Deficiencies in assay data for concentrates, precipitates, and products are shown in the succeeding appropriate sections on assays on concentrates and precipitates. The lack of assay data on foreign and domestic concentrates, on calcines, and on some dusts and in unaccounted losses, severely limited the throughput picture for roasting, reverberatory smelting, and converting. The lack was further complicated by different recycling procedures used by the various companies and by the lack of quantitative (as well as assay) data on matte and slags. Data on platinum and palladium were particularly scarce.

In refinery material balances, the lack of data for some intermediate products appeared responsible for the discrepancies between minor metals in feed and products.

ACKNOWLEDGMENTS

The complexity and inadequacy of basic data for determining qualitative and quantitative data on the byproducts necessitated voluminous correspondence with smelting-refining management, visits with operating personnel, and acquiring numerous samples of feed materials and intermediate products, all of which invaluable assistance is gratefully acknowledged and without which the study would have been extremely difficult.

MINOR METAL PRODUCTION ASSOCIATED WITH COPPER PRODUCTION

Of the byproduct metals, arsenic is almost wholly derived from gold, silver-nickel-cobalt, a few specific copper properties, or from copper ores associated with lead and zinc (54). Enargite, an arsenic-bearing copper sulfide mineral found in the Butte, Mont., ores and in Mountain Province, the Philippines, contains up to 19 percent arsenic.

More than 80 percent of the world's output of selenium is a byproduct of copper refining, but it also occurs with some lead ores and with copper-nickel and copper-zinc ores (1). Fully 90 percent of U.S. production is derived from the anode muds produced at copper electrolytic refineries (72). Assays of blister copper obtained for this study ranged from 0.0025 to 0.043 percent selenium, while anodes ranged from 0.0035 to 0.048 percent. Over an 8-year period, 0.52 pound of selenium per ton of refined copper was recovered in domestic refineries compared with 1.28 pounds of selenium per ton of copper in Canadian refineries (33). The increasing use of in situ leaching of copper ores could reduce selenium supply because the selenium does not accompany the copper in the leach-precipitation process. Lakin and Davidson indicate coal as the most important potential source of selenium in the United States by a factor of 100 (72, p. 575).

Of U.S. tellurium production, 80 percent is from anode mud deposited in copper electrolytic refining (35, p. 629). The average of 0.02 percent tellurium in blister copper differs from recent assays on blister copper obtained in this study (0.0015, 0.002, and 0.004 percent). Some assays on anode copper show 0.001, 0.015, 0.0195, 0.0035, and 0.005 percent tellurium.

About 42 percent of contained tellurium is said to be recovered from slime residue (anode mud); 6,750 tons (13.5 million pounds) of tellurium was estimated to be available in identified copper resources, or 21 percent of that found with domestic coal resources (74 percent), and lead ores the remainder. Most tellurium is thought to be in oceanic manganiferous nodules. In the total (domestic and foreign) identified copper resources, 85 percent of tellurium (990,000 tons) occurs in the oceanic nodules, 12 percent in coal, about 2.5 percent in copper ores, and about 0.5 percent in lead ores.

In 1973 over half of the 15 leading domestic gold-producing mines were primarily copper producers (116). One was in Utah, five in Arizona, one in Nevada, and one in Montana. Ores from these copper mines were processed by copper smelters. The gold contents of concentrates in the byproduct study ranged from trace amounts to as high as 0.65 ounce per ton. Other assay data are given in another section of this study.

About 47 percent of 1973 gold production was a byproduct of mining for other metals. This compares with 1969 when byproduct gold accounted for 40 percent of total U.S. gold output (103). Eighty percent of this (about 32 percent of total) was said to have come from copper ores and the rest principally from complex ores of lead, zinc, and copper. Simons and Prinz indicate that the gold assay data on base-metal ores are very sparse, but that they appear to contain 0.001 to 0.025 ounce (103, p. 271).

It was said that porphyry copper deposits supply about 20 percent of the domestic production of silver (58). The silver tenor of the ore is very low--about 0.01 to 0.1 ounce of silver per ton of ore. Silver assays made on Arizona copper concentrates used in this study ranged from about 0.8 to 4.65 ounces per ton. Other data on the silver content of concentrates are given later.

Ore at the Bingham, Utah, open pit mine contained 0.065 ounce of silver per ton. Kennecott Copper Corp.³ produced 3.62 million ounces of silver from copper ore in 1974 compared with 4.2 million in 1973 and 4.3 million in 1972 (32). From 1880 to 1964, total production at Butte, Mont., averaged about 1 ounce of silver for each 25 pounds of copper (79). The Anaconda Co. extracted 3.57 million ounces of byproduct silver from 197,543 tons of copper (9, 32). In Arizona, Magma mine ore has averaged 1.93 ounces of silver per ton of ore. The White Pine, Mich., copper shales were said to contain more silver than those at Kornberg, West Germany (that is, more than 0.29 troy ounce of silver per ton) (58, p. 590). The company's Lake Brand copper contains 12 ounces of silver or more per ton. Of domestic identified resources in which silver is a byproduct, 741 million troy ounces (52 percent of the total 1.43 billion ounces of silver in the resources) is in porphyry copper deposits (58, p. 596). In hypothetical resources, 725 million troy ounces (less than 23 percent of the 3.21 billion troy ounces of silver in the resources) is in the porphyries.

The platinum-group metals consist of platinum, palladium, iridium, osmium, rhodium, and ruthenium. These metals occur with copper ores, they become concentrated in the blister copper, and they are recovered from the anode muds at the electrolytic copper refineries. Palladium and platinum are the most abundant of the group, constituting about 80 percent of the total in nature. Ageton and Ryan reported that about 1 ounce of platinum-group metals is recovered for each 35 tons of copper produced from domestic ores (2). Using the available crustal abundance figures, 1 ounce of platinum-palladium (with palladium being twice that of platinum) is recovered from each 45 tons of copper produced.

Split-off points for minor metals are shown in figure 1. The lead-zinc byproduct study showed the following: roasting of the copper charge produces fume sometimes containing arsenic trioxide; slag sometimes containing cobalt; electrolyte from electrolysis sometimes containing nickel sulfate; and slimes sometimes containing silver, gold, platinum and palladium, sodium slag, selenium, and tellurium. Other copper plant products go to lead and zinc plants for further processing.

³Reference to specific manufacturers or trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

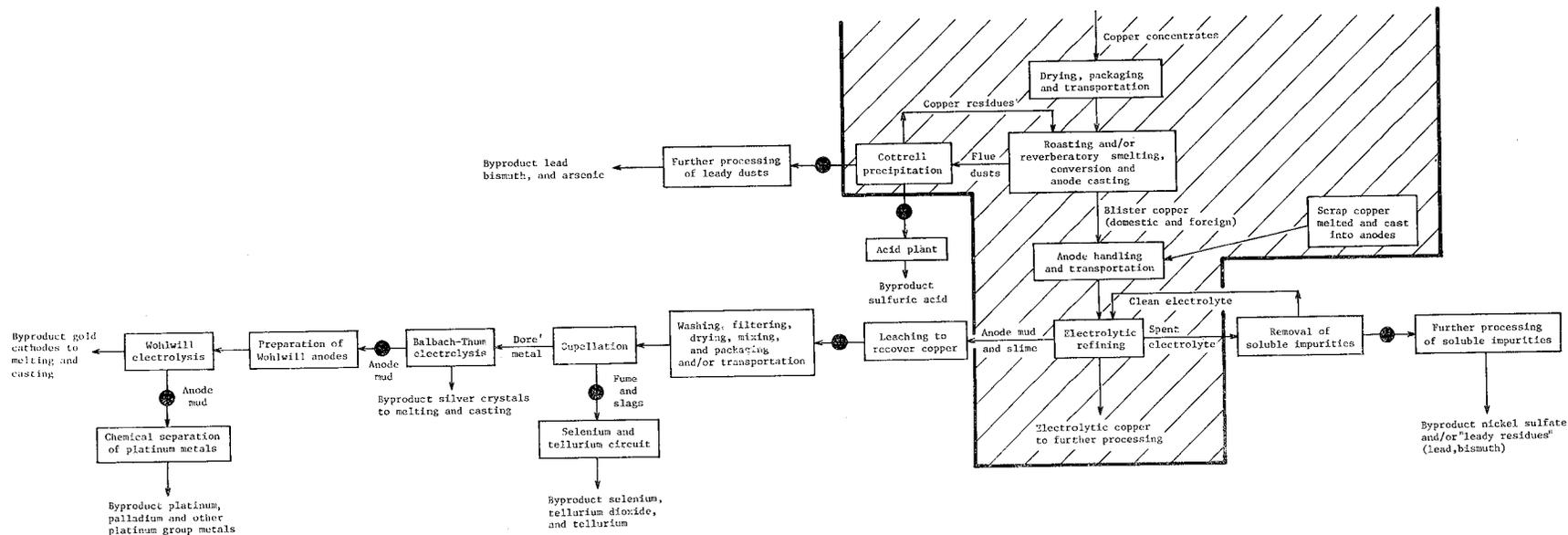


FIGURE 1. - Copper smelting and refining, showing principal byproduct metals.

GENERALIZATIONS ON MATERIALS FLOW IN COPPER SMELTING

Presmelting Processing

Essentially, all sulfide copper ores are concentrated by methods discussed in the Bureau of Mines materials survey on copper (76, pp. 96-101). Minor metals contained in the material are concentrated with the copper. Losses, however, do occur in leaching copper ores. For example, in leaching copper ores in place (in situ) only 50 to 60 percent of the copper is recovered and byproduct metals such as molybdenum, gold, and selenium are left in the rock (34).

As shown later, concentrates and copper precipitates are the most important and abundant primary materials used as feed. The copper precipitates (cement copper) are products of a process described in several metallurgical treatises (20, 38, 52, 61, 86).

Copper Smelting Procedures

As used on sulfide ores, these procedural steps consist of roasting, reverberatory furnace smelting, and converting, followed by fire or electrolytic refining. The various processing steps are described in several publications (20, 25, 38, 56, 76, 86, 89, 93).

To produce mattes with optimum copper contents, ore high in iron and sulfur are roasted under oxidizing conditions (76, p. 106); the method removes sulfur and volatile impurities such as arsenic, antimony, and bismuth.

Some copper smelters consist of roasting, reverberatory furnacing, and converting units; others consist of only reverberatory furnacing and converting sections. In this paper, the plants that feed first to roasters will be referred to as plant type 1, and those that bypass roasting and feed directly to reverberatory furnaces will be known as plant type 2.

Most precipitates are fed to the reverberatory furnaces and some are fed to converters. Some type 1 smelters use precipitates as part of the roaster feed.

Practices, including copper leaching, used at various plants were described in several Bureau of Mines publications, as well as in some of the publications listed previously (76, pp. 101-105; 102).

A few companies have switched recently from reverberatory to electric furnace smelting (for example, Cities Service Co., Copperhill, Tenn., and Inspiration Consolidated Copper, Co., Miami, Ariz). The Anaconda Co. installed a 37,000-kw electric furnace in 1975 to replace some reverberatory furnaces (10).

Dust, fume, and gases produced in roasting, smelting, and converting copper are referred to as metallurgical smoke (76, p. 113). Fume is said to contain principally arsenic, antimony, lead, and zinc oxides. Because the

fume has been condensed when the gases are cooled in the flue system, the mixture of dust and fume is known as flue dust. Cottrell precipitators, instead of baghouses, are used in copper smelters because of the high temperatures and acid gases generated in reverbs and converters; McMahon describes the methods (76, p. 114). Although most materials will be sintered, briquetted, and fed back to the smelting circuit normally at the reverberatory furnace, some materials such as arsenic accumulate in the flue system and are subsequently removed for special treatment. According to Phillips, flue dust in most plants is usually circulated back to the charge (93, p. 660).

Several of the metallurgical texts on copper contain detailed descriptions of the generation, collection, and treatment of dust and fume (20, pp. 128-132; 38, pp. 112-113, 118-122; 86, pp. 237-247).

Slag is produced in (1) the primary smelting of ores and concentrates, (2) in converting matte to blister, (3) in refining blister to anodes, and (4) in melting cathodes to produce wirebar and other finished shapes (57). In an integrated plant, converter slag is returned to the reverberatory furnaces and anode copper and cathode copper slags are returned to the reverberatory furnaces or converters.

DATA ACQUISITION

Data on throughput materials at copper smelters and refineries were obtained through the cooperation of various companies. Efforts to use 1971 as the year on which to base the acquisition of quantitative and assay data were successful in part. Plants with about 46 percent of the 1971 smelter capacity reported for that year (3, p. 30). Most of the remaining data acquired were for 1973 with one smelter sending second-half 1974 material flow and assay data and samples for testing. Companies whose smelters exceeded 90 percent of the published capacities in 1971-73 cooperated in the project (3, p. 30; 9, p. 31).

Practically all copper refinery data accumulated were for 1971. These constituted about 90 percent of the capacities of the fire and electrolytic refineries listed for the year (3, p. 27).

DOMESTIC COPPER SMELTERS AND REFINERIES

Figure 2 and table 1 show the locations of domestic copper smelters and refineries operating during 1971-74 by ownership, type, size, and nature of feed materials.

TABLE 1. - Domestic copper smelters and refineries operating, 1971-74

Map location	Operating company	Type of operation	Capacity, ¹ 1,000 tons	Feed materials
Tacoma, Wash.....	ASARCO Inc.....	(² ³)	600	Smelter: concentrates from mines in Arizona, California, Colorado, Idaho, Nevada, Canada, Peru, and the Philippines; also matte (foreign and domestic), speiss, flue dust (domestic), slag, and others. Refinery: blister and anode copper from Arizona, Texas, Washington, and Peru.
		(⁴)	156	
Anaconda, Mont....	The Anaconda Co.....	(²)	750	Concentrates from mines in Idaho, Utah, Montana, Nevada, and Canada. Also matte from Utah.
Great Falls, Mont.	.....do.....	(⁴)	180	Anaconda anodes.
McGill, Nev.....	Kennecott Copper Corp.	(²)	400	Concentrates and precipitates from mine in Nevada.
Garfield, Utah....	.....do.....	(²)	1,000	Smelter: concentrates and precipitates from mine in Utah; concentrates from mines in Arizona and New Mexico. Refinery: smelter anodes from Arizona and Maryland.
		(⁴)	186	
Miami, Ariz.....	Inspiration Consolidated Copper Co.	(²)	450	Smelter: concentrates and precipitates from mines in Arizona. Refinery: anodes from smelter.
		(⁴)	70	
Hayden, Ariz.....	Kennecott Copper Corp.	(² ³)	420	Smelter: concentrates and precipitates from mine in Arizona.
Do.....	ASARCO Inc.....	(² ³)	960	Concentrates from mines in Arizona and Missouri; precipitates from mines in Arizona; also crude, tailings, flue dusts, and others.
Ajo, Ariz.....	Phelps Dodge Corp....	(²)	250	Concentrates from mines in Arizona and New Mexico; precipitates from mine in New Mexico.
San Manuel, Ariz..	Magma Copper Co.....	(²)	670	Smelter: concentrates from mines in Arizona.
Douglas, Ariz.....	Phelps Dodge Corp....	(⁴)	200	Refinery: anodes from San Manuel smelter. Concentrates from mines in Arizona and New Mexico; refinery slag from New York and Texas.
		(² ³)	700	
Morenci, Ariz.....	.....do.....	(² ³)	900	Concentrates from mines in Arizona and New Mexico.
Hurley, N. Mex....	Kennecott Copper Corp.	(²)	400	Smelter: concentrates and precipitates from mines in New Mexico. Refinery: blister from smelter.
		(⁵)	103	
El Paso, Tex.....	ASARCO Inc.....	(² ³)	576	Concentrates from mines in Arizona, Colorado, Michigan, Missouri, Nevada, New Mexico, Oklahoma, Texas, and Utah; ore from Mexico; precipitates from Arizona, Nevada, and New Mexico; also blister, dross, sludge, speiss, matte, and scrap.

Do.....	Phelps Dodge Refining Corp.	(⁴) (⁵)	420 ⁶ 25	Anodes, blister, and shot from Arizona. High purity anode for fire refinery.
White Pine, Mich..	White Pine Copper Co.	(²) (⁵)	90 90	Concentrates from mines in Michigan and Arizona. Blister from smelter.
Copperhill, Tenn..	Cities Service Co....	(² ³)	90	Concentrates from mines in Tennessee.
Baltimore, Md.....	ASARCO Inc.....	(⁴ ⁷)	318	Blister and anode copper from Arizona, Nevada, New Mexico, Utah, and Peru.
Anne Arundel County, Md.	Kennecott Refining Corp.	(⁴)	276	Blister from Arizona, Nevada, Tennessee, and Peru; anode from Arizona and Utah; scrap and wire.
Carteret, N.J.....	United States Metals Refining Co. (subsidiary of AMAX Corp.).	(² ⁸) (⁴) (⁵)	180 175 85	Smelter: scrap and wire. Electrolytic refinery: anode from New Jersey. ⁹ Fire refinery: blister from Chile and Peru. ¹⁰
Perth Amboy, N.J..	ASARCO Inc.....	(⁴ ¹¹)	168	Blister and anode copper from Arizona, Pennsylvania, Texas, Mexico, and Peru.
Raritan and Perth Amboy, N.J.	The Anaconda Co.....	(⁴ ¹²)	115	Blister from Arizona and Montana; cathodes from Arizona; anodes from Montana; anodes and blister from Chile; slimes from Arizona, Montana, and New Jersey.
Laurel Hill, N.Y..	Phelps Dodge Refining Corp.	(⁴) (⁵)	72 20	Blister from Arizona, Tennessee, and Peru; anodes from Arizona, Michigan, and Pennsylvania; shot copper and others.

¹Smelter: tons of material except for White Pine Copper in tons of product; refinery: tons of copper. From Year-book of the American Bureau of Metal Statistics, 1973.

²Smelter.

³Has roaster(s).

⁴Electrolytic refinery.

⁵Fire refinery.

⁶From Morenci, Ariz., ores.

⁷Closed in December 1975. A new refinery in Amarillo, Tex., by yearend 1975 was producing at a rate of 216,000 tons of copper per year or about 50 percent of planned capacity.

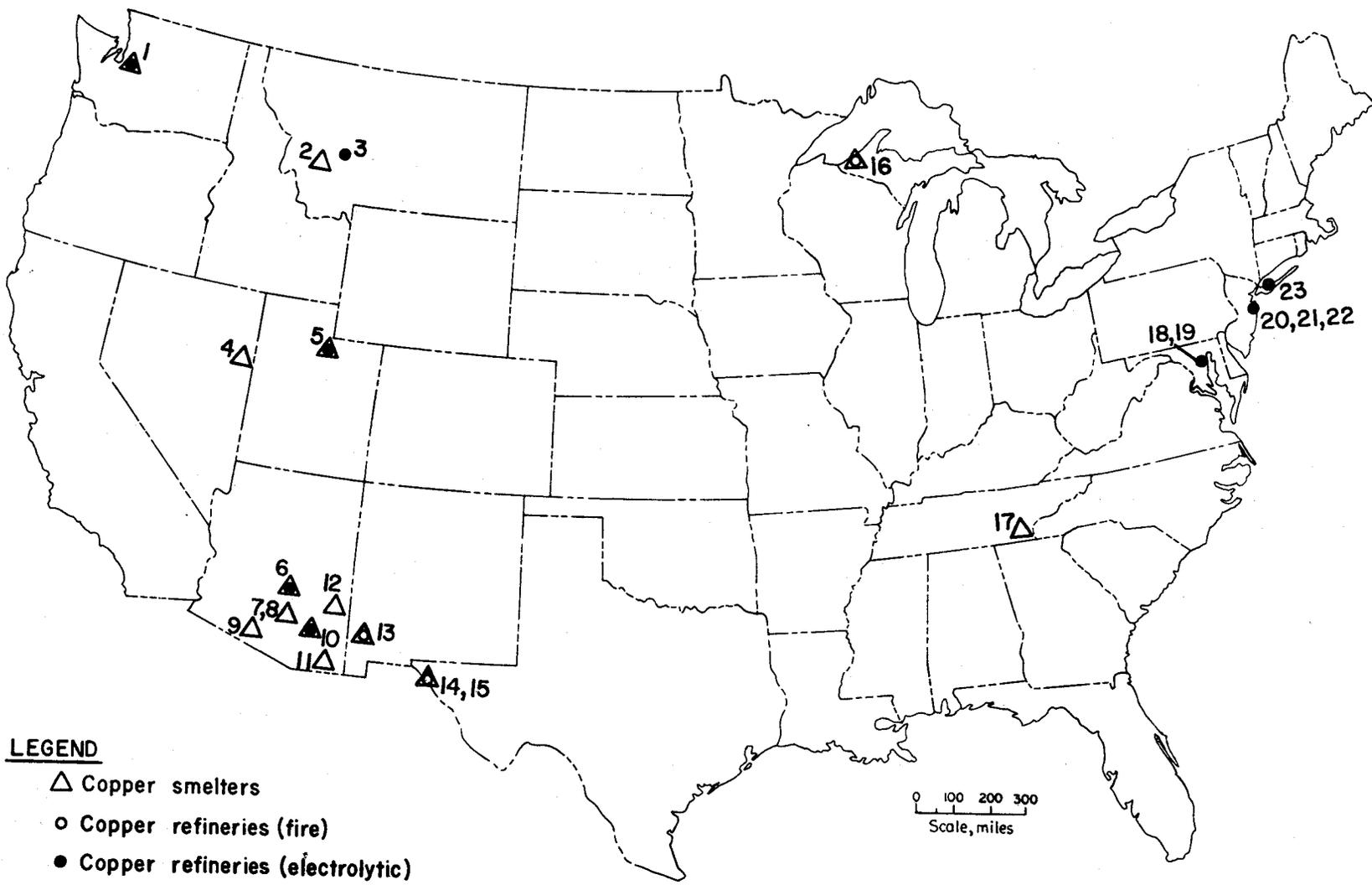
⁸Smelts secondary material.

⁹Anode furnace inputs varied with blister from New Jersey and anodes from Arizona, Michigan, Tennessee, Chile, Mexico, the Republic of South Africa, South-West Africa, and Peru.

¹⁰Precious metals refinery uses slimes from other electrolytic copper refineries.

¹¹Phased out in March 1976.

¹²Closed in midsummer 1975.



LEGEND

- △ Copper smelters
- Copper refineries (fire)
- Copper refineries (electrolytic)

FIGURE 2. - Locations of domestic copper smelters and refineries operating, 1971-74.

Some recent developments affect and modify the data given in table 1. At the ASARCO Inc. (formerly American Smelting and Refining Co.), Hayden, Ariz., smelter in 1973, an anode casting plant was installed to eliminate the casting of blister copper cakes that previously had to be remelted for casting into anodes at the refinery (5, p. 10). The company's Baltimore, Md., refinery was closed in December 1975, after the new Amarillo, Tex., refinery came on-stream in midyear (6, p. 7).

In 1973, the anode copper capacity of the Anaconda, Mont., smelter was raised from 15,000 tons per month to 17,500 tons per month (8, p. 7). Cathode copper capacity at the Great Falls, Mont., electrolytic refinery was raised from 15,000 tons per month to 20,500 tons per month in 1975 (10, p. 16). In October 1974, the first cathodes were produced by the new 36,000-ton-per-year Arbiter plant, which was said to be the first commercial application of a hydrometallurgical refining process based on sulfide ore in the industry (9, pp. 11-12).

The Cities Service smelting operation at Copperhill, Tenn., made blister copper for shipment to refineries and copper pellets (shot) for the production of copper sulfate (15). The firm's reverberatory furnace was replaced by an electric furnace which supplies matte to two converters and permits off-gas recovery of most of the sulfur throughput.

Based on a Finnish development, the first domestic flash smelting copper plant started production on July 1, 1976, at Playas, Hidalgo County, N. Mex. (92, p. 4). Initial capacity was said to be about 1,400 tons of concentrate per day and about 100,000 tons of anode copper per year (90, p. 6; 91, p. 5). In 1976, the plant produced 37,944 tons of copper anodes, mostly from Tyrone concentrates.

SMELTER FEED MATERIALS

Feed materials consisting of ores, concentrates, and copper precipitates from mines and smelter intermediate materials such as calcines, mattes, converter slags, fume and dusts, together with plant scrap and spills are treated as shown in figure 3. The minor metal byproducts are concentrated at various points in the processing and are shown in subsequent flowsheets. Smelter and refinery feed materials to individual plants are shown in table 1.

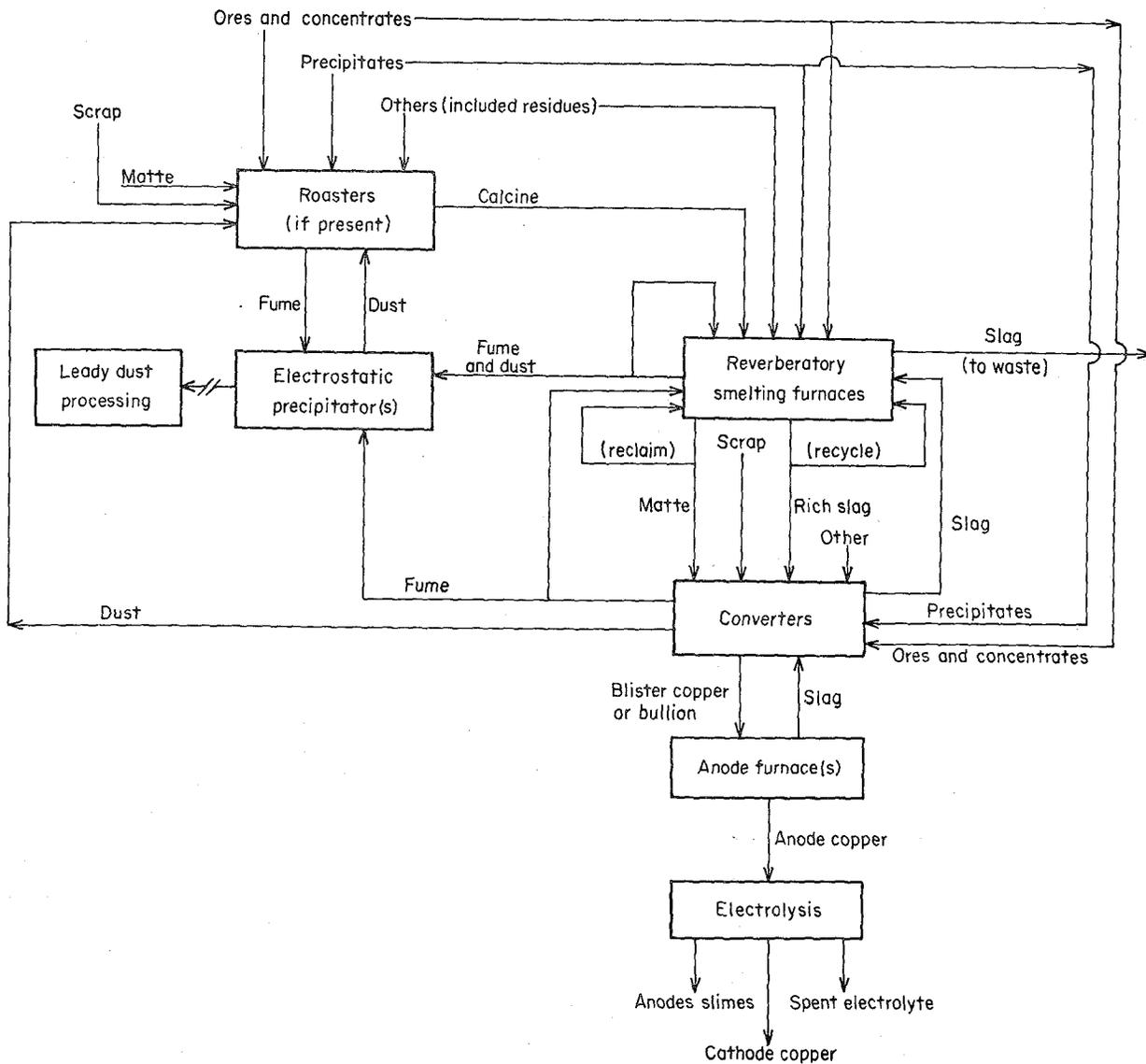


FIGURE 3. - Generalized flowsheet for copper processing.

DISTRIBUTION OF DOMESTIC AND FOREIGN CONCENTRATES

Of the total weight of copper concentrates used (over 5.3 million tons), an estimated 97 percent was of domestic origin. A composite of 1971-74 data indicates that about 50 percent of domestic feed came from Arizona. New Mexico provided about 16 percent; Utah provided almost 14 percent; Montana and Nevada each provided about 7 percent; and Michigan, Tennessee, Missouri, Oklahoma, Colorado, and Idaho provided practically all of the remainder. About 0.2 percent of domestic concentrates could not be identified by State origin.

Approximately 37 percent of foreign concentrates used by one smelter came from the Philippines. Canada provided about 32 percent, of which practically all came from British Columbia and New Brunswick, with a small quantity from the Northwest Territories. The remainder came from South America, largely from Peru.

DOMESTIC SOURCES OF COPPER CONCENTRATES, 1971-74

Arizona

Arizona has been the leading source of copper concentrates used by domestic copper smelters. Data indicated that Arizona mines yielded about 820,000 tons of copper in 1971 and about 859,000 tons in 1974, about 54 percent of domestic primary mine production in each year (47, 82). About 14 percent by weight of domestic concentrates used by smelters in 1971 came from Utah, and about 12 percent came from New Mexico. Other States supplying copper concentrates were Montana, about 7 percent; Nevada, about 6 percent; Michigan, nearly 4 percent; and Tennessee, Missouri, Oklahoma, Colorado, California, and Idaho provided the rest.

As seen in table 2, Arizona had most of the major domestic copper mines. In 1974, Magma's San Manuel mine ranked first in the State and second nationally. This is the only underground copper mine remaining in Arizona. Thirteen of the other major Arizona producing mines are open pits. All Bisbee underground mines were shut down by 1975, after nearly 100 years of operation, because of lower copper prices, ore depletion, and high operating costs (91, p. 5). The Cities Service Copper Cities ore reserves were depleted by 1975, but some copper will continue to be recovered by leaching operations for several years (30, p. 8). The Pinto Valley open pit mine and mill that opened in 1974 operated at design level of 40,000 tons of copper per year during much of 1975.

Major Arizona mines also supplying precipitates to smelters are Ray, Mineral Park, Silver Bell, and Esperanza. Other Arizona mines supplying feed materials for smelters include Christmas (concentrate), San Xavier (cement copper), Sahuarita (concentrate), and Ox Hide and Live Oak (cement copper from heap leaching).

Output from the Kennecott Copper Corp.'s Bingham open pit mine ranked first in the United States, and it was the major reason for Utah being second in supplying copper concentrates. The Mayflower mine, operated by Hecla Mining Co., was shut down in 1972.

TABLE 2. - Arizona: Fifteen leading copper-producing mines operating, 1971-74¹

State rank in 1974	U.S. rank in 1974	Mine	County	Operator	Source of copper in 1972
1..	2..	San Manuel...	Pinal...	Magma Copper Co.....	Copper ore.
2..	3..	Morenci.....	Greenlee	Phelps Dodge Corp.....	Copper ore and copper precipitates.
3..	6..	Ray.....	Pinal...	Kennecott Copper Corp...	Do.
4..	7..	Pima.....	Pima....	Pima Mining Co.....	Copper ore.
5..	8..	Sierrita.....	...do...	Duval Sierrita Corp.....	Do.
6..	11..	Inspiration..	Gila....	Inspiration Consolidated Copper Co.	Copper ore and copper precipitates.
7..	12..	Twin Buttes..	Pima....	Anamax Mining Co.....	Copper ore.
8..	13..	New Cornelia.	...do...	Phelps Dodge Corp.....	Copper and gold-silver ores.
9..	14..	Mission.....	...do...	American Smelting and Refining Co.	Copper ore.
10..	17..	Magma.....	Pinal...	Magma Copper Co.....	Do.
11..	19..	Silver Bell..	Pima....	ASARCO Inc.....	Copper ore and copper precipitates.
12..	21..	Mineral Park.	Mohave..	Duval Corp.....	Do.
13..	22..	Esperanza....	Pima....	.....do.....	Do.
14..	23..	Bagdad.....	Yavapai.	Cyprus Bagdad Copper Co.	Copper ore.
15..	24..	Copper Cities	Gila....	Cities Service Co.....	Copper ore and copper precipitates.

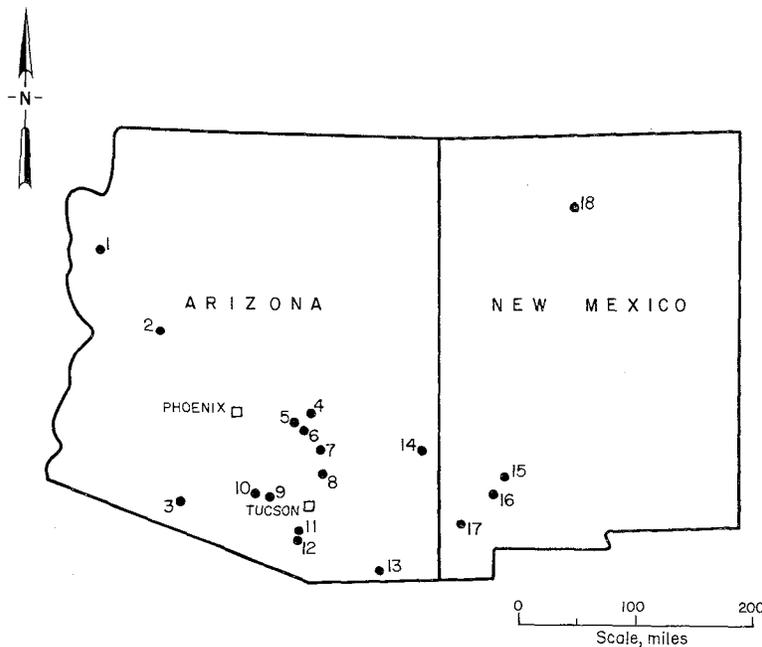
¹Adapted from table 8 in reference 49.

New Mexico mines included Kennecott Copper Corp.'s Chino, Phelps Dodge Corp.'s Tyrone, and U.S. Smelting, Refining, and Mining Co.'s (now UV Industries, Inc.) Continental mine, near Bayard and Fierro. In 1971, these mines supplied about 98 percent of the New Mexico concentrates used by domestic smelters; smaller quantities of concentrates came from Earth Resources Co.'s Nacimiento mine, Federal Resources Bonney-Misers Chest and "85" mines, and Goldfield Corp.'s San Pedro mine.

Other States and mines supplying copper concentrates used by the smelters in 1971 include: Montana, mostly Berkeley pit (5th nationwide in 1973-74); Nevada, Kennecott Copper Corp.'s Nevada mines including the Ruth pit (15th in 1973 and 16th in 1974) at McGill, The Anaconda Co.'s Yerington mine at Weed Heights (16th in 1973 and 15th in 1974), and Duval Corp.'s Battle Mountain (Copper Canyon) operation (25th nationwide in 1972); Michigan, the White Pine mine (8th in 1973 and 10th in 1974); Tennessee, Cities Services' Copperhill operations in Polk County; Missouri, Cominco American's Magmont lead mine and St. Joe Minerals Corp.'s lead mines in the Viburnum Trend (for example, Viburnum and Fletcher); Oklahoma, Eagle Picher's Creta mine; Colorado, mostly from Idarado Mining Corp.'s mine near Ouray; California, Union Carbide Corp.'s operations in Inyo County; and Idaho, Sunshine Mining Co.'s Sunshine mine.

Additional company and mine production data may be found in recent Bureau of Mines Minerals Yearbook chapters on copper and on the various States in which copper is mined; also in the annual, International Directory of Mining and Mineral Processing Operations (44).

In Arizona, the major sources of current production are the large, low-grade ore bodies, mostly of Mesozoic and early Tertiary age, commonly referred to as "disseminated" or "porphyry copper" (11). This type of deposit has been defined as "deposit(s) of disseminated copper sulfide that are in or near to felsic intrusive body..." (34, p. 169). Sulfide minerals were, in order of abundance, pyrite (FeS_2), chalcopyrite (CuFeS_2), molybdenite (MoS_2), and bornite (Cu_5FeS_7). The general features of porphyry copper deposits and the character of the ore bodies are discussed by Anderson (11, pp. 139-144); he includes examples of various features of mining operations.



MINES

- | | |
|---|--|
| 1. Mineral Park | 10. Lakeshore |
| 2. Bagdad and Bruce | 11. Pima, Twin Buttes, Mission, and San Xavier |
| 3. New Cornena | 12. Esperanza and Sierrita |
| 4. Live Oak, Thornton, Red Hill, Ox Hide, and Copper Cities | 13. Lavender Pit and Copper Queen |
| 5. Magma | 14. Morenci |
| 6. Ray | 15. Chino Mines |
| 7. Christmas | 16. Tyrone |
| 8. San Manuel | 17. Bonney, Miser's Chest, and "85" |
| 9. Silver Bell | 18. Nacimiento |

FIGURE 4. - Copper mines of Arizona and New Mexico operating, 1971-74.

The important copper mines in Arizona and New Mexico are shown in figure 4 (13). The open pit Morenci mine near Clifton in Greenlee County, south-eastern Arizona, was the third largest domestic copper producer in 1974. The first copper ore was discovered here in 1872. Although three types of ore bodies exist in the Morenci area, mining since the spring of 1942 has been by the open pit method in a medium-hard monzonite porphyry (76, p. 48). Since 1901, when the rich copper carbonate ores were mined out, chalcocite (Cu_2S) has been the chief ore mineral.

The San Manuel underground mine is in the Old Hat mining district, Pinal County, about 45 miles north-east of Tucson, with its concentrator, smelter, and other facilities in the town of San Manuel, 7 miles south-east of the mine area (76, p. 50). The ore body is a disseminated or porphyry copper deposit in quartz monzonite, monzonite porphyry,

and diabase; the primary minerals are chalcopyrite, pyrite, and quartz, but minor amounts of molybdenite are present. Other minerals include chrysocolla ($\text{CuSiO}_3 \cdot \text{H}_2\text{O}$), chalcocite, and various iron oxides; some cuprite (Cu_2O), native copper, and black copper oxides are present.

The Kennecott Copper Corp.'s Ray mine is in the Mineral Creek mining district, about 80 miles east and slightly south of Phoenix (76, p. 49). After being operated by the underground method since 1911, the operation was converted over a period of 7 years to open pit methods in 1955. The ores in schist and intrusive porphyry consist mainly of supergene chalcocite; the diabase ores contain predominantly chalcopyrite. In the schist, copper silicates, cuprite, malachite [$\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$], tenorite (CuO), and native copper compose 20 percent of the ore.

The ratios of gold to copper and silver to copper in Ray ores were said to be 1:1,000,000 and 1:15,000 (0.029 and 1.94 ounces per ton) (12, p. 620).

The open pit Pima mine (Cyprus Mines, Union Oil, and Utah International) is in the northeast part of the Pima mining district about 20 miles south-southwest of Tucson (76, p. 49). The geology and mineralization of the district, which contains the Pima, Mission, Esperanza, and Twin Buttes mines, was summarized by Ridge (96, pp. 246-248). Production of copper concentrates started in 1957 from a deposit consisting of highly altered limestone with relatively high-grade mineralization and volcanics and sediments with low-grade disseminated mineralization. Chalcopyrite is the principal ore mineral; pyrite and magnetite [$(\text{Fe}, \text{Mg})\text{Fe}_2\text{O}_4$] are accessory. Oxidation products consisting of chrysocolla and tenorite occur a short distance below the bedrock surface.

The Phelps Dodge Lavender pit and underground Copper Queen mines were formerly operated at Bisbee in the Warren mining district (76, pp. 46-47; 91, p. 5). The Lavender pit, which has been stripped since 1951, was closed on December 14, 1974, due to the exhaustion of ore reserves. The district's complex geology and mineralization were described by Bryant and Metz (24) and by Ridge (96, pp. 224-227). The breccias contain chalcopyrite and bornite. The copper deposits in limestone at the Copper Queen were described by Anderson (11, p. 146).

The ore at the open pit New Cornelia mine at Ajo, about 85 miles south-southwest of Phoenix, was said to be mostly hypogene chalcopyrite with some bornite and occasional small amounts of supergene chalcocite and native copper in a monzonite porphyry (76, pp. 48-49). Malachite, azurite [$2\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$], cuprite, tenorite, and chrysocolla were found in the oxidized zone above the hypogene sulfides. In the New Cornelia ores, the ratios of gold to copper and silver to copper were 1:70,000 and 1:6,500 (0.42 and 4.49 ounces per ton) (12, p. 620).

Initial stripping at the Anamax Twin Buttes open pit mine operated by The Anaconda Co. and AMAX began in late 1965; the mine and 30,000-ton-per-day concentrator went into production in September 1969 (11, p. 135). Like the Mission and Pima mines, the Twin Buttes deposit is in silicated limestone,

sandstone, and siltstone cut by sill-like bodies of intrusive quartz monzonite porphyry and rhyolite (11, p. 140).

An oxide-ore treatment plant at Twin Buttes, that began operation in June 1975, will produce 100 tons per day of commercial quality copper cathodes from oxidized copper ore through a leach-electrowinning process (10, p. 14).

The Inspiration Consolidated Copper Co. mines, 6 miles west of Globe, include two large open pit porphyry properties, the Live Oak and the Thornton (76, p. 46). Recent production has come also from the Red Hill mine north of the Live Oak pit. Mineralization is characterized by the supergene ore minerals, chalcocite, and covellite (CuO) (11, p. 142). Important oxide minerals also being mined are chrysocolla, malachite, azurite, and brochantite [$\text{CuSO}_4 \cdot 3\text{Cu}(\text{OH})_2$], which is formed by oxidation of the chalcocite blanket. Primary copper minerals below the blanket are pyrite, chalcopyrite, molybdenite, and some bornite. The gold to copper and silver to copper ratios in ore of the Miami area were said to be 1:1,000,000 and 1:15,000 (0.029 and 1.94 ounces per ton) (12, p. 620).

The open pit mine at Ox Hide, 4 miles west of Miami, and those of the Inspiration division used heap leaching on oxide ores. Minerals at the Ox Hide mine include chrysocolla, malachite, azurite, tenorite, and cuprite. In the Inspiration leaching system, about 30 percent of the copper recovered is in electrowon cathodes; 70 percent shows up as cement copper (37, pp. 63-74).

The ASARCO open pit Mission mine is about 15 miles southwest of Tucson; its mineralization is similar to that in the Pima mine. Like the Pima and New Cornelia, the Mission ore body has a content of copper in the primary or hypogene zone sufficiently high for profitable mining; locally, large pods of chalcopyrite-bearing ore contain 5 to 15 percent copper (11, pp. 140, 144).

The Copper Cities open pit mine, now owned by Cities Service Corp., is 3 miles north of the Miami mine (76, p. 47). The Copper Cities deposit is a mixture of supergene and hypogene sulfide minerals with chalcopyrite and chalcocite disseminated in quartz monzonite and quartz monzonite porphyry (11, p. 143).

Duval Corp.'s Mineral Park open pit mine produces copper and byproduct molybdenite north of Kingman, Mohave County, Ariz. (11, pp. 121, 136). The ore mineralization is similar to that at the Bagdad and Copper Cities deposits in which the ore bodies are in stocks of granodiorite or quartz monzonite that were fractured and mineralized (11, p. 139).

The ASARCO Silver Bell operation, about 40 miles northwest of Tucson, consists of the Oxide and El Tiro open pit mines and a concentrator (76, p. 50). The ore bodies contain supergene chalcocite as a main copper mineral in alaskite, dacite, andesite, and monzonite porphyry.

Duval Corp.'s open pit Esperanza mine, which started producing in March 1959, is 28 miles south of Tucson (76, p. 46). The mine produces copper and molybdenum from a quartz monzonite porphyry ore; minerals consist of supergene chalcocite in a blanket, primary chalcopyrite, and molybdenite.

Just west of the West Esperanza pit, Duval started producing from the Sierrita open pit mine (100). The ore in the Sierrita pit is characteristically like that of the Esperanza, and, as the Sierrita is expanded, it will encompass the west side of the Esperanza West pit.

The Cyprus Bagdad Copper Corp.'s open pit Bagdad mine is in western Yavapai County (76, p. 45). The ore body is a chalcocite-enriched zone in a quartz monzonite porphyry. Copper minerals mined by open pit methods are largely hypogene chalcopyrite with a little chalcocite enrichment (11, p. 143). Compared with precious metal contents of other Arizona ores, the gold of Bagdad seemed to be lower, but silver was higher. The gold to copper and silver to copper ratios were 1:12,000,000 and 1:9,000 (0.002 and 3.24 ounces per ton).

The Magma Copper Co. underground mine at Superior is about 65 miles east of Phoenix in the Pioneer (Superior) mining district, Pinal County (76, p. 47). The mine contains two types of ore bodies, steeply dipping vein deposits, and replacement ore bodies in limestone. The vein deposits, which have supplied most of the ore, contain chalcopyrite with enargite (Cu_3AsS_4), bornite, and hypogene chalcocite. Other vein minerals are tennantite ($\text{Cu}_{12}\text{As}_4\text{S}_{13}$) and digenite (Cu_9S_5) (11, p. 148). The replacement ore bodies, more important in recent years, contain chalcopyrite, bornite, and chalcocite.

The average grade of silver and gold in the ore produced for about 50 years (1915-64) is 1.93 ounces of silver per ton and 0.031 ounce of gold per ton (54).

The Christmas mine, owned by Inspiration Consolidated Copper Co., is in Gila County, 8 miles north of Winkelman and 22 miles south of Globe (9, pp. 45-46). The largest and most common ore bodies have been bedded limestone replacement deposits in which the principal hypogene minerals are chalcopyrite, bornite, magnetite, pyrite, sphalerite [$(\text{Zn},\text{Fe})\text{S}$], and pyrrhotite (Fe_{1-x}S); the supergene minerals include chalcocite, native copper, copper oxides, and copper carbonates (11, p. 147). Other ore bodies are irregular replacement deposits, pipelike or chimney-type deposits, and vein deposits (40).

At the original Lakeshore open pit operation, south of Casa Grande, owned by El Paso Natural Gas Co. and Hecla Mining Co., chrysocolla ore containing 2 percent copper was mined (11, p. 136). Design capacity for the facilities is 9,000 tons per day of sulfide ore and 6,500 tons per day of oxide ore (83). The underground mine and related plant facilities for producing copper precipitates and cathode copper became operational in 1976 (101). At yearend, the oxide ore mine was operating at full capacity; the sulfide ore mine was operating at 40 percent of design capacity.

Cyprus Mines Corp.'s Bruce mine was formerly the Old Dick mine. It is located in the Bagdad area, section 19, T 14 N, R 9 W, Yavapai County. Small quantities of chalcopyrite are present along with appreciable sphalerite and small quantities of galena (PbS) and pyrite (11, p. 151).

California

At the Pine Creek Mine, Bishop district, Inyo County, Calif., owned by Union Carbide Corp., copper is a byproduct of tungsten mining. In 1970, the mine provided over 98 percent of the State's copper output (81). The geology and mineralization at the mine are discussed by Gray, Hoffman, Bagan, and McKinley (51).

Colorado

Two mining operations in Colorado provided copper concentrates to the industry. In 1971-72, the Idarado Mining Co.'s mine and property in the Red Mountain and Upper San Miguel mining districts, 12 miles south of Ouray and 2 miles east of Telluride, accounted for over 60 percent of the State's copper production (70-71). Chalcopyrite, along with sphalerite, galena, and native gold, are the major minerals (59).

The Summitville Joint Venture, Inc., mine in Rio Grande County closed in 1972 because of declining ore reserves. This operation was a joint enterprise of Union Pacific Railroad Co., Cleveland Cliffs Iron Co., and W. S. Moore Co. Although the grade of the ore, processed at a 300-ton-per-day mill only since mid-1971, was estimated at about 3.5 percent copper; gold had been the principal mineral recovered (96, p. 322). It was associated with enargite (the chief copper mineral in primary ores), tennantite ($\text{Cu}_{12}\text{As}_4\text{S}_{13}$), and covellite. Lesser amounts of chalcocite and chalcopyrite were present.

Idaho

Sunshine Mining Co. operates a mine near Kellogg, Idaho, which is known principally for its production of silver and antimony but which also produces small quantities of copper (28). The mine is in the Page-Galena Belt in the Coeur d'Alene district, the geology and mineralogy are discussed in detail by Hobbs and Fryklund (60). The mine produced 3.8 million ounces of silver in 1974 (36).

Michigan

The White Pine operations include a mine, smelter, fire refinery, and other facilities in Ontonagon County, Mich. The copper deposits are at the eastern end of the Porcupine Mountains about 120 miles east of Duluth, Minn. (96, pp. 356-357). The deposit is a large stratiform ore body, 4 to 25 feet thick and several miles across (46).

The copper-bearing beds occur in the upper part of the Copper Harbor Conglomerate and in the lower part of the Nonesuch Shale; both are of the late Precambrian Keeweenawan series. The principal mineral is chalcocite, but the top of the cupriferous zone also contains bornite and chalcopyrite with small quantities of covellite. The ore also contains silver; 40 ounces of silver are recovered for each ton of copper or about 1 part silver per 730 parts of copper (45).

Missouri

The Viburnum Trend (New Lead Belt), the area in which all new producing lead mines in southeastern Missouri are located, is in the form of a narrow, north-south band extending from a few miles north of Viburnum to about 12 miles northwest of Ellington (106). It extends through parts of Crawford, Washington, Iron, and Reynolds Counties. The ore bodies, about 1,100 feet below the surface, occur irregularly along the 40-mile-long trend which is about 5 miles wide. The ore minerals are predominantly galena with chalcopryrite and sphalerite and lesser amounts of siegenite $[(Co,Ni)_3S_4]$. The deposits occur as bedding replacements and in collapse breccias in the dolomite of the Cambrian Bonneterre Formation. St. Joe Mineral Corp.'s Nos. 27-29 mines all recover a copper concentrate as does the Magmont mine of Cominco American, Inc. (117). It was estimated that recoverable copper metal would range between 5 and 6 percent of total lead production.

Montana

Copper deposits of the Butte, Mont., district consist of steeply dipping veins in a fissure system cutting quartz monzonite; replacement ore minerals along the fissures include pyrite, chalcocite, enargite, tennantite, bornite, sphalerite, chalcopryrite, and covellite (115).

In the Berkeley pit, the primary copper sulfides are chiefly enargite and chalcocite with subordinate amounts of bornite (79, p. 1407).

Nevada

In 1971, the Kennecott Copper Corp. (Nevada Mines Div.) phased out its Tripp-Veteran pit after it had opened the New Ruth pit in 1970 to extend the life of the copper property (26-27). The mine is in the Robinson mining district, White Pine County, a few miles west of Ely (76, p. 52). The porphyry-type ore bodies occur in monzonite and monzonite porphyries which have invaded limestones, quartzites, and shales. It was reported that gold, silver, lead, zinc, manganese, and the platinum metals are also present (67, p. 85).

The ratios of gold to copper and silver to copper at Ely were 1:30,000 and 1:10,000 (0.97 and 2.92 ounces per ton) (12, p. 620).

The Anaconda Yerington deposit near Weed Heights, Lyon County, 80 miles southeast of Reno, commenced operating in November 1953, with most of the production first coming from oxide ores (66, pp. 85-86) and then from sulfide ore in late 1961.

The primary sulfides in this porphyry intrusive are pyrite and chalcopryrite but minor quantities of bornite, covellite, and chalcocite are present; the primary ore was said to contain no appreciable gold or silver values (118, pp. 30-34). The principal oxidation mineral is chrysocolla.

New Mexico

At the Chino Mines Div., Kennecott Copper Corp., copper ore is mined, concentrated, smelted, and refined. The mine and leach-precipitation plant is at Santa Rita in the Central mining district of Grant County, N. Mex., and the mill and smelter are at Hurley, about 9 miles from the mine (76, p. 53). The ore deposits are of two types: a disseminated or porphyry-type in igneous and sedimentary rocks in which copper mineralization consists mostly of chalcocite and minor native copper, associated locally with abundant molybdenite; and a limestone replacement ore, usually with little or no enrichment, in which the chief ore mineral, chalcopyrite, occurs with magnetite, pyrite, quartz, and calc-silicate minerals (62, 98). Much of the copper produced at the Chino mine is precipitated from leach solutions pumped to and onto the leach dumps.

The Bonney, Miser's Chest, and "85" mines are in vein deposits in the Lordsburg district in Hidalgo County (62, p. 171; 76, p. 53). At the Bonney and Miser's Chest mines in the southern part of the district, the veins cut basalt and contain chalcopyrite as well as gold and silver in a barite (BaSO_4) and carbonate gangue. The Emerald vein of the "85" mine was discussed by Anderson (14, p. 87).

Earth Resources Co.'s Nacimiento copper mine and 3,000-ton-per-day mill near Cuba, Sandoval County, began producing in 1971, and output was raised to 4,000 tons per day in 1972 (104, 107-108). The copper occurs in Permian and Triassic red beds which are reddish brown sandstones and shales containing less than 1 percent copper. Minerals include chalcocite, bornite, covellite, and secondary copper minerals (34, p. 175). The operation was closed in February 1975 because of depressed copper prices.

Phelps-Dodge Tyrone property is in the Big Burro Mountains, Grant County, about 10 miles southwest of Silver City (76, p. 53). Chalcocite is disseminated regularly through large masses of fractured country rock or concentrated along strong veins or shear zones.

In 1970, Goldfield Mining Co. started developing the old San Pedro mine, northeast of Albuquerque (104). The deposits consist of carbonate rocks in which copper is associated with lead and zinc (62, p. 170).

Oklahoma

The Eagle Picher Industries, Inc., Creta mine in southwestern Jackson County, Okla., operated from September 1965 until it was closed in March 1975 because of economic conditions (109-110). Ore is mined there by open pit methods from a red bed copper shale 6 to 10 inches thick, and concentrates are shipped to an El Paso, Tex., smelter. The copper minerals of the type of deposit typified by the Creta operation generally occur in gray to light brown members in red sandstones and shales of Permian, Triassic, and Jurassic age (105). At the Creta deposit the copper occurs in flat-lying rocks of the Permian Flowerpot shale. Malachite occurs in outcrops but chalcocite is the main ore mineral which is preserved under a shallow cover less than 40 feet thick covering a considerable area.

The Bureau of Mines studied the possibility of exploiting and extracting copper from red beds such as occur at Creta (18, 111). Stroud and others reported that the silver content of the ore was 1 to 3 ounces per ton.

Tennessee

Recently, Cities Service Corp. has operated the Cherokee, Boyd, Calloway, and Eureka mines in the Ducktown Basin mining district, Polk County, in extreme southeastern Tennessee (15-16). The deposits are in massive sulfides extending up to thousands of feet on the strike and up to 300 feet thick (76, p. 54). The minerals include pyrrhotite, pyrite, chalcopyrite, magnetite, and some chalcocite.

The Cities Service copper smelter at Copper Hill uses copper concentrates from the Ducktown ore deposits. The eight massive sulfide ore bodies contain the ore minerals pyrrhotite (the most abundant), pyrite, chalcopyrite, sphalerite, and magnetite in Precambrian highly folded and metamorphosed graywacke, graywacke conglomerate, mica schist, chlorite-garnet schist, and staurolite schist (77).

Small quantities of arsenic, selenium, gold, and silver were determined in copper concentrate from Copper Hill.

Utah

The Utah Copper open pit mine of Kennecott Copper Corp., about 20 miles southwest of Salt Lake City, is the largest copper mine in the United States, and the second largest copper producer in the world. Copper ores, typical of disseminated copper deposits, are found in the Bingham stock which is composed of quartzites, limestones, and shales intruded by monzonite. The monzonite, which has been intensely shattered and altered, contains the primary ore minerals, chalcopyrite and pyrite, and some bornite and molybdenite. All the primary sulfide, oxide, and supergene minerals of the Bingham ore body are shown (88).

With respect to contents of gold and silver in Bingham ores, the ratios of each to copper were 1:40,000 and 1:4,000 (0.73 and 7.29 ounces per ton) (12, p. 620). Recent assays on concentrates from the Bingham area, acquired for the byproduct study, showed gold to copper and silver to copper ratios to be about 1:22,500 and about 1:2,650 (1.3 and 11.01 ounces per ton).

The Mayflower mine, which was closed in 1972, was in the southeastern part of the Park City district, Wasatch County, about 20 miles east-southeast of Salt Lake City and 8 miles north of Heber City (97). The primary ore bodies contain the copper minerals chalcopyrite, chalcocite, and bornite; oxidized copper minerals are mostly azurite and malachite.

FOREIGN SOURCES OF COPPER CONCENTRATES, 1971-74

Canada

British Columbia

In the Province of British Columbia, Anaconda Britannia Mines, a subsidiary of Anaconda Canada, Ltd., supplied concentrates and precipitates on toll to The Anaconda Co. smelter, Anaconda, Mont. It also supplied concentrates to the ASARCO, Tacoma, Wash., smelter.

The mines are at Britannia Beach (49°36.6'N, 123°08.5'W) in the Vancouver mining division, 40 miles by road north of Vancouver on the landward side of Howe Sound. Some of the older ore bodies have been closed for years, and more were closed recently when the Victoria and Bluff bodies were exhausted and shut down in 1970 (96). Effective November 1, 1974, the operation of the mine and concentrator was discontinued because of the combination of limited ore reserves, rising costs, and reduced copper prices (9, p. 14).

The geology of the Britannia mine was discussed in a British Columbia Government publication (21, pp. 233-246). Sulfide minerals include pyrite (the principal mineral), chalcopyrite, and sphalerite with minor galena, tennantite, and tetrahedrite [(Cu,Fe)₁₂Sb₄S₁₈].

New Brunswick

Because of the exhaustion of minable open pit copper ore, the Caribou copper mine and concentrator (jointly owned by Anaconda and Cominco, Ltd.) near Bathurst, New Brunswick, was suspended on October 1, 1974 (9, p. 14).

Northwest Territories

Although it is considered primarily a uranium-silver deposit, Echo Bay Mines, Ltd., Port Radium, Northwest Territories, supplied copper concentrates to the ASARCO, Tacoma, Wash., smelter. Copper sulfides include chalcopyrite; cobalt-nickel, arsenides, and sulfides also are present (96, p. 52).

A small amount of copper concentrates came from a mine and mill operated by Terra Mining and Exploration, Ltd., in the Camsell River area, 27 miles south of Port Radium (28, p. 364).

Peru

The Quiruvilca mine and mill of Northern Peru Mining Corp. (a wholly owned subsidiary of ASARCO) in the Province of Santiago de Chuco, Department of Libertad, Peru, sent concentrate to the ASARCO, Tacoma, Wash., smelter. Copper veins, which were said to occur in a small portion of a large mineralized area, were the foci of the larger operations in this district (76, p. 63).

Philippines

Lepanto Consolidated Mining Co. in the Mountain Province, North Central Luzon, the Philippines, shipped concentrates to the ASARCO, Tacoma, Wash., smelter. Because of their high arsenic content, its concentrates are treatable only at the ASARCO smelter and at a Peruvian smelter (23).

The operation is the largest vein copper mine in the country with the ore minerals consisting of luzonite, enargite (Cu_3AsS_4), and precious metals. The ore contains small quantities of chalcopyrite, bornite, covellite, chalcocite, and tetrahedrite and averages nearly 3 percent copper and 0.12 ounce of gold per ton (84, 120). The enargite contains about 85 to 90 percent of the copper in the ore (85).

Because of its high arsenic content (9 to 10 percent), Lepanto concentrate has been heavily penalized at the smelter, and studies have been conducted to determine the possibility of volatilizing the arsenic sulfide from the enargite (19).

PUBLISHED ASSAY DATA ON SMELTER MATERIALS, 1971-74

A 1974 report to the U.S. Environmental Protection Agency (EPA) presented typical data, including analyses, for domestic copper smelters (75). The so-called "dirty smelters" which handle materials with arsenic content of more than 0.2 percent were discussed. The listed average 1971-73 level of impurities in concentrates used at domestic smelters were as follows: 0.003 to 4.2 percent arsenic for nine plants with one concentrate containing a maximum of 12.8 percent arsenic, 0.0005 to 0.03 percent selenium for eight plants, and 0.0001 to 0.08 percent tellurium for seven plants. In the same period, precipitates at one plant contained 0.37 percent arsenic. Lead plant byproducts used as feed at three plants include speiss, residues, and matte (lead and zinc). The speiss in 1971-73 ranged from 11.47 to 19.8 percent arsenic, 0.007 to 0.04 percent selenium, and 0.008 to 0.048 percent tellurium. Residues processed at one plant contained 7.5 percent arsenic. Matte used at two plants ranged from 0.05 percent arsenic (in zinc matte) to 2.0 percent arsenic (in lead matte), 0.03 percent selenium (in lead matte) to 0.09 percent selenium (in zinc matte), and 0.002 percent tellurium (in zinc matte) to 0.061 percent tellurium.

Reverts at four smelters contained 0.07 to 21.4 percent arsenic; those at one plant contained 0.02 percent selenium and 0.002 percent tellurium. The average smelter charge ranged from 0.002 to 5.2 percent arsenic for eight plants, 0.0003 to 0.015 percent selenium for six plants, and 0.0006 to 0.0025 percent tellurium for five plants.

SOLICITED ASSAY DATA, 1971-74

Assay data needed in this study to determine the various inputs of minor metals included in concentrates and other feed materials and in various intermediate and product materials were obtained from the companies directly or, where data were not available, samples for additional assays were solicited from the firms. There was a wide range of response from industry.

Arsenic in Concentrates

In assays of more than 20 Arizona concentrates, mostly from 1973 production, the arsenic content ranged from 0.003 to 0.68 percent. Three assays averaged as high as 0.35 percent arsenic, most were much lower.

In two Colorado concentrates, there was an extremely wide range (from 0.02 to nearly 7 percent) in arsenic content. One Idaho location produced a high-arsenic concentrate; whereas a concentrate from one Michigan company was said to contain only 0.003 percent arsenic, another concentrate assayed 0.4 percent arsenic. Concentrates from two Missouri firms averaged a little more than 0.5 percent arsenic; concentrates from two Nevada producers averaged nearly as much, but a concentrate from a third property assayed 0.82 percent arsenic. Most of the New Mexico concentrates contained about 0.2 to 0.35 percent arsenic, but one was very low (about 0.0002 percent). Tennessee concentrate was extremely low in arsenic. Oklahoma and Utah concentrates averaged about as high in arsenic as the higher-arsenic-bearing Arizona concentrates.

Assays on concentrates from five foreign sources, two each from Canada and Peru and one from the Philippines, averaged about 9.5 percent arsenic. Most of this was in the Peruvian and Philippines concentrates which averaged 10.7 percent arsenic.

Deposits at Butte, Mont., as well as some in Peru and that at Lepanto in the Philippines, are known to be important for their arsenic contents (53, p. 54).

Selenium in Concentrates

Assays were available for selenium in about 20 Arizona concentrates in which the selenium content ranged from 0.002 to 0.14 percent. The sample containing 0.14 percent selenium was the only one greater than 0.1 percent. In about half the Arizona concentrates, the selenium appeared to range between 0.01 and 0.02 percent. Other higher selenium percentages were in concentrates from Tennessee (0.04 percent) and Nevada (0.028 percent). Data available on foreign concentrates ranged from 0.005 to 0.034 percent selenium, the latter on a concentrate from the Philippines.

Tellurium in Concentrates

Seventeen Arizona concentrates contained tellurium with a low of 0.0003 percent; most were less than 0.004 percent tellurium.

Other States for which tellurium data were available include California, one; Colorado, two; Idaho, one; Nevada, two; and Utah, three. The highest content (0.053 percent tellurium) was in a Colorado concentrate. Assays for the other concentrates ranged from 0.0005 to 0.018 percent tellurium.

The foreign concentrate with the highest tellurium content (0.066 percent) was from the Philippines.

Gold in Concentrates

Twenty-one assays on Arizona concentrates showed gold contents ranging from a trace through 0.002 to as much as 0.126 ounce per ton. About two-thirds of the assays showed 0.01 ounce per ton or less. Assays on concentrates from other States were available for California, one; Colorado, two; Idaho, one; Michigan, one; Nevada, two; New Mexico, one; Tennessee, one; and Utah, concentrates from two mills. The gold content of concentrates from these States ranged from trace amounts in Michigan and Tennessee, through about 0.03 ounce per ton in the New Mexico concentrate, to as high as 0.577 ounce per ton in a Colorado concentrate, and 0.65 ounce per ton in a Nevada concentrate. A Philippine concentrate contained 1.57 ounces of gold per ton.

Silver in Concentrates

More data (28 assays) were available for silver in Arizona concentrates than for any of the other minor or precious metals included in the byproduct study. Arizona concentrates ranged from about 0.8 to 4.65 ounces of silver per ton. Assays on silver were available for concentrates from California, one; Colorado, two; Idaho, one; Michigan, one; Missouri, three; Nevada, two; New Mexico, one; Tennessee, one; and Utah, two. Some of these concentrates were considerably higher in their silver contents than were those from Arizona. Almost 120 ounces per ton were present in an Idaho concentrate. Colorado concentrates also were high in silver content, those for Missouri and Tennessee were low.

Silver assays were available on two Canadian concentrates (one as high as 592 ounces per ton), on two South American concentrates (averaging about 45 ounces per ton), and on a Philippine concentrate which contained considerably less than concentrates from Colorado, Idaho, and Nevada.

Platinum and Palladium in Concentrates

Palladium was detected in five domestic concentrates, either by the producing companies or in samples for assay provided by the firms. In a total of nine palladium determinations, the highest was 0.003 ounce per ton. The other eight assays were between 0.001 and 0.002 ounce of palladium per ton.

Byproduct Metals in Precipitates

Although relatively little arsenic, selenium, tellurium, or precious metals are recovered in the production of precipitates, assays of precipitates do show small quantities of these elements.

The arsenic content of 20 domestic samples of precipitates ranged from 0.0046 to 0.28 percent. Selenium content of precipitates from six samples ranged from 0.0005 to 0.007 percent. Assays of tellurium in precipitates were available from six plants. Three plants reported that if tellurium were present, it was below the limits of detection or less than 0.0002 percent. Precipitates processed at one smelter contained 0.003 percent tellurium.

An earlier report (61, p. 826) lists a typical analysis of precipitates to contain 0.045 percent arsenic, 0.0044 percent selenium, and 0.0046 percent tellurium.

Gold in precipitates from only two plants showed contents of 0.01 and 0.02 ounce of gold per ton. Assays of silver in two samples of precipitates smelted in 1973 were 0.1 ounce per ton and a trace. Two other samples of precipitates smelted in 1971 contained 0.31 and 0.58 ounce of silver per ton.

The richest of two copper precipitates received at an Arizona smelter showed 0.001 ounce of platinum-group metals per ton.

ARSENIC, 1971-73

Arsenic in Concentrates, Precipitates, and Other Feed to Type 1 Plants

Figure 5 shows a flowsheet for roasting which, when used with the appropriate table, indicates the flow of the various minor metals through the roasting process; likewise, each table shows quantities and assays on the pertinent minor metal. All of the tables (3-35) contain quantities and assays based on 1971-73 data.

Input and output of arsenic in feed materials to roasting are shown in table 3. The difference between known arsenic in input and in output (calcines and dust) is due primarily to the lack of assay data on the output materials.

TABLE 3. - Arsenic in type 1 plants operating, 1971-73--roaster feed

Item	Total quantity, tons	Plants with assay data				Indicated quantity of arsenic
		No.	Percent of total quantity	Assays, ounce per ton Range	Average	
Feed to roaster: ¹						
Concentrates.....	2,353,960	7	91.8	0.0005-10.8	0.5	² 10,845.8
Speiss.....	13,579	2	100	11.9 -17.83	15.1	2,049.6
Matte.....	8,072	1	96.4	.63 - 3.76	1.46	113.8
Dust.....	9,044	1	33.5		15.7	475.3
Pyrite.....	4,001	1	100		3.3	132.4
Residues and sludges.....	3,091	2	100	.3 -15.68	2.1	66
Precipitates.....	56,962	4	77.4	.0095- .33	.086	37.7
Copper ores.....	35,272	1	3	.14 - .26	.2	2
Slags (other).....	369	1	100		.3	1.0

¹Total tons of roaster feed materials for which there were no assays for arsenic are: flux 119,888, tailings 78,372, scrap 5,196, refinery slag 1,932, other (including slag and matte shells) 34,322.

²Large tonnage, mostly from one plant.

PLANT TYPE 1

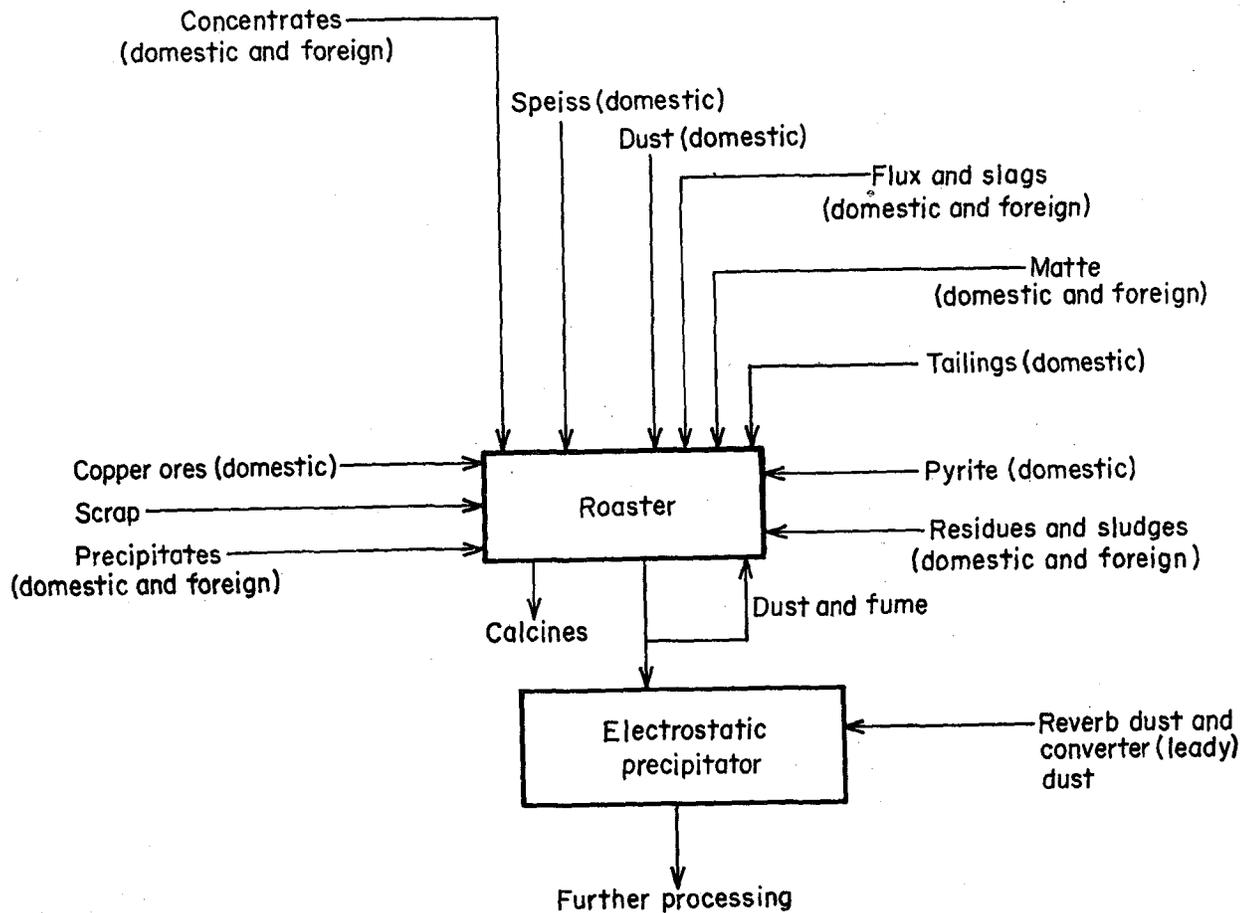


FIGURE 5. - Roasting.

About 2,270 tons of the arsenic in domestic concentrates roasted at seven plants composed about 44 percent of the total known arsenic in domestic materials fed to roasting. Almost all of the arsenic in roasted domestic concentrates was accounted for in the feed to five plants. About 72 percent of the arsenic in domestic concentrates came from Arizona; most of the rest was from Nevada and New Mexico sources (about 11 and 8 percent). Lesser quantities came from Missouri, Colorado, Oklahoma, Idaho, Utah, Michigan, and Tennessee (the last two in minor amounts).

Concentrates accounted for nearly all of the arsenic in foreign materials fed to roasting; only a small amount was in mattes and precipitates. A large quantity of arsenic was present in foreign concentrates, of which practically all came from Peru and the Philippines. The percentages of arsenic in Peruvian and Philippines concentrates are comparable with the published data (9 to 10 percent) on enargite concentrate (19). Canadian matte containing arsenic was fed to roasting at one plant.

Arsenic in Roaster Calcines

Only two plants provided quantitative and assay data on calcines for determining quantities of minor metals present. The two plants produced 1,162,433 tons of calcines (table 4). This is about 93 percent of the total arsenic in concentrate feed to the two plants. These data are insufficient to make a reliable estimate of arsenic contained in roaster calcines.

TABLE 4. Arsenic in type 1 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of arsenic
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Feed to reverberatory: ¹						
Calcines.....	² 1,859,879	2	62.5	0.004 -0.046	0.04	413.6
Converter slag....	1,180,309	2	57.6	.0005- .005	.002	13.9
Dust (mostly converter Cottrell).	10,710	1	94.1		.103	10.4
Slag and Matte shells.....	1,164	1	100		.27	3.1
Concentrates.....	475,380	1	100	.0035- .4	.014	68.5
Reverberatory products: slag discarded.....	1,923,983	2	63.6	.0015- .028	.015	187

¹Total tons of reverberatory feed materials for which there were no assays for arsenic are: precipitates (cement copper) 16,911.

²Of these 16.7 percent are mixed with dust at one plant.

Minor Metals in Dust and Fume

Because gaseous and volatile emissions emanate from various parts of copper processing (roasting, reverberatory furnacing, and converting), because recycling of dust and fume is carried out to different extents in plants, and because quantities and assay data often are not available, the total of the minor metals in these materials cannot be accurately determined.

Of the elements arsenic, selenium, and tellurium collected in dusts and fume, arsenic is the most predominant. All roaster dusts are recycled or sent to other parts of processing. In type 1 plants, data indicated that converted Cottrell (lead) dusts contained the greater quantities of the minor metals compared with those calculated from meager data on reverberatory dusts.

Two type 1 plants provided no usable data for dust and fume, although one produced nearly 31,000 tons of flue dusts. A third type 1 plant provided reverberatory furnace and converter dust assay data for all of the elements in the study except platinum and palladium.

In contrast with type 1 plants, all type 2 plants provided quantitative and assay data on reverberatory furnace and converter emissions. Minor metal contents in reverberatory and converter dusts from type 2 plants were usually less than those in type 1 plants.

Arsenic in Dust and Fume

In plants of type 1, the known quantity of arsenic in dust and fume was about 1,409 tons mostly in converter dust (table 6). Three smelters provided arsenic assays of converter dusts which are also shown in table 6. One company provided no quantitative or assay data on dusts.

In type 2 smelters (table 7) most of the arsenic in fume and dust was in converter emissions. Arsenic in reverberatory dusts ranged from 0.018 to 7.278 percent; arsenic in converter dusts ranged from 0.0017 to 4.77 percent.

Minor Metals in Reverberatory Smelting Furnace Feed

As shown in table 4, only one type 1 plant fed concentrates to its reverberatory furnaces. However, plants also fed calcines, recycled converter slag, slag and matte shells, and roaster flue dust to reverberatory smelting, but assay data were limited. One plant used a calcining procedure and fed a wet mixture, concentrate, precipitates, and recycled secondaries (dusts) to its reverberatory furnaces. This latter plant is not shown on the tables. Another plant fed a mixture of calcines and dust. One type 1 plant fed concentrates to both roasters and reverberatory furnaces. This plant also fed calcines, converter slag, and precipitates to its reverberatory furnaces.

There are six type 2 plants at which feed consisted of concentrates, precipitates, converter cleanup, dusts and slags, refinery residues, pyrites (at one plant), and anode slimes cleanup (at one plant) (table 5).

TABLE 5. - Arsenic in type 2 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of arsenic
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Feed to reverberatory: ¹						
Concentrates.....	1,951,680	5	86.4	0.0002-0.154	0.065	1,103
Converter slag.....	967,558	5	100	.0005- .01	.005	52
Precipitates (cement copper).....	133,559	4	96.9	.0046- .025	.013	17
Other (including pyrite). Residues (refinery and other).....	23,780	1	80.8		.002	.4
Dust.....	10,666	2	100		.38	41
Anode slimes.....	3,850	1	75.8		.059	2
Reverberatory products: slag (discarded).....	626	1	100		.0007	(²)
	1,291,892	4	87.5	.0005- .006	.0047	52

¹Total tons for reverberatory feed materials for which there were no assays for arsenic are: flux 15,345.

²Trace amount.

Arsenic in Reverberatory Furnace Feed

Reverberatory furnace smelting is an integral part of copper processing at three types of plants: plant types 1 and 2 and one other that uses a drying step preliminary to reverberatory smelting.

From calculations made with available quantitative and assay data, it appears that about 1,725 tons of arsenic were introduced to reverberatory furnaces, and that about 70 percent of this was introduced at type 2 plants.

In type 1 plants, about 510 tons of arsenic was known and 82 percent of this was in calcines, about 13 percent in concentrates, and the remainder in slag and converter dust. In the type 2 plants, of the 1,215 tons of arsenic, 91 percent was introduced in concentrates; about 5 percent was in precipitates and residues, 4 percent in slag, and a small amount in dust and pyrites.

Minor Metals in Reverberatory Furnace Products

Minor metal data were available for matte and slag, with some for matte shells and skulls at one plant and for a rich slag at another. Because most of these materials continue in process, as can be seen in figure 6, tables 4-5

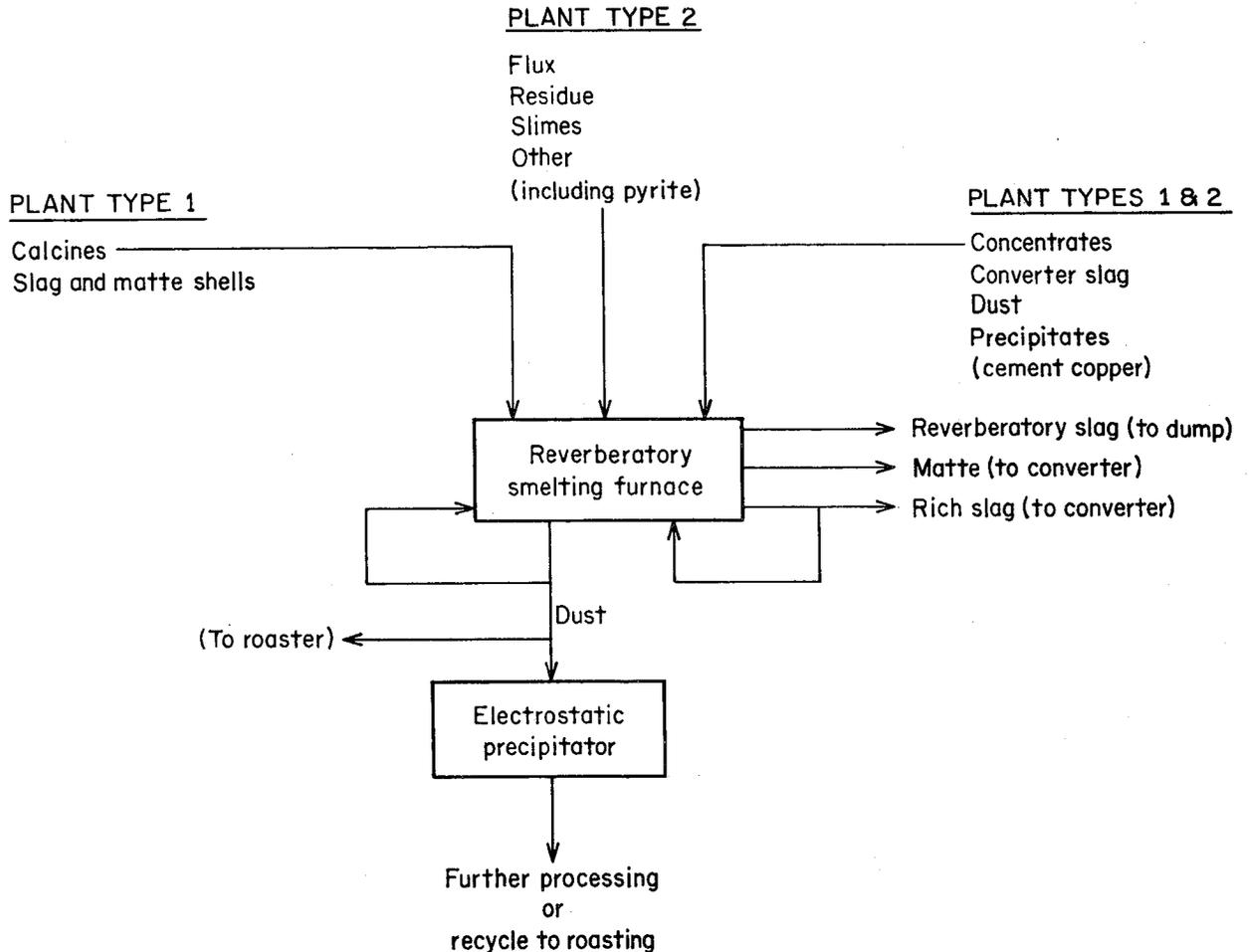


FIGURE 6. - Reverberatory smelting.

show only known throughput of arsenic in discarded slag. Other tables present pertinent minor metal data in reverberatory slag at both type plants.

Arsenic in Reverberatory Furnace Products

Although throughput data are shown only for slag, mattes produced in reverberatory furnaces contained 0.0015 to 0.02 percent arsenic at type 1 plants and 0.0007 to 0.027 percent arsenic at type 2 plants. One of the type 2 plants indicated matte shells and skulls assayed about 0.13 percent arsenic.

The preceding arsenic assays on copper mattes are well below that of 0.045 percent quoted by Bray (20, p. 104) for 1941 and likely indicated better metallurgical practice.

Minor Metals in Converter Feed

As shown in figure 7 and tables 6-7, converter feed usually consists of molten matte with siliceous fluxing ores or silica rock that sometimes contain significant quantities of minor metals. Other materials such as blister and enriched slags from fire refineries are used also. The matte input is usually about 90 percent of all converter input excluding recycled materials. The total quantity of matte fed to all smelters was reported at about 3.5 million tons.

TABLE 6. - Arsenic in type 1 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of arsenic
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Converter feed: ¹						
Blister.....	20,284	2	100	0.008 - 0.019	0.11	23
Matte (reverb)... ²	1,919,296	3	50.3	.0015- .02	.005	88.7
Matte (lead).....	19,231	1	100		1.05	202
Flux.....	76,760	1	30		.26	60.9
Converter products: ³						
Blister (anode)..	709,916	6	90.5	.0004- .29	.1	629
Dust:						
Cottrell.....	26,354	3	90.5	.103 -10.91	3.6	867
Flue and other (to copper roasters).....	8,736	2	100	.32 -10.91	6.2	542
Slag.....	1,180,309	2	57.6	.0005- .005	.002	13.9

¹Total tons of converter feed materials for which there were no assays for arsenic are: scrap 23,580, byproducts 7,570, dust 41,946, scale 240, slag 1,604, refinery furnace slag 6,165, precipitates 5,848, and ores 33,836.

²One plant had assay data for arsenic but no weights.

³Total tons of converter products for which there were no assays for arsenic are: matte and slag reverts 19,837.

TABLE 7. - Arsenic in type 2 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of arsenic
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Converter feed: ¹						
Matte.....	1,523,170	5	94.0	0.0014-0.018	0.0089	127
Matte shells and skulls.....	41,908	1	100	.012 - .13	.079	33
Flux.....	122,348	1	55.2		.0025	1.7
Concentrates.....	17,264	2	100	.0165- .154	.148	25.6
Cement copper (including precipitates)....	17,275	1	80.9	.007 - .022	.012	1.7
Dust (reverber flue) Residues ²	325	1	100		.3	1.0
Anode slimes cleanup.....	123	1	100		.0007	.09
Converter products: ³						
Blister (anode)...	581,622	4	82.1	.0001- .029	.0176	84.1
Slag.....	967,558	5	100	.0005- .0055	.0053	51.7
Dust ⁴	10,023	3	67.0	.0017-4.77	1.908	128.1

¹Total tons of converter feed materials for which there were no assays for arsenic are: refinery slag 2,900, rich slag 2,898, and scrap 2,172.

²There were no data for residues.

³Total tons of converter products for which there were no assays for arsenic are: scrap regulus and cleanings 84,155, and converter cleanings 5,360.

⁴Includes leady dust.

The one plant which used its roasters to dry materials prior to reverberatory smelting indicated it used reverberatory matte, ore, slag, scrap copper and brass, and scrap and reject anodes as converter feed.

Arsenic in Converter Feed

The total known quantity of arsenic in converter feed at type 1 plants was 375 tons of which about 24 percent was in copper matte and 54 percent was in lead matte used by one plant. The rest of the known arsenic in type 1 plant feed was in blister copper and fluxing ores used by two plants. Neither of these two plants, however, provided assay data on matte used.

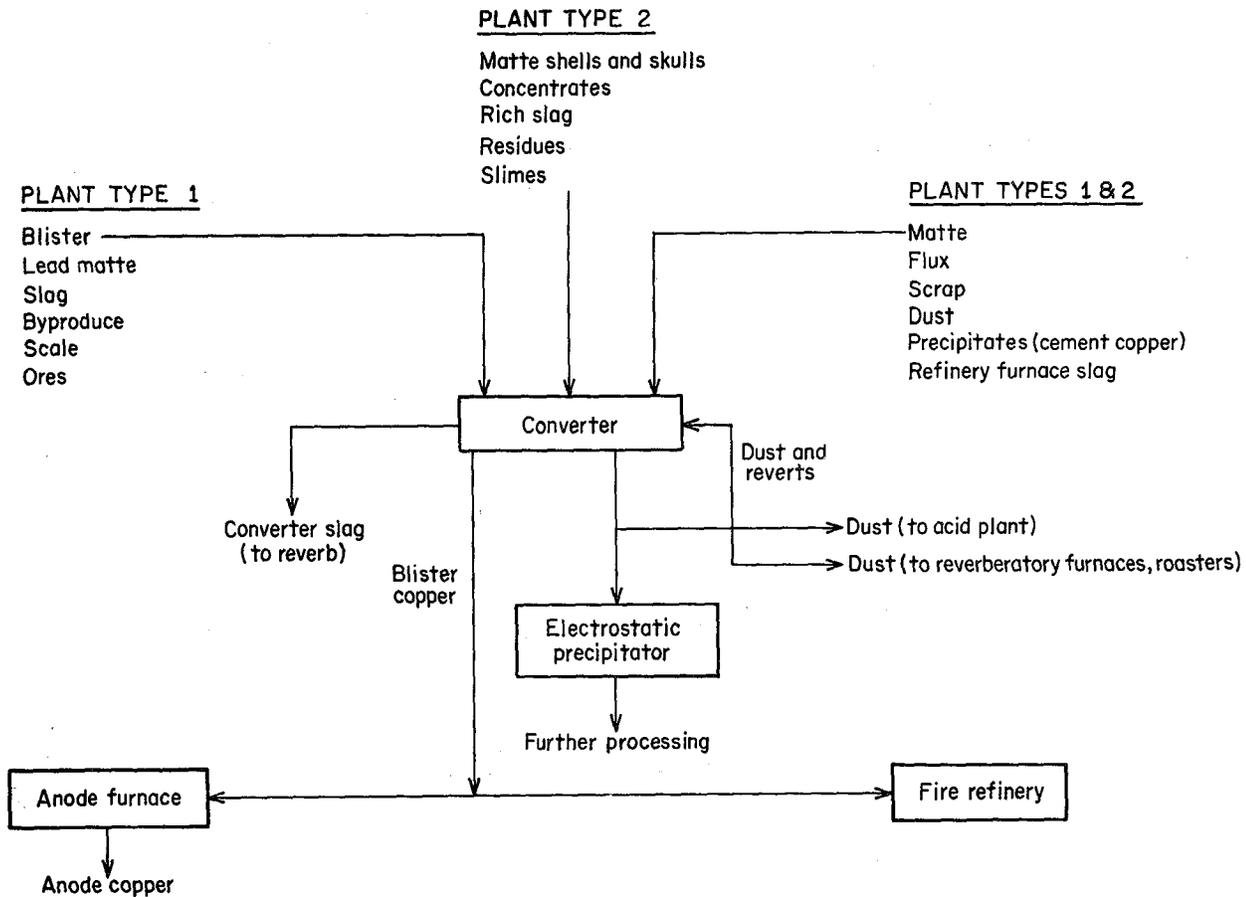


FIGURE 7. - Converting.

Known arsenic in converter feed in type 2 plants was about 190 tons, of which 84 percent was in matte and almost 14 percent was in concentrates. As shown in table 7, the rest was in cement copper, dust, flux, and anode slimes.

Minor Metals in Converter Products

Converter products consist of blister copper, dusts, and slag. Blister is converted to anode in anode furnaces. Converter slags are generally recycled to the reverberatory furnaces.

Quantitative data were available or estimated for blister copper products of both type plants (tables 6-7). The type 1 plants produced about 55 percent of the blister copper for the survey period. The 1.66 to 1 ratio of total quantity of slag produced to that of blister reported in the literature (56, p. 79) was confirmed by this survey.

Arsenic in Converter Products

The known quantity of arsenic in converter products from type 1 plants shown in table 6 was 2,052 tons, of which 31 percent was in blister and other unrefined copper, nearly 69 percent in dust, and the remainder in slag.

Known arsenic in converter products from type 2 plants was 264 tons as shown in table 7, of which 35 percent was in blister and other unrefined copper, 54 percent in dust, and 21 percent in slag.

SELENIUM, 1971-73

Selenium in Concentrates, Precipitates, and Other Feed to Type 1 Plants

Total concentrates processed at type 1 plants contained 222 tons of selenium, or 94.9 percent of the total known selenium content of domestic materials in roaster feed (table 8). About 10 percent of the selenium content in concentrates was in foreign materials. Selenium in roasted domestic concentrates was largely contained in feed to five plants. About 73 percent came from Arizona; lesser quantities came from Tennessee and Nevada, and trace amounts came from Utah, Colorado, and California.

TABLE 8. - Selenium in type 1 plants operating, 1971-73--roaster feed

Item	Total quantity, tons	Plants with assay data				Indicated quantity of selenium
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Feed to roaster: ¹						
Concentrates.....	2,353,960	7	94.7	0.0004-0.14	0.01	221.8
Speiss.....	13,579	1	67.6	.009 - .035	.012	1.1
Matte.....	8,072	1	96.4	.063 - .139	.12	9.3
Dust.....	9,044	1	33.5		(²)	(³)
Pyrite.....	4,001	1	100	.005	.005	.2
Residues and sludges.....	3,091	0	0		.001	(³)
Precipitates.....	56,962	2	43.2	.0065- .007	.007	1.6
Copper ores.....	35,272	1	1.4		.001	(³)

¹Total tons of roaster feed materials for which there were no assays for selenium are: flux 119,888, tailings 78,372, scrap 5,196, refinery and other slags 2,301, and other 34,322.

²Negligible.

³Trace amount.

Only one plant indicated any significant quantity of selenium in foreign concentrates. Most of this came from Peru and Canada.

Other domestic roaster feed materials contained 5.1 percent of the total selenium in domestic roaster feed. These include the materials shown with assay and other data in the table.

Selenium in Roaster Calcines

The calcines from three plants providing full data contained 70.3 tons of selenium (table 9). This is about 78 percent of the total known selenium in feed to these three plants.

TABLE 9. - Selenium in type 1 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of selenium
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Feed to reverberatory: ¹						
Calcines..... ²	1,859,879	3	79.2	0.003-0.01	0.005	70.3
Converter slag.....	1,180,309	1	19.7		.0005	1.2
Dust (mostly converter Cottrell)..	10,710	1	94.1		.023	2.3
Concentrates.....	475,380	1	100	.003- .12	.003	15.8
Reverberatory products ³						

¹Total tons of reverberatory feed materials for which there were no assays for selenium are: precipitates 16,911, and slag and matte shells 1,164.

²Of these 16.7 percent are mixed with dust at one plant.

³Total tons of reverberatory products for which there were no assays for selenium are: discarded slag 1,923,983.

Selenium in Dust and Fume

In type 1 plants, the known quantity of selenium in dust and fume was very small with practically all being in converter dust (table 11). As seen in table 11, two plants provided assays on selenium in the Cottrell dust.

In type 2 plants, the known selenium content and assays are shown in table 12. Selenium in recycled reverberatory dusts showed 0.009 percent in type 1 plants, and it ranged from 0.0035 to 0.083 percent in type 2 plants.

Selenium in Reverberatory Furnace Feed

About 602 tons of selenium were taken in by the plants in reverberatory furnace feed; 513 tons (85 percent of the total) were fed directly to the reverberatory furnaces at type 2 plants (table 10). Of the 89 tons fed to furnaces in type 1 plants (table 9), 78 percent was in calcines, nearly

18 percent in concentrates, and the rest in converter dusts and slag. As shown in table 10, in the direct reverberatory smelting feed at type 2 plants, 47 percent of the selenium was in concentrates, 39 percent in anode slimes cleanup, almost 9 percent in slag, almost 6 percent in precipitates (cement copper) and residues (mostly refinery residues from one plant), and the remainder was in dust and pyrite.

TABLE 10. - Selenium in type 2 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	No.	Plants with assay data			Indicated quantity of selenium
			Percent of total quantity	Assays, percent		
				Range	Average	
Feed to reverberatory: ¹						
Concentrates.....	1,951,680	5	99.9	0.0004-0.027	0.012	241
Converter slag.....	967,558	5	100	.0007- .0095	.005	44
Precipitates (cement copper)...	133,559	4	96.9	.0046- .025	.005	6
Other (including pyrite).....	23,780	1	80.8		.0012	.2
Residues (refinery and other).....	10,666	2	100	.014 - .27	.21	22.5
Dust.....	3,850	1	75.8		.023	.7
Anode slimes cleanup.....	626	1	100		31.7	198.4
Reverberatory products: slag (discarded).....	1,291,892	3	84.7	.0002- .002	.0013	14

¹Total tons of reverberatory feed materials for which there were no assays for selenium are: flux 15,345.

Selenium in Reverberatory Furnace Products

Assays on reverberatory furnace mattes from type 1 plants indicated the presence of 0.0025 to 0.0175 percent selenium. As shown in the preceding section on arsenic in reverberatory furnace products, matte is a recycled material and throughput data are not shown. One assay on slag indicated 0.0035 percent selenium, but the lack of quantitative data on the slag prevented determination of selenium quantity.

In type 2 plants, matte assays ranged from 0.0013 to 0.018 percent selenium. One plant also indicated the presence of 0.017 percent selenium in matte shells and skulls. As seen in table 10, slags at these plants ranged from 0.0002 to 0.002 percent selenium for a known total of 14 tons of selenium.

Selenium in Converter Feed

The known quantity of selenium in converter feed to type 1 plants was about 63 tons, of which about 79 percent was in matte and the rest in blister copper. The assays on copper matte and on blister copper are shown in table 11. Although not shown in the table, silica flux at one plant assayed 0.001 percent selenium.

TABLE 11. - Selenium in type 1 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of selenium
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Converter feed: ¹						
Blister.....	20,284	2	100		0.064	13
Matte (reverb)...	² 1,919,296	3	50.3	0.0025-0.0175	.005	50.2
Converter products: ³						
Blister (anode)...	709,916	7	100	.014 - .064	.03	218.3
Dust, Cottrell...	15,243	1	47.7	.011 - .023	.023	2.9
Slag.....	1,080,309	1	19.7		.0006	1.2

¹Total tons of converter feed material for which there were no assays for selenium are: lead matte 19,231, scrap 23,580, byproducts 7,570, flux 76,760, dust 41,946, scale 240, slag 1,604, refinery furnace slag 6,165, precipitates 5,848, and ores 33,836.

²One plant had assay data for selenium but no weights.

³Total tons of converter products for which there were no assays for selenium are: dust to copper roasters 8,736, and matte and slag reverts 19,837.

Known selenium in converter feed to type 2 plants was 293 tons, of which more than 83 percent was in matte, 13 percent in anode slimes, and the rest in the other feed materials shown in table 12.

Selenium in Converter Products

As seen in table 11, the known quantity of selenium in converter products from type 1 plants was more than 222 tons, of which more than 98 percent was in blister and other unrefined copper, more than 1 percent in dust, and the rest in slag at one plant.

Table 12 shows known selenium in converter products at type 2 plants as 229 tons, of which 80 percent was in blister, 19 percent in slag, and the rest in dust.

TABLE 12. - Selenium in type 2 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	No.	Plants with assay data			Indicated quantity of selenium
			Percent of total quantity	Assays, percent		
				Range	Average	
Converter feed: ¹						
Matte.....	1,523,170	6	100	0.0015-0.019	0.0157	238.9
Matte shells and skulls.....	41,908	1	100	.0085- .017	.0134	5.6
Flux.....	122,348	1	55.2		.002	1.4
Concentrates.....	17,264	2	100	.0025- .017	.0168	2.9
Cement copper (including precipitates).....	17,275	2	99.1	.0005- .011	.0019	.33
Slag (refinery)....	2,900	1	100		.14	4.1
Dust (reverb flue). Residues ²	325	1	100		.083	.3
Anode slimes cleanup.....	123	1	100		31.7	39
Converter products: ³						
Blister (anode)....	581,622	5	89.4	.0025- .048	.0352	183.5
Slag.....	967,558	5	100	.0007- .0095	.0045	43.5
Dust ⁴	10,023	4	76.3	.002 - .043	.029	2.2

¹Total tons of converter feed materials for which there were no assays for selenium are: rich slag 2,898, and scrap 2,172.

²There were no data for residues.

³Total tons of converter products for which there were no assays for selenium are: scrap regulus and cleanings 84,155; converter cleanings 5,360.

⁴Includes leady dust.

TELLURIUM, 1971-73

Tellurium in Concentrates, Precipitates, and Other Feed to Type 1 Plants

Tellurium in domestic concentrates to roasting at six smelters totaled 40.4 tons and was 89 percent of the total known tellurium in domestic materials in roasting feed. Of the 43.1 tons of tellurium in foreign materials fed to the type 1 plants, concentrates accounted for practically all, except for a small quantity in Canadian matte (table 13).

TABLE 13. - Tellurium in type 1 plants operating, 1971-73--roaster feed

Item	Total quantity, tons	Plants with assay data				Indicated quantity of tellurium
		No.	Percent of total quantity	Assays, percent Range	Average	
Feed to roaster: ¹						
Concentrates.....	2,353,960	5	83.8	0.0006-0.066	0.004	83.5
Speiss.....	13,579	1	67.6	.008 - .026	.0009	.8
Matte.....	8,072	1	96.4	.014 - .056	.04	3.2
Dust.....	9,044	1	33.5	.006	.006	.2
Pyrite.....	4,001	1	100	.02	.02	.8
Residues and sludges.....	3,091	0	0		.006	(²)
Precipitates.....	56,962	1	.3		.003	(²)
Copper ores.....	35,272	1	1.4		.01	(²)
Slags (other).....	369	1	100		.03	.1

¹Total tons of roaster feed materials for which there were no assays for tellurium are: flux 119,888, tailings 78,372, scrap 5,196, refinery slag 1,932, and other 34,322.

²Trace amounts.

Practically all of the tellurium in domestic concentrates used in roasting was at plants owned by two large smelting firms. About 79 percent of the tellurium in domestic concentrates came from Arizona; lesser quantities came from Nevada and New Mexico, and trace amounts came from Utah, Colorado, and California.

Only one plant indicated any significant quantity of tellurium in foreign concentrates. Most of this came from the Philippines (about 88 percent) but small quantities also came from Peru and Canada.

Tellurium in Roaster Calcines

The assays from one of the two plants which provided calcine data showed the presence of 0.001 percent tellurium for a total of 8.7 tons of tellurium. The output of tellurium in calcines on the basis of reported assays was about 10 percent greater than that in concentrate input at the plant but this may be due to discrepancies in the assays. No tellurium was detected in samples representative of 288,246 tons of calcines at the second plant.

Tellurium in Dust and Fume

Tellurium in dust and fume at type 1 smelters totaled only about 1/3 ton, chiefly in converter dusts (table 16). Only one plant provided assay data, 0.0005 percent tellurium in reverberatory dust and 0.0028 percent tellurium in converter dust.

Smelters of type 2 produced 4.4 tons of tellurium in dust and fume (table 17). Only one plant provided assay data (0.124 and 0.15 percent tellurium) for recycled reverberatory furnace dusts. The same plant with

two others provided converter dust assays ranging from 0.0013 to 0.115 percent tellurium. The one facility which indicated it produced 31,000 tons of flue dust showed an assay of 0.0004 percent tellurium.

Tellurium in Reverberatory Furnace Feed

Total tellurium in reverberatory feed, used by both types of plants, was about 103 tons, of which 75 percent was in type 2 plants. Type 1 plants fed nearly 26 tons of tellurium in materials to their reverberatory smelters. Concentrates contained 53 percent of this tellurium; calcines, 34 percent; slag, 12 percent; and converter dust the rest. In feed at type 2 plants, about 58 percent of the tellurium was in precipitates and residues (almost all in the latter refinery residues), 22 percent in concentrates, 14 percent in slag, 3 percent in anode slimes cleanup, and the rest in dust and pyrite.

Tellurium in Reverberatory Furnace Products

One matte assay at a type 1 plant indicated 0.0016 percent tellurium; discarded slag at the same plant assayed 0.0003 percent or 1.9 tons of tellurium (table 14).

TABLE 14. - Tellurium in type 1 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of tellurium
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Feed to reverberatory: ¹						
Calcines.....	^a 1,859,879	1	47		0.001	8.7
Converter slag....	1,180,309	2	57.6	0.0004-0.0005	.0004	3.0
Dust (mostly converter Cottrell).	10,710	1	94.1		.0028	.3
Concentrates.....	475,380	1	100	.0008- .08	.003	13.5
Reverberatory products: slag (discarded).....	1,923,983	1	30.6		.0003	1.9

¹Total tons of reverberatory feed materials for which there were no assays for tellurium are: precipitates 16,911, and slag and matte shells 1,164.

^aOf these, 16.7 percent are mixed with dust at one plant.

In type 2 plants, matte assays ranged from 0.0002 to 0.002 percent tellurium. One plant indicated 0.005 percent tellurium in matte shells and skulls. A limited number of assays showed 0.0004 to 0.001 percent or 7 tons tellurium in discarded slags (table 15).

TABLE 15. - Tellurium in type 2 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of tellurium
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Feed to reverberatory: ¹						
Concentrates.....	1,951,680	4	73.1	0.0003-0.0025	0.0012	17
Converter slag.....	967,558	4	81.7	.0002- .002	.0014	11
Precipitates.....	133,559	1	38.2		.001	.5
Other (including pyrite).....	23,780	1	80.8		.005	1.0
Residues (refinery and other).....	10,666	2	100	.0005- .54	.415	44.3
Dust.....	3,850	1	75.8		.048	1.4
Anode slimes.....	626	1	100		.36	2.3
Reverberatory products: slag (discarded).....	1,291,892	3	72.2	.0004- .001	.0008	7

¹Total tons for reverberatory feed materials for which there were no assays for tellurium are: flux 15,345.

Tellurium in Converter Feed

The total known quantity of tellurium in converter feed at type 1 smelters was 9 tons, of which 71 percent was in matte and the rest was in blister (table 16).

TABLE 16. - Tellurium in type 1 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of tellurium
		No.	Percent of total quantity	Assays, percent		
				Range	Average	
Converter feed: ¹						
Blister.....	20,284	2	100		0.013	2.6
Matte (reverb).....	1,919,296	1	20.9		.0016	6.4
Converter products: ²						
Blister (anode)....	709,916	7	100	0.002 -0.048	.011	80.6
Dust, Cottrell.....	26,354	1	38.2		.0028	.3
Slag.....	1,080,309	2	57.6	.0004- .0005	.0005	3.0

¹Total tons of converter feed materials for which there were no assays for tellurium are: lead matte 19,231, scrap 23,580, byproducts 7,570, flux 76,760, dust 41,946, scale 240, slag 1,604, refinery furnace slag 6,165, precipitates 5,848, and ores 33,836.

²Total tons of converter products for which there were no assays for tellurium are: dusts to copper roasters 8,736, and matte and slag reverts 19,837.

Known tellurium in converter feed to type 2 (table 17) smelters was nearly 22 tons, of which 87 percent was in matte.

Tellurium in Converter Products

The known quantity of tellurium in converter products from type 1 smelters was 84 tons, of which 96 percent was in blister and other unrefined copper, more than 3 percent was in slag at two plants, and the remainder was in Cottrell dust at one plant.

Known tellurium in converter products at type 2 plants was about 54 tons as shown in table 17. Of this, 72 percent was in blister, almost 21 percent was in slag, and the rest was in dusts.

TABLE 17. - Tellurium in type 2 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	No.	Plants with assay data			Indicated quantity of tellurium
			Percent of total quantity	Assays, percent		
				Range	Average	
Converter feed: ¹						
Matte.....	1,523,170	5	94.0	0.0002-0.0019	0.0013	18.9
Matte shells and skulls.....	41,908	1	100	.001 - .005	.0033	1.4
Flux.....	122,348	1	55.2		.001	.7
Concentrates.....	17,264	2	100	.0008- .0025	.0017	.3
Cement copper (including precipitates).....	17,275	1	18.3		.001	.1
Residues ²						
Anode slimes cleanup.....	123	1	100		.36	.4
Converter products: ³						
Blister (anode)....	581,622	4	77.9	.001 - .015	.0086	38.9
Slag.....	967,558	4	81.7	.0002- .002	.0014	11.1
Dust ⁴	10,023	3	67.0	.0013- .115	.0655	4.4

¹Total tons of converter feed materials for which there were no assays for tellurium are: refinery slag 2,900, rich slag 2,898, scrap 2,172, and reverberatory flue dust 325.

²There were no data for residues.

³Total tons of converter products for which there were no assays for tellurium are: scrap regulus and cleanings 84,155, and converter cleanings 5,360.

⁴Includes leady dust.

GOLD, 1971-73

Gold in Concentrates, Precipitates, and Other Feed to Type 1 Plants

Gold in domestic concentrates in feed at six type 1 plants totaled 58,157 ounces or about 57 percent of that known in domestic feed materials. Concentrates accounted for almost all of the gold in foreign materials fed to

roasting. Practically all of the gold in domestic concentrates was roasted and smelted by five plants.

Nearly 59 percent of the gold in domestic concentrates came from Arizona; 30 percent from Nevada; 5 percent from Colorado; 4 percent from New Mexico; 2 percent from Utah; and trace amounts from California, Idaho, and other sources.

Only one plant indicated any significant quantity of gold in foreign concentrates. Almost all of this came from the Philippines with smaller amounts from Canada and Peru.

Other domestic roaster feed materials contained 43 percent of the gold in total domestic roaster feed. These materials (table 18) included speiss, matte, dust, pyrite, residues and sludges, precipitates, copper ores, and tailings. Only a few ounces of gold were in Canadian matte fed to roasting at one plant.

TABLE 18. - Gold in type 1 plants operating, 1971-73--roaster feed

Item	Total quantity, tons	Plants with assay data				Indicated quantity of gold
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to roaster: ¹						
Concentrates.....	2,353,960	6	85.9	0.002-1.57	0.078	157,026.5
Speiss.....	13,579	1	67.6	.595-4.977	4.62	42,415
Matte.....	8,072	1	96.4	.01 - .56	.06	467
Dust.....	9,044	1	33.5	.01	.01	30
Pyrite.....	4,001	1	100	.011	.011	44
Residues and sludges.	3,091	1	11.8	.01	.01	3.7
Precipitates.....	56,962	1	.9	.01	.01	5.3
Copper ores.....	35,272	1	3.8	.024- .36	.2	247
Tailings.....	78,372	1	100		.005	392

¹Total tons of roaster feed materials for which there were no assays for gold are: flux 119,888, scrap 5,196, refinery and other slags 2,301, and other 34,322.

Gold in Roaster Calcines, Dust, and Fume

Data on calcines from two type 1 plants are shown in table 19. Gold in converter and other dusts totaled 1,083 ounces, as shown in table 21. One plant provided gold assays for reverberatory furnace dusts (0.0386 ounce per ton); this plant and three others provided gold assays for Cottrell dusts.

Data on type 2 plants are shown in tables 20-22. One plant indicated its reverberatory dusts (not shown in table 22) contained about 0.4 ounce of gold per ton; another plant contained 0.014 ounce of gold per ton. These plants also produced converter dusts containing 0.04 and 0.16 ounce of gold per ton totaling 730 ounces of gold. Another plant showed 0.109 ounce of gold per ton in dusts which were undifferentiated as to origin from reverberatory furnaces

or converters. These dusts contained about 20 percent of the gold known in dust and fume.

The preceding assay data may be compared with those from the literature. Analyses of flue dusts from all departments at the Anaconda smelter showed the presence of 0.02 ounce of gold per ton (20, p. 128).

Gold in Reverberatory Furnace Feed

Known gold in reverberatory furnace feed totaled 469,564 ounces, of which about 90 percent was introduced directly to the smelting furnaces (table 20). Of the 46,241 ounces fed to reverberatory smelting in type 1 plants (table 19), 75 percent was in calcines, nearly 21 percent was in concentrates, over 3 percent was in slag, and a small quantity was in converter dusts. Of the 423,323 ounces of gold fed directly to reverberatory smelting (type 2 plants), 80 percent was in concentrates; 14 percent was in precipitates and residues (99 percent of which were in the latter, almost all of refinery origin); about 5 percent was in slag; and the rest was in anode slimes cleanup, pyrite, dust, and plant cleanings.

Gold in Reverberatory Furnace Products

As shown in tables 19-20, discarded slags at type 1 plants contained 0.0002 to 0.00056 ounce of gold per ton or 555 ounces; slags at type 2 plants contained 0.0045 to 0.006 ounce of gold per ton or 3,381 ounces.

TABLE 19. - Gold in type 1 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of gold
		No.	Percent of total quantity	Assays, ounce per ton Range	Average	
Feed to reverberatory: ¹						
Calcines.....	^a 1,859,879	2	62.5	0.0208-0.033	0.03	34,844
Converter slag...	1,180,309	2	57.6	.002 - .003	.002	1,593
Dust (mostly converter Cottrell)	10,710	1	94.1		.0212	214
Concentrates.....	475,380	1	100	.005 - .0282	.02	9,590
Reverberatory products: slag (discarded).....	1,923,983	3	74.6	.0002- .00056	.0004	555

¹Total tons of reverberatory feed materials for which there were no assays for gold are: precipitates 16,911, and slag and matte shells 1,164.

^aOf these, 16.7 percent are mixed with dust at one plant.

In type 2 plants, matte assays ranged from 0.029 to 0.482 ounce of gold per ton, but quantities are not shown. Data on discarded slags at two plants are shown in table 20. A so-called "rich slag," produced and recycled at one plant, contained 0.001 ounce of gold per ton or 6 ounces of gold.

TABLE 20. - Gold in type 2 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of gold
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to reverberatory: ¹						
Concentrates.....	1,951,680	5	89.5	0.005 -0.409	0.195	339,858
Converter slag.....	967,558	3	68.9	.009 - .047	.033	21,847
Precipitates.....	133,559	1	20.4		.02	545
Other (including pyrite).....	23,780	2	99.8	.005 - .007	.005	126.7
Residues (refinery and other).....	10,666	2	100	.185 -7.23	5.6	59,743
Dust.....	3,850	1	24.2		.037	34.4
Anode slimes.....	626	1	100		1.868	1,168
Reverberatory products: slag (discarded).....	1,291,892	2	54.2	.0045- .006	.0048	3,381

¹Total tons of reverberatory feed materials for which there were no assays for gold are: flux 15,345.

Compared with the preceding matte assays, a typical matte from a reverberatory furnace contained 0.30 ounce of gold per ton (20, p. 104).

Gold in Converter Feed

The total known quantity of gold in converter feed at type 1 plants was 72,877 ounces, of which 91 percent was in matte and the rest was in blister copper (table 21).

TABLE 21. - Gold in type 1 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of gold
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Converter feed: ¹						
Blister.....	20,284	2	100		0.323	6,552
Matte (reverb).....	² 1,919,296	5	72.1	0.01 -0.11	.048	66,324.5
Converter products: ³						
Blister (anode).....	709,916	6	90.5	.0202-1.89	.338	217,342
Dust:						
Cottrell.....	26,354	4	100	.005 - .03	.021	548.9
Flue and other (to copper roasters)...	8,736	2	100	.03 - .10	.061	534.3
Slag.....	1,080,309	2	57.6	.002 - .003	.003	1,593

¹Total tons of converter feed materials for which there were no assays for gold are lead matte 19,231, scrap 23,580, byproducts 7,570, flux 76,760, dust 41,946, scale 240, slag 1,604, refinery furnace slag 6,165, precipitates 5,848, and ores 33,836.

²One plant had assay data for gold but no weights.

³Total tons of converter products for which there were no assays for gold are: matte and slag reverts 19,837.

Table 22 indicates known gold in various converter feed at type 2 smelters was 380,407 ounces, of which 98 percent was in matte and practically all the rest was in concentrates. As can be noted, small quantities of gold were present in flux, cement copper, refinery slag, rich slag, scrap, dust, and anode slimes.

TABLE 22. - Gold in type 2 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of gold
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Converter feed:						
Matte.....	1,523,170	5	94.0	0.029-0.482	0.2534	362,791
Matte shells and skulls.....	41,908	1	100	.21 - .268	.2427	10,170
Flux.....	122,348	1	.3		.0458	16.8
Concentrates.....	17,264	2	100	.004- .409	.3813	6,582.1
Cement copper (including precipitates).....	17,275	1	.9		.215	33.4
Slag (refinery).....	2,900	1	100		.17	500
Slag (rich).....	2,898	1	100		.002	5.8
Scrap.....	2,172	1	17.3	.064- .077	.0703	26.4
Dust (reverb flue)...	325	1	100		.015	4.9
Residues ¹						
Anode slimes cleanup.	123	1	100		2.245	276.4
Converter products:						
Blister (anode).....	581,622	5	88.5	.07 -1.304	.732	376,811
Slag.....	967,558	3	68.9	.009- .047	.0328	21,847
Dust ²	10,023	3	61.6	.04 - .16	.1182	729.5
Scrap regulus and cleanings.....	84,155	1	100		.035	2,985.7
Converter cleanings..	5,360	1	100		.006	34.2

¹There were no data for residues.

²Includes leady dust.

Gold in Converter Products

The known quantity of gold in converter products from type 1 plants was 220,018 ounces, of which 98.8 percent was in blister and anode, about 0.7 percent was in slag, and the rest was in dust. As shown in table 21, assays ranged up to 1.89 ounces of gold per ton in blister and anode, 0.005 to 0.1 ounce of gold per ton in dust (the high assay dust being sent to a copper roaster), and 0.002 to 0.003 ounce of gold per ton in slags.

Known gold in converter products at type 2 plants (table 22) was 402,407 ounces, of which 94 percent was in blister, and practically all the rest was in slags at three plants.

Type 1 plants provided more complete assay data on converter products than they did on converter feed materials. This accounts for apparent anomalies between gold in converter feeds and products (nearly 73,000 ounces in feed versus about 220,000 ounces in products at roaster plants, and more than 380,000 ounces in feed and over 402,000 ounces in products at type 2 plants).

SILVER, 1971-73

Silver in Concentrates, Precipitates, and Other Feed to Type 1 Plants

Silver in domestic concentrates fed to roasting known from type 1 plants (about 5.48 million ounces) composed 51 percent of the total known silver in domestic materials. Of silver in foreign materials fed to roasting, concentrates (with nearly 1.8 million ounces) accounted for about 97 percent; the rest was mostly in Canadian matte.

Of silver in domestic concentrates used in roasting, about 93 percent was used by five plants. Nearly 74 percent of the silver in domestic concentrates came from Arizona; lesser quantities came from New Mexico, 13 percent; Nevada, 7 percent; Idaho, 3 percent; and even smaller amounts from Colorado, Tennessee, California, Missouri, Utah, and other sources.

Only one plant indicated any significant quantity of silver in foreign concentrates. Most of this came from Peru, with most of the remainder from Canada and a smaller amount from the Philippines.

Other domestic roaster feed materials contain 49 percent of the silver in total domestic roaster feed as shown in table 23. About 12 percent of the silver in matte fed to roasting at one plant was of Canadian origin.

TABLE 23. - Silver in type 1 plants operating, 1971-73--roaster feed

Item	Total quantity, tons	Plants with assay data				Indicated quantity of silver
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to roaster: ¹						
Concentrates.....	2,353,960	7	95.5	0.49-592.12	3.24	7,283,745.3
Speiss.....	13,579	1	67.6	87.32-498.43	464.3	4,261,905
Matte.....	8,072	1	96.4	35.35- 81.47	68.14	530,015
Dust.....	9,044	1	33.5		.13	394
Pyrite.....	4,001	1	100		124.32	497,404
Residues and sludges.....	3,091	1	11.8		.78	285
Precipitates.....	56,962	1	1.2	.31- .58	.36	247
Copper ores.....	35,272	1	3.8	.62- 17.02	8.53	10,760
Tailings.....	78,372	1	100		.37	28,998
Refinery slag.....	1,932	1	100		8.87	17,137

¹Total tons of roaster feed materials for which there were no assays for silver are: flux 119,888, scrap 5,196, slags 369, and other 34,322.

Silver in Roaster Calcines, Dust, and Fume

As may be seen in table 24, calcines from three type 1 plants assayed from 0.8 to 2.01 ounces of silver per ton. In type 1 plants, table 26 shows silver quantities and assays in dusts totaling 280,410 ounces.

TABLE 24. - Silver in type 1 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of silver
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to reverberatory: ¹						
Calcines.....	² 1,859,879	3	79.2	0.8 - 2.01	1.675	2,467,955
Converter slag.....	1,180,309	3	79.2	.06 - .151	.15	138,711
Dust (mostly converter Cottrell)...	10,710	1	94.1		2.822	28,479
Concentrates.....	475,380	1	100	1.352-3.105	1.45	689,126
Reverberatory products: slag (discarded).....	1,923,983	4	89.8	.039- .096	.05	80,436

¹Total tons of reverberatory feed materials for which there were no assays for silver are: precipitates 16,911, and slag and matte shells 1,164.

²Of these, 16.7 percent are mixed with dust at one plant.

Products of type 2 plants are shown in table 27. Of dusts produced, about 48 percent was in Cottrell dusts shipped elsewhere. Assays on dusts ranged from 3.61 to 9 ounces silver per ton.

The preceding assay data may be compared with others in the literature. Analyses on flue dusts from all departments at the Anaconda smelter showed the presence of 6.8 ounces of silver per ton (20, p. 128). Analyses of flue dusts from Garfield converters showed 25.1 ounces of silver per ton.

Silver in Reverberatory Furnace Feed

Of the 9,705,356 ounces of silver in total feed to reverberatory smelting, 66 percent was fed directly to reverberatory furnaces at type 2 plants. In the 3,324,271 ounces of silver used in reverberatory furnaces of the type 1 plants, 74 percent was in calcines, 21 percent was in concentrates, 4 percent was in slag, and the rest was in converter dusts.

In the 6,381,085 ounces of silver fed directly to type 2 smelters (table 25), 71 percent was in concentrates, about 22 percent was in refinery residues, 5 percent was in slag, almost 2 percent was in anode slimes cleanup, and the remainder was in precipitates, pyrite, plant cleanings, dust, and scrap.

TABLE 25. - Silver in type 2 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of silver
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to reverberatory: ¹						
Concentrates.....	1,951,680	6	99.9	0.6 - 4.5	2.33	4,550,623
Converter slag.....	967,558	4	81.7	.09- .598	.377	298,359
Precipitates.....	133,559	2	36.0	.1 - .4	.27	13,008
Other (including pyrite).....	23,780	2	100	.3 - 1.01	.435	10,355
Residues (refinery and other).....	10,666	2	100	2.95-170.53	131.79	1,405,621
Dust.....	3,850	1	24.2		4.43	4,127
Anode slimes.....	626	1	100		158.13	98,992
Reverberatory products: slag (discarded).....	1,291,892	4	82.0	.04- .07	.057	60,639

¹Total tons of reverberatory feed materials for which there were no assays for silver are: flux 15,345.

Silver in Reverberatory Furnace Products

Assays on reverberatory furnace mattes from type 1 plants (not shown in table 24) showed 0.40 to 17.3 ounces of silver per ton, but the table shows that slag at type 1 smelters contained 0.039 and 0.096 ounce of silver per ton for a total of 80,436 ounces. Assays were known on silver in matte and slag from one plant but lack of quantitative data on the materials prevented determination of the silver contents.

In type 2 plants (not shown in table 27) matte assays ranged from 0.9 to 10.0 ounces of silver per ton. One plant also indicated 3.005 ounces of silver per ton in matte shells and skulls. Discarded slag data were shown in the table. A rich slag recycled at one plant contained 0.5 ounce of silver per ton or 2,475 ounces.

Compared with assays on the preceding mattes, a typical reverberatory furnace matte contained 60.4 ounces of silver per ton (20, p. 104).

Silver in Converter Feed

As shown in table 26, the total known quantity of silver in converter feed at type 1 plants was 6,821,615 ounces. Nearly 96 percent of this was in matte. The rest of the silver was in blister copper and refinery slag.

TABLE 26. - Silver in type 1 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of silver
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Converter feed: ¹						
Blister.....	20,284	2	100		13.02	264,097
Matte (reverb).....	^a 1,919,296	6	90.1	0.4 - 17.3	3.78	6,540,380.7
Refinery furnace slag....	6,165	1	40.8		6.81	17,137
Converter products: ³						
Blister (anode).....	709,916	7	100	2.8 -112.7	25.37	18,009,465
Dust:						
Cottrell.....	26,354	4	100	2.822- 9.87	5.35	140,872
Flue and other (to copper roasters).....	8,736	2	100	9.87 - 23.6	15.97	139,537.8
Slag.....	1,080,309	3	79.2	.06 - .24	.16	138,711

¹Total tons of converter feed materials for which there were no assays for silver are: lead matte 19,231, scrap 23,580, byproducts 7,570, flux 76,760, dust 41,946, scale 240, slag 1,604, precipitates 5,848, and ores 33,836.

^aOne plant had assay data for silver but no weights.

³Total tons of converter products for which there were no assays for silver are: matte and slag reverts 19,837.

Data on known silver in converter feed at type 2 smelters, as seen in table 27, indicated 5,337,660 ounces, of which 98 percent was in matte, with lesser amounts in concentrates, anode slimes and cement, scrap, fire refinery and rich slags, dust, and siliceous ore (flux).

TABLE 27. - Silver in type 2 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of silver
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Converter feed:						
Matte.....	1,523,170	6	100	0.9 -10.0	3.381	5,149,087
Matte shells and skulls.....	41,908	1	100	.586 - 3.005	1.949	81,666
Flux.....	122,348	2	55.2	.2 - 1.28	.207	13,984
Concentrates.....	17,264	2	100	1.051 - 3.445	3.273	56,501
Cement copper (including precipitates).....	17,275	1	.9		11.43	1,707
Slag (refinery).....	2,900	1	100		1.91	5,548
Slag (rich).....	2,898	1	100		.48	1,402
Scrap.....	2,172	1	25.2	.08 - 6.27	4.325	2,366
Dust (reverb flue).....	325	1	100		2.54	825
Residues ¹						
Anode slimes cleanup.....	123	1	100		199.63	24,574
Converter products:						
Blister (anode).....	581,622	6	100	2.63 -16.0	9.679	5,629,429
Slag.....	967,558	4	81.7	.0873- .598	.377	298,359
Dust ²	10,023	4	70.9	3.61 - 9.0	6.089	43,265
Scrap regulus and cleanings.	84,155	1	100		2.17	182,606
Converter cleanings.....	5,360	1	100		.99	5,306

¹There were no data for residues.

²Includes leady dust.

Silver in Converter Products

Table 26 shows that the known quantity of silver in converter products from type 1 plants was 18,428,586 ounces, of which nearly 98 percent was in blister and anode and the rest was in slags and dusts.

Table 27 shows that known silver in converter products at type 2 smelters was 6,158,965 ounces, of which 91.4 percent was in blister and anode, 4.8 percent was in slags, and the rest was in dusts and other materials.

PLATINUM, 1971-73

Platinum in Concentrates, Precipitates, and Other Feed to Type 1 Plants

No platinum quantities were estimated in domestic or foreign concentrates to roasting at type 1 plants due to the lack of platinum assay data. Arizona contributed 72 percent of the domestic concentrates total; New Mexico, 22 percent; Tennessee, 3 percent; followed by Nevada, Missouri, Oklahoma, Colorado, Utah, California, Idaho, Michigan, Washington, and other sources.

Although only one plant used foreign concentrates (mostly from the Philippines), the lack of platinum assay data prevented estimation of platinum in these materials.

Platinum in Roaster Calcines, Dust, and Fume

About 1 million tons of calcines were produced from roasting at two plants.

Platinum in Reverberatory Furnace Feed and Products

Only 226 ounces of platinum were known in feed materials at two type 2 plants. Of these, 75 percent was believed to be present in the anode slimes cleanup at one plant, and the rest in refinery residues at another plant (table 28).

TABLE 28. - Platinum in type 2 plants operating, 1971-73--reverberatory furnace feed products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of platinum
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to reverberatory: ¹						
Residues (refinery and other).....	10,666	1	76.9		0.007	57.4
Anode slimes cleanup.....	626	1	100		.27	169
Reverberatory products ²						

¹Total tons of reverberatory feed materials for which there were no assays for platinum are: concentrates 1,951,680, converter slag 967,558, precipitates 133,559, other (including pyrite) 23,780, flux 15,345, and dust 3,850.

²Total tons of reverberatory products for which there were no assays for platinum are: discarded slag 1,291,892.

Platinum in Converter Feed and Products

There were very little platinum assay data on which to base the quantities of the metal in mattes, blister copper, or other material fed to converters. All platinum known in converter feed to type 1 plants was in blister at one plant (table 29).

TABLE 29. - Platinum in type 1 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				
		No.	Percent of total quantity	Assays, ounce per ton		Indicated quantity of platinum
				Range	Average	
Converter feed ¹						
Converter products: ²						
blister (anode).....	709,916	1	20.8		0.001	148

¹Total tons of converter feed materials for which there were no assays for platinum are: reverberatory matte 1,919,296, blister 20,284, lead matte 19,231, scrap 23,580, byproducts 7,570, flux 76,760, dust 41,946, scale 240, slag 1,604, refinery furnace slag 6,165, precipitates 5,848, and ores 33,836.

²As with palladium, assays for platinum were available for blister and anode.

Platinum was known only in anodes at one type 2 plant (table 30). Two assays existed, one of which was a company assay for 0.001 ounce of platinum per ton, and the other was a Bureau of Mines assay for 0.005 ounce of platinum per ton.

TABLE 30. - Platinum in type 2 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				
		No.	Percent of total quantity	Assays, ounce per ton		Indicated quantity of platinum
				Range	Average	
Converter feed ¹						
Converter products:						
copper (anode) ²	241,823	1	41.6	0.001-0.005	0.003	725

¹Total tons of converter feed materials for which there were no assays for platinum are: matte 1,523,170, flux 122,348, matte shells and skulls 41,908, concentrates 17,264, cement copper (including precipitates) 17,275, refinery slag 2,900, rich slag 2,898, scrap 2,172, reverberatory flue dust 325, and anode slimes 123.

²The only converter product with assays for platinum was anode copper from one plant.

PALLADIUM, 1971-73

Palladium in Concentrates, Precipitates, and Other Feed to Type 1 Plants

Table 31 shows palladium in domestic concentrates roasted at type 1 plants. All material with assays came from Arizona. The lack of assay data on palladium in other domestic roaster feed materials made the calculation of quantities of palladium in these materials impossible.

TABLE 31. - Palladium in type 1 plants operating, 1971-73--roaster feed

Item	Total quantity, tons	Plants with assay data				Indicated quantity of palladium
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to roaster: ¹ concentrates.....	2,353,960	3	55.4	0.001	0.0003	419.2

¹Total tons of roaster feed materials for which there were no assays for palladium are: speiss 13,579, matte 8,072, dust 9,044, pyrite 4,001, residues and sludges 3,091, precipitates 56,962, copper ores 35,272, flux 119,888, tailings 78,372, scrap 5,196, refinery and other slags 2,301, and other 34,322.

Palladium in Roaster Calcines, Dust, and Fume

Assays were lacking for palladium in calcines at the two type 1 plants mentioned previously; quantities of palladium in the material could not be estimated. Also, no palladium data for dust and fume were available at type 1 plants.

Two type 2 plants produced the small quantity of palladium in dusts shown in table 35.

Palladium in Reverberatory Furnace Feed and Products

As seen in tables 32-33, of 7,624 ounces of palladium known in reverberatory furnace feeds, 96 percent was fed directly to type 2 plants and the 301 ounces of palladium fed to reverberatory furnaces at type 1 plants were in concentrates. Of the 7,323 ounces of palladium known in feed at type 2 plants, almost 62 percent was in anode slimes cleanup, 29 percent was in concentrates, almost 8 percent was in refinery residues, and most of the rest was in slag.

TABLE 32. - Palladium in type 1 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of palladium
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to reverberatory: ¹ concentrates.....	475,380	1	100		0.0006	301
Reverberatory products ²						

¹Total tons of reverberatory feed materials for which there were no assays for palladium are: calcines 1,859,879, precipitates 16,911, converter slag 1,180,309, dust (mostly converter Cottrell) 10,710, and slag and matte shells 1,164.

²Total tons of reverberatory products for which there were no assays of palladium are: discarded slag 1,923,983.

TABLE 33. - Palladium in type 2 plants operating, 1971-73--reverberatory furnace feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of palladium
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Feed to reverberatory: ¹ Concentrates.....	1,951,680	2	47.2	0.001-0.003	0.002	2,110
Converter slag.....	967,558	1	12.8		.001	123.8
Precipitates.....	133,559	1	5.9		.001	7.9
Residues (refinery and other).....	10,666	1	76.9		.07	574.2
Anode slimes cleanup.....	626	1	100		7.2	4,507
Reverberatory products ²						

¹Total tons of reverberatory feed materials for which there were no assays for palladium are: other (including pyrite) 23,780, flux 15,345, and dust 3,850.

²Total tons of reverberatory products for which there were no assays for palladium are: discarded slag 1,291,892.

Although they are not shown in tables 32-33, some assay data at one type 1 plant showed 0.002 ounce of palladium per ton; also, limited data on matte in type 2 plants showed 0.002 and 0.003 ounce of palladium per ton, and one plant also showed 0.005 ounce of palladium per ton in its matte shells and skulls.

Palladium in Converter Feed and Products

The known quantity of palladium in converter feed to type 1 plants was from one plant at which assays indicated 0.002 ounce of palladium per ton for

a total of 802 ounces of the metal (table 34). Known palladium in converter feed at type 2 plants was mostly in matte and matte shells and skulls at one plant (table 35).

TABLE 34. - Palladium in type 1 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of palladium
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Converter feed: ¹ matte (reverb).....	1,919,296	1	20.9		0.002	802
Converter products: ^{2 3} blister (anode).....	709,916	2	47	0.001-0.25	.11	37,084

¹Total tons of converter feed materials for which there were no assays for palladium are: blister 20,284, lead matte 19,231, scrap 23,580, byproducts 7,570, flux 76,760, dust 41,946, scale 240, slag 1,604, refinery furnace slag 6,165, precipitates 5,848, and ores 33,836.

²Total tons of converter products for which there were no assays for palladium are: dust (Cottrell or leady) 26,354, dusts to copper roasters 8,736, slag 1,080,309, and matte and slag reverts 19,837.

³Assays for palladium were available for blister and anode.

TABLE 35. - Palladium in type 2 plants operating, 1971-73--converter feed and products

Item	Total quantity, tons	Plants with assay data				Indicated quantity of palladium
		No.	Percent of total quantity	Assays, ounce per ton		
				Range	Average	
Converter feed: ^{1 2} Matte.....	1,523,170	2	53.7	0.002 - 0.003	0.0027	2,213
Matte shells and skulls.....	41,908	1	56.3		.005	118
Concentrates.....	17,264	2	100	.001 - .003	.0025	42.6
Cement copper (including precipitates)....	17,275	1	1.9		.001	.3
Converter products: ³ Blister (anode)...	581,622	2	59.3	.0065 - .008	.0076	2,607
Slag.....	967,558	1	12.8		.001	124
Dust ⁴	10,023	2	37.9	.001 - .003	.0016	6.1

¹Total tons of converter feed materials for which there were no assays for palladium are: flux 122,348, refinery slag 2,900, rich slag 2,898, scrap 2,172, reverberatory flue dust 325, and anode slimes 123.

²There were no data for residues.

³Total tons of converter products for which there were no assays for palladium are: scrap regulus and cleanings 84,155, and converter cleanings 5,360.

⁴Includes leady dust.

All palladium known in converter products at type 1 plants was in blister at two plants (table 34).

In type 2 plants, palladium was detected in blister and anode, dust, and slag (table 35).

The anomalies on palladium input versus output are because type 1 plants provided more complete assay data on converter products.

GENERALIZATIONS ON THE REFINING OF COPPER, MATERIALS FLOW, AND MINOR METALS CONTENTS

For most applications, blister copper (or black copper produced from smelting oxidized ores or native copper ores) has to be refined to remove impurities. Fire refining is the first step of refining operations. This employs oxidation, fluxing, and reducing. Sulfur, cadmium, and zinc are volatilized as furnace gases. Iron, magnesium, and aluminum are slagged off as silicates, while arsenic and antimony may be slagged off with additions of soda ash (Na_2CO_3) and lime to the charge. If enough of the impurities are removed and if recovery of contained precious metals are not of economic interest, the resultant product can be marketed as fire-refined copper. However, most of the partially fire-refined product is cast into anodes and requires electrolytic refining to produce copper of desired purity. Products of electrolytic refining include copper cathodes, tankhouse slimes or electrolytic muds, refinery residues from electrolyte purification, and spent electrolyte (17, 20, 38, 41, 56, 73, 76, 78, 80, 86, 89, 93).

In the electrolytic refining, impurities such as gold, silver, platinum-group metals, arsenic, selenium, and tellurium are recovered. Of the crude copper metal handled by commercial refining plants, it was indicated that the following recoveries were made: gold, 375 ounces per 500 tons of copper; silver, 25,000 ounces per 500 tons of copper; and platinum-group metals, 0.5 to 1 ounce per 500 tons of copper, with more palladium than platinum.

Selenium and tellurium in the anodes go to the slimes as silver selenides and tellurides; excess selenium and tellurium combine with copper and report to the slimes as copper selenides and tellurides. Arsenic dissolves at the anodes as arsenic acid and goes to the electrolyte.

Some typical analyses of six blister coppers fed to anode furnaces ranged from 0.01 to 3.2 ounces of gold per ton, 2.4 to 195.0 ounces of silver per ton, 0.01 to 0.40 percent arsenic, 0.005 to 0.30 percent selenium, and 0.01 to 0.04 percent tellurium (17, p. 124).

The efficiency of electrolytic copper refining is shown by comparing the amount of impurities in the input copper anodes and the output refined cathode copper. In a typical tankhouse, gold was reduced from 0.265 ounce to trace quantities per ton while silver was reduced from 62.44 ounces to 0.30 ounce per ton (78, pp. 165-166). Arsenic was reduced from 0.0435 percent to 0.001 percent, selenium was reduced from 0.0176 percent to 0.0003 percent, and tellurium was reduced from 0.0122 percent to 0.0002 percent.

Some typical analyses on anodes fed to electrolytic refining were: gold, 0.01 to 3.6 ounces per ton; silver, 2.4 to 91.0 ounces per ton; arsenic, 0.004 to 0.32 percent; selenium, 0.01 to 0.20 percent; and tellurium, 0.006 to 0.08 percent (17, p. 125). Anodes treated at the Great Falls, Mont., refinery from 1929 to 1932 averaged 0.073 percent arsenic, 0.011 percent selenium, and 0.079 percent tellurium (86, p. 285). Assays on anodes treated at the Raritan Copper Works of The Anaconda Co. showed 30 ounces of silver per ton, 0.40 ounce of gold per ton, 0.06 percent arsenic, 0.048 percent selenium, and 0.038 percent tellurium (86, p. 274).

In a typical tankhouse, of the approximately 5.4 pounds of arsenic contained in the portion of the anode corroded in processing, over 2 pounds is removed in the slimes. All of the selenium, tellurium, and gold and practically all of the silver go to the slimes.

The anode mud (slimes) from the anode feed for domestic plants ranged from about 2 to 3 pounds to as high as 18 pounds of slime per ton of anode copper feed (73, p. 160). The slimes fall at certain plants was: ASARCO, Baltimore, Md., 12.5 pounds per ton; Kennecott, Garfield, Utah, 10 pounds per ton; Phelps Dodge, El Paso, Tex., 2 to 3 pounds per ton; Anaconda, Raritan, N.J., 8 pounds per ton; and U.S. Metals Refining Co. (AMAX), Carteret, N.J., 18 pounds per ton. Other data included ASARCO, Perth Amboy, N.J., 16.4 pounds per ton; ASARCO, Tacoma, Wash., 17 pounds per ton; Anaconda, Great Falls, Mont., 5.6 pounds per ton; and Phelps Dodge, Laurel Hill, N.Y., 5.8 pounds per ton (41, p. 214-219). Data, received in this study, indicate that refinery slimes at five plants range from about 3.1 to 21.0 pounds per ton of anode.

The following assays were shown for anode muds at various domestic refineries (78, table 27, pp. 150-157). Gold, from about 1.5 ounces per ton at Garfield, Utah, to 508 ounces per ton at Tacoma, Wash.; silver, from about 17.1 ounces per ton at Garfield to about 11,107 ounces per ton at Great Falls, Mont. Other data on arsenic, selenium, and tellurium were incomplete, being presented for only six plants. Other anode slimes assays were available in the literature (38, p. 136; 86, p. 242). Silver ranged from 300 to 5,000 ounces per ton and from 3,000 to 14,900 ounces per ton, gold ranged from 10 to 500 ounces per ton and from 16 to 200 ounces per ton, arsenic ranged from 0.5 to 5.0 percent and 2.7 to 3.9 percent, selenium ranged from 2 to 20 percent and 1.5 to 9 percent, and tellurium ranged from a trace to 4 percent and from 0.8 to 6 percent.

Some electrolytic plants have slime treatment plants; some do not. For example, The Anaconda Co.'s Great Falls refinery lacks a slimes treatment plant and shipped slimes to the company's Raritan Copper Works (86, p. 284). The leached slimes from Great Falls assayed about 13,300 ounces of silver per ton, 75 ounces of gold per ton, 5.0 percent arsenic, 2.0 percent selenium, and 15.6 percent tellurium (86, p. 286).

Slimes produced from Anaconda anodes at the Raritan works assayed 12,610 ounces of silver per ton, 68.4 ounces of gold per ton, 3.88 percent arsenic, 1.46 percent selenium, and 6.14 percent tellurium (86, p. 280). At the plant the slimes were said to average 0.6 percent (12 pounds per ton) of the weight of the anodes.

A simplified flowsheet and a description of copper slimes treatment shows leaching to remove copper; cupellation to remove arsenic, lead, antimony, and bismuth; formation of niter slag to remove selenium and tellurium; electrolysis to remove silver and gold; and the recovery of platinum-group metals (93, pp. 661-663). Methods used to remove selenium and tellurium and the Moebius, Balbach-Thum, and Wohlwill processes to refine gold and silver are described and illustrated (20, 28, 42-43, 74, 89). As shown in figure 1, Doré metal serves as anode in Balbach-Thum electrolysis which removed silver. The anode mud from this process contains gold and is removed, washed, dried, and parted with sulfuric acid, and eventually melted and cast into anodes for the Wohlwill process which produces gold cathodes and anode muds enriched in platinum-group metals.

The three main methods used to remove selenium include soda roasting, acid roasting, and smelting with sodium and niter; the last method is illustrated by Petrick, Bennett, Starch, and Weisner (89, p. 60). Soda smelting was used at AMAX Garteret, and sulfuric acid roasting at Kennecott Copper Corp., Utah (43, pp. 812, 816). Other methods include soda roasting (a Swedish process) and direct oxidation, currently or formerly used in Europe.

With soda smelting, selenium recovery was said to be about 80 percent efficient because of losses in slags, flue dusts, and flue gas; but the method was said to be simple and economical (43, p. 813). Although selenium extraction with soda roasting may show a recovery of 95 percent, the presence of high tellurium content is detrimental. At a Canadian plant, most of the overall losses of about 7 percent were in the selenium solution to the sewer, to the return to smelter in refinery slag, and to the anode furnace stack (31, p. 517).

It was said that the decopperized slimes containing tellurium are treated (1) by refining with soda ash in a doré or cupelling furnace; (2) by oxidizing and alkalizing by roasting or baking a slimes-soda mix; (3) by deselenizing roasting and caustic soda leaching, and (4) by boiling slimes with caustic soda (42, pp. 759-760). The products of soda slag and roaster product can be water-leached to extract sodium tellurite.

DOMESTIC COPPER REFINERIES

The names, locations, and pertinent data on domestic copper refineries are shown in figure 2 and table 1. Operating data were given for domestic and foreign electrolytic copper refineries by Eichrodt and Schloen (41, pp. 214-219).

Published data on products and capacities at these plants, although incomplete, are as follows: Kennecott's Garfield, Utah, daily refinery capacity is reported to be 592 tons of copper, 1,059 ounces of gold, 7,821 ounces of silver, 1.1 ounces of platinum, 4.9 ounces of palladium, and 10,625 pounds of selenium (120). Phelps Dodge Annual Report 1976 stated the 1976 combined production of the firm's El Paso and Laurel Hill refineries as 540,362 short tons of copper, 3,025,084 ounces of silver, and 48,396 ounces of gold (92). The El Paso plant also produced platinum, palladium, selenium, and tellurium.

According to Skinner, ASARCO's Perth Amboy plant could produce 460 tons of copper and 180,000 ounces of silver per day. Other plants with their published daily capacities for refined copper follow: ASARCO, Tacoma, Wash., 425 tons; Inspiration, Miami, Ariz., 210 tons; Magma, Ariz., 600 tons; Kennecott, Hurlley, N. Mex., 280 tons; Phelps Dodge, Laurel Hill, N.Y., 500 tons; White Pine, Mich., 220 tons; and Kennecott Refining Corp., Baltimore, Md., 1,085 tons (49).

Cast electrolytic copper (cathodes) at Raritan assayed 0.001 percent silver (0.29 troy ounce per ton), 0.00001 percent gold (0.003 troy ounce per ton), and 0.0015 percent arsenic (86, p. 280). Other typical analyses of refined copper showed the following: gold, 0.002 to 0.01 troy ounce per ton; silver, 0.05 to 0.5 troy ounce per ton; arsenic, 0.0001 to 0.001 percent; selenium, 0.0003 to 0.001 percent; and tellurium, 0.0001 to 0.0009 percent (73, p. 158).

Near Amarillo, Tex., ASARCO dedicated a new electrolytic copper refinery in June 1976. By yearend 1975 it had been operating at about 50 percent of its planned capacity of 420,000 tons per year 99.9 percent pure cathodes (6, p. 7; 7, pp. 4, 7). The plant is refining copper cathodes from blister and anode it receives from El Paso, Tex., Hayden, Ariz., and other sources. A byproducts facility has the capability of recovering gold, silver, selenium, tellurium, and nickel salts from refinery residues. The silver refining plant, the largest in the world, can produce 60 million ounces of refined silver per year. When the Amarillo refinery came on-stream, the Baltimore refinery was phased out.

Domestic refineries used blister and anode copper from Arizona, Michigan, Montana, Nevada, New Jersey, New Mexico, New York, Pennsylvania, Tennessee, Texas, Utah, and Washington, as well as Chile, Mexico, Peru, the Republic of South Africa, and the Territory of South-West Africa.

About 92 percent of the blister and anode (with a small amount of cathodes and other materials) used by domestic refineries was of domestic origin. The largest amount of domestic feed (about 42 percent) came from Arizona. In diminishing quantities, the rest were from Utah (about 14 percent), Montana (about 11 percent), New Jersey (9 percent), Texas (5 percent), and smaller amounts from Washington, New Mexico, Michigan, Nevada, New York, Tennessee, and Pennsylvania. At least 3 percent of feed was in the form of scrap.

Of the foreign countries providing anodes and blister copper, the most important was Peru (with about 61 percent of foreign total), followed by Chile (with 24 percent), the Republic of South Africa and the Territory of South-West Africa (with about 6 percent each), and Mexico (3 percent).

Three companies in Chile provided blister and anode copper to U.S. refineries. Compañía Minera Disputada de las Condes S.A. operated a smelter at Chagres which had an annual capacity of 20,000 metric tons of blister copper (49, p. 190). Compañía de Cobre Chuquicamata, part of Corporación del Cobre (CODELCO), operated a smelter at Chuquicamata which produced blister, anodes, and cakes (44, p. 224). Corporación Nacional del Cobre de Chile (CODELCO-Chile)

operated a smelter at Potrerillos which produced blister, anodes, and cakes (44, p. 225).

The Industrial Minera Mexico S.A. smelter at San Luis Potosí, State of San Luis Potosí, Mexico, formerly owned by ASARCO Mexicana, supplied blister to ASARCO's Perth Amboy refinery. The company is owned 51 percent by Mexican interests and 49 percent by ASARCO. A new 45,000-ton-per-year refinery at San Luis Potosi was completed in 1976 (44, p. 255; 99).

The Toquepala smelter of Southern Peru Copper Corp. at Ilo, Peru, was owned by the following companies: ASARCO, 51.5 percent; Phelps Dodge, 16 percent; Cerro Corp., 22.25 percent; and Newmont, 10.25 percent. The plant supplied blister to refineries owned by Kennecott Refining Corp. in Baltimore, Md., Phelps Dodge in New York, and anode copper to AMAX, Carteret, N.J.

In the Republic of South Africa, O'Okiep Copper Co., Ltd., sent blister from its Nababeep, Namaqualand, smelter to the AMAX Carteret refinery. The smelter has operated since August 1940 (49, p. 446).

The Tsumeb smelter owned by Tsumeb Corp., Ltd., in the Territory of South-West Africa, sent blister to the AMAX Carteret refinery. The smelter has been operated since November 1962 and was said to have an annual output capacity of 20,000 tons blister copper (49, p. 570).

MINOR METALS IN REFINERY FEED, 1971-74

As indicated in the previous section and in table 1, refinery feed materials consist mostly of blister and anode copper, but cathodes and scrap are used also.

Assays for the minor metals in domestic blister are shown in the previous sections and tables on converter products. Assays for these, for cathodes, and for foreign unrefined copper (blister and anodes) are shown in the following sections on the individual minor metals. The quantities estimated for each element in the anodes and blister are restricted in some cases by the lack of both quantitative and assay data. There were no assays for platinum or palladium in foreign feed materials and no assays for any of the minor metals in copper cakes and molds.

Flowsheets showing the input and output of refinery materials in the fire refining and electrolytic refining of copper are shown in figures 8-9.

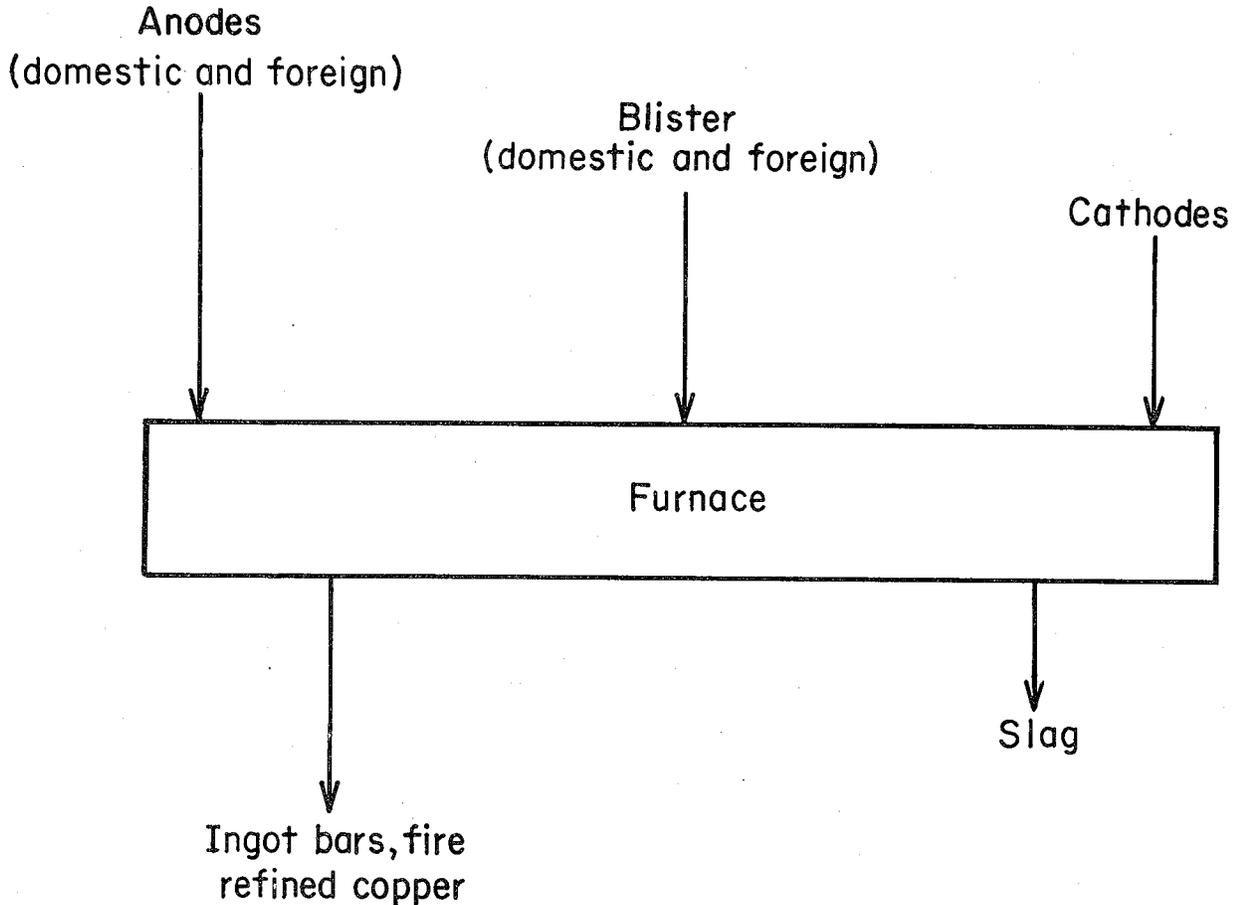


FIGURE 8: - Fire refining of copper.

Arsenic in Blister, Anode, and Other Refinery Feed

Ninety-one percent (nearly 596 tons) of the known arsenic in domestic and foreign blister and anode (about 658 tons) was in material smelted in the United States. Of the arsenic in domestic blister and anode, Washington supplied 43 percent; Texas, 23 percent; New Jersey, 15 percent; Utah, 11 percent; Arizona, about 5 percent; followed by Michigan, Nevada, Pennsylvania, New Mexico, and New York. Assays ranged from 0.0002 percent arsenic in materials from New Mexico and Tennessee to 0.29 percent arsenic in the Washington blister.

Of the 63 tons of arsenic estimated in foreign blister and anode, 73 percent came from Peru, 12 percent each came from the Territory of South-West Africa and Mexico, and the rest came from Chile and the Republic of South Africa. Assays ranged from 0.002 percent arsenic in Chilean blister to 0.25 percent arsenic in Mexican blister.

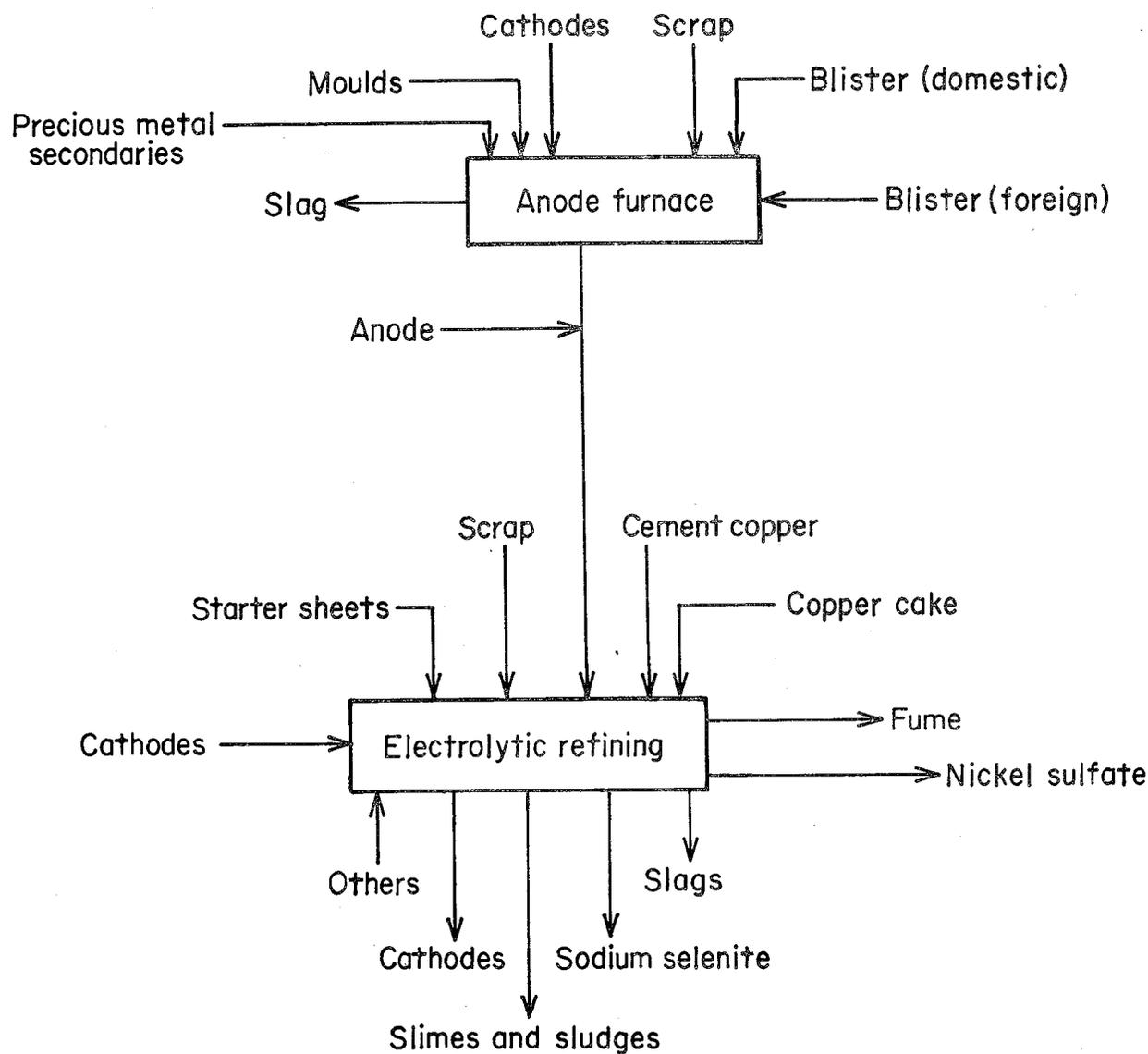


FIGURE 9. - Electrolytic refining of copper.

Some of the domestic copper refineries also used feed other than anode; five fed scrap; one, molds; and one, copper cakes. Based on an assay from one plant only, the scrap feed (anode scrap and reject anodes) contained only about 0.1 ton arsenic.

Selenium in Blister, Anode, and Other Refinery Feed

Ninety-two percent (353 tons) of the known selenium in domestic and foreign blister and anode (total 583 tons) was in material smelted in the United States. Of the selenium in domestic blister and anode, New Jersey supplied 27 percent; Arizona, 25 percent; Utah, 22 percent; Texas, 12 percent; Washington, 6 percent; followed by New Mexico, Nevada, Tennessee, Michigan,

and New York. Assays ranged from 0.0025 percent selenium in Michigan blister to 0.07 percent selenium in materials from Tennessee and Texas.

Of the 48 tons of selenium in foreign materials, Mexico supplied 47 percent; the Territory of South-West Africa, 22 percent; Peru, 18 percent; the Republic of South Africa, 10 percent; and Chile, 3 percent. Assays ranged from 0.01 percent selenium in Chilean and Peruvian materials to as high as 0.56 percent in Mexican blister.

Based on assays (0.001 and 0.032 percent) from two plants, scrap feed (including anode scrap and reject anodes) contained about 1 ton of selenium.

Tellurium in Blister, Anode, and Other Refinery Feed

Ninety-three percent (about 114 tons) of the known tellurium in domestic and foreign blister and anode (a total of about 122 tons) was in material smelted in the United States. Of tellurium in domestic blister and anode, New Jersey supplied 32 percent; Utah, about 31 percent; Texas, 18 percent; Arizona, 16 percent; followed by Washington, Nevada, New Mexico, Tennessee, Michigan, and New York. Assays ranged from 0.0002 percent tellurium in Michigan blister to 0.025 percent tellurium in Texas anodes.

Of the 8 tons of tellurium in foreign materials, the Republic of South Africa supplied 70 percent; Mexico, 15 percent; Peru, 13 percent; and the Territory of South-West Africa and Chile, 2 percent. Assays on foreign materials ranged from 0.0005 percent tellurium in Chilean blister to 0.06 percent tellurium in the Territory of South-West Africa material.

Based on assays (0.001 and 0.0018 percent) from two plants, scrap feed (including anode scrap and reject anodes) contained about 0.4 ton tellurium.

Gold in Blister, Anode, and Other Refinery Feed

More than 99 percent of the total known gold in domestic and foreign blister and anode (1,046,625 troy ounces) was in domestically produced metal with new Jersey supplying 38 percent of this; Utah, 31 percent; Washington, 16 percent; Arizona, 6 percent; followed by Nevada, Texas, New Mexico, Pennsylvania, Tennessee, Michigan, and others. Assays ranged from 0.015 ounce per ton in some Arizona material to 2.89 ounces per ton in New Jersey anodes.

From the data available, it was estimated that less than 1 percent of the gold in blister and anode came from foreign sources. Of this, Mexico supplied about 61 percent; the Republic of South Africa, 19 percent; Peru, 8 percent; the Territory of South-West Africa, 7 percent; and Chile, 5 percent. Assays ranged from 0.0079 ounce per ton in Peruvian blister to 1.15 ounces per ton in Mexican blister.

Only about 90 ounces of gold were calculated in anode scrap and reject anodes at one plant.

Silver in Blister, Anode, and Other Refinery Feed

Ninety-seven percent of the total known silver in domestic and foreign blister and anode (32,330,522 ounces) was in metal processed in the United States. Of this, 32 percent came from Washington State, 23 percent from New Jersey, 16 percent from Arizona, 14 percent from Texas, 10 percent from Utah, and the rest from Michigan, New Mexico, Nevada, Tennessee, and Pennsylvania. Assays ranged from 0.2 ounce of silver per ton in an Arizona material to 112.7 ounces per ton in Washington unrefined copper.

About 3 percent of the silver in blister and anode came from foreign sources, of which Peru supplied 49 percent; the Territory of South-West Africa, 40 percent; Chile, 6 percent; the Republic of South Africa, nearly 5 percent; and Mexico the rest. Assays ranged from 1.49 ounces of silver per ton for some Mexican blister to almost 48 ounces of silver per ton in material from the Territory of South-West Africa.

Anode scrap and reject anodes at one plant contained 11,254 ounces of silver.

Platinum-Group Metals in Blister, Anode, and Other Refinery Feed

Of the 21,275 ounces of platinum known in domestically produced metal, 81 percent was in anodes at a New Jersey plant, about 16 percent was in unspecified material, about 1.5 percent was in blister from a Pennsylvania plant, and the rest was from Utah and Arizona. Assays ranged from 0.001 ounce of platinum per ton in Arizona and Utah anodes to 0.2 ounce of platinum per ton in Pennsylvania blister. Of the 113,884 ounces of palladium known in U.S. materials, 62 percent was in anodes from a New Jersey plant, 29 percent came from Arizona materials, about 3 percent came from unspecified material, and the rest came from Pennsylvania blister and Utah anodes. Assays ranged from 0.001 ounce of palladium per ton for some Arizona materials to 0.86 ounce of palladium per ton for Pennsylvania blister.

MINOR METALS IN REFINERY PRODUCTS, 1971-74

It was previously shown that refinery products consist mostly of cathodes (12 plants) and fire-refined copper (5 plants) but slimes and sludges, slags, dusts, nickel sulfate, and other materials are generated also. Actually, these products are intermediates that are reprocessed with the refinery shipping gold and silver bullion, refined copper, and other refined metals or products.

The quantities estimated for each element in the refinery products are restricted by the lack of data in some cases. For example, certain data were lacking for slags at five plants (both fire and electrolytic), nickel sulfate at four electrolytic plants, and dusts, slimes, and cathodes at several plants. Also note the anomalies between inputs and outputs on gold, silver, and platinum-group metals, some of which are explained later.

Arsenic

The known quantity of arsenic in products was 192 tons compared with 658 tons known in refinery feed. The largest quantity of arsenic known in these products occurred in slimes and sludges (about 58 percent) followed by slags (about 32 percent), sodium selenite (7 percent), and cathode, fume, and fire-refined copper.

Assays for arsenic in slimes and sludges ranged from 0.0007 to 6.02 percent with 3.25 percent in an arsenical sludge. Arsenic in slags ranged from 0.18 to 2.58 percent. A sodium selenite contained 6.66 percent arsenic and copper samples contained 0.0001 to 0.0008 percent arsenic. Residues from one plant, probably a precious metal refinery, included items such as flue dust, refinery pit metallics, sweepings, cobbings, arsenical and foul cathodes, sludge, and slag. These averaged 0.38 percent arsenic.

Selenium

The selenium known in these products was 694 tons compared with the 583 tons known in refinery feed. Slimes and sludges contained the largest quantity of selenium (62 percent of the total known), followed by slags with 32 percent, sodium selenite with about 3 percent, fire-refined copper (about 2 percent), and cathodes and fume.

Assays on slimes and sludges ranged from 4.19 to 31.7 percent selenium, slags ranged from 0.14 to 24.6 percent (in a selenium-sodium slag), and sodium selenite was 8.91 percent. Fire-refined copper contained 0.002 and 0.0134 percent selenium, cathode copper contained 0.000107 to 0.00044 percent selenium, and a small amount of baghouse dust contained 1.50 percent selenium. Precious metal refinery residues, in which a doré slag contained 1.13 percent selenium, averaged 0.27 percent selenium.

Tellurium

The tellurium known in these products was 284 tons compared with only 122 tons known in refinery feed. Slags contained 48 percent of the tellurium, and slimes and sludges contained 44 percent. Sodium selenite contained almost 8 percent, and fire-refined copper and cathode copper contained the rest.

Slimes contained 0.36 to 5.04 percent tellurium, and slags contained 0.35 to 4.23 percent (in a selenium-sodium slag). Sodium selenite contained 10.69 percent tellurium, one fire-refined copper contained 0.0013 percent, cathodes contained 0.00005 to 0.00023 percent, and baghouse fume contained 1.17 percent. Precious metal refinery residues, in which a doré slag contained 1.76 percent tellurium, averaged 0.54 percent tellurium.

Gold

The known gold in these products was 759,565 ounces compared with more than 1 million ounces known in refinery feed. Ninety-five percent of the known gold in refinery intermediate products occurred in slimes and sludges,

about 2.5 percent in slags, and practically all the rest in fire-refined and cathode copper.

Several sludges contained 0.015 (in an arsenic sludge) to 0.126 ounce of gold per ton; slimes ranged from 47.1 to 267 ounces of gold per ton. Slags contained from 0.064 to 9.38 ounces of gold per ton. Fire-refined copper ranged from 0.015 to 0.1 ounce of gold per ton, and cathode ranged from 0.002 to 0.02 ounce of gold per ton. Precious metal refinery residues, in which a doré slag contained 38.06 ounces of gold per ton, averaged 7.23 ounces of gold per ton.

Silver

The known silver in these products was 31,687,997 ounces compared with over 32.3 million ounces known in refinery feed. About 87.5 percent of known silver in refinery intermediate products was in slimes and sludges and about 7.5 percent was in slags (mostly in lead slag). More than 4 percent was in fire-refined copper, and the remainder was in cathode, sodium selenite, and fume.

Arsenical sludge contained 0.16 ounce of silver per ton, and sludge contained 4.75 ounces of silver per ton. Slimes ranged from 1,927.2 to 9,103.8 ounces of silver per ton. Slags contained 0.1 through 493 ounces of silver per ton in lead slag and 651.33 ounces per ton in a so-called "sharp" slag. Cathode copper ranged from a trace to about 0.6 ounce of silver per ton, and fire-refined copper ranged from 1.89 to 16 ounces of silver per ton. Dust from one plant contained over 18 ounces of silver per ton.

Precious metal refinery residues, with a doré slag containing 1,156.7 ounces of silver per ton, averaged 170.53 ounces of silver per ton.

Platinum-Group Metals

In these products the known platinum was 906 ounces compared with 21,275 ounces in feed, the known palladium was 5,367 ounces compared with 113,884 ounces in feed. The apparently anomalous contents of platinum and palladium in the products compared with those in feed materials are because companies provided more complete assay data on the feed.

Almost 98 percent of platinum in products was in slimes and the rest in slags. Practically all of the palladium in products was in slimes; only a small amount occurred in slags. Platinum in slimes ranged from 0.27 to 0.81 ounce per ton, and palladium in slimes ranged from 1.01 to 7.77 ounces per ton.

NEWER TECHNOLOGY

Efforts to control pollution emissions has led to the development of several new processes, both pyrometallurgical and hydrometallurgical, for extracting copper (94). These new technologies, if extensively used, would have an important impact on the recovery of contained byproduct metals. However, information on these potential recoveries is inadequate to make any definitive judgments.

Pyrometallurgical processes consist of the Mitsubishi, WORCRA, and Noranda continuous, direct-smelting methods which maximize sulfur dioxide concentration and economic recovery. Other pyrometallurgical methods being developed include the Australian Britcosmaco, Canadian TBRC, Russian Kivcet, and Federal Bureau of Mines autogeneous smelting processes.

In hydrometallurgy, the Sherritt Gordon (Canadian) process is a commercially proved process for the direct leaching of sulfide concentrates. The process was designed to leach nickel, copper, and cobalt from Lynn Lake, Canada, concentrates, but Treilhard (113) says it has not been competitive with conventional smelting processes for treating copper sulfide concentrates of lower unit value. The chemistry of the leaching and copper precipitation steps and the effects of various factors were discussed in an earlier article (50, pp. 457-463).

Three domestic hydrometallurgical processes are currently operative or are nearly ready for industrial usage. They consist of The Anaconda Co.'s Arbiter, Cyprus Mining's Cymet, and Duval's Clear processes.

The Arbiter hydrometallurgy process plant at Anaconda, Mont., went on-stream in September 1974. In this method, concentrates are leached with ammonia and oxygen at atmospheric pressure and ambient temperature (94). Subsequently, the copper is extracted from the filtered pregnant solution with an organic solvent; the copper is stripped from the organic by an acid electrolyte and recovered in cathode form by electrowinning. If arsenic is present, it dissolves and is subsequently precipitated with iron and stabilized as ferric arsenate (69). Percentages of silver and arsenic in products from the leaching of copper concentrates are presented in the tables. Tests of the Victoria, Nev., chalcopryrite concentrates, which are high in bismuth content (as bismuthinite), indicate that most of the bismuth reports to the residue from leaching.

In an April 1975 presentation, it was shown that the Arbiter process is a versatile system for performing chemical and physical separations (68). An enargite sample contained 63.8 volume-percent enargite with lesser quantities of chalcopryrite, tetrahedrite, covellite, bornite, and others. Of the nearly 10 percent arsenic in the heads of the enargite sample, nearly 75 percent reported to the tails in the flotation of the leach residue in the processing of the concentrate.

It is believed that oxidizing ammoniacal leaching has a definite potential for the economic recovery of zinc from concentrates. A copper-cadmium residue is obtained after filtering the products of copper-cadmium cementation. The gold and silver values, if present, report to the residue flotation tails and are recovered by cyanide leaching.

As part of the conclusion, it was pointed out that the conventional concentrate grade requirements set by smelters need not be met and that penalty elements in concentrates are no longer relevant. The latter is true because those elements can be included with flotation concentrates and then separated by selective leaching or solvent ion exchange.

The "Cymet" process under development by Cyprus Metallurgical Process Corp. at a plant south of Tucson, Ariz., seeks a pollution-free alternate to pyrometallurgy in reducing base-metal sulfides to metal. The process involves electro-oxidation of sulfide to sulfur at an anode with the simultaneous solution of metal ions and their consequent reduction to metal at a cathode. Copper, sulfur, and iron are recovered as the elements, while solution purification captures arsenic, bismuth, and lead through cementation with metallic zinc (67). On the basis of laboratory studies, possible advantages of the process in treating nickel-copper sulfides were indicated.

A flowsheet for Duval Corp.'s Clear process was published and a patent (U.S. 3,785,944, January 15, 1974) indicates the information presented to date on this method (39). Several other research efforts on hydrometallurgical processes were also indicated; for example, an Australian process used leaching by a solution of sulfuric acid and acetonitrile. Another process combines leaching and electrowinning into a single continuous step for direct recovery of copper from sulfide concentrates, cement copper, copper scrap, and copper oxide slurries (87).

With the Treadwell hydrometallurgical process, which has been tried by The Anaconda Co., corrosion problems have prevented commercial acceptance (94).

The Federal Bureau of Mines is working toward developing simple, economic, nonpolluting, and low-capital-cost metal extraction methods. In one process under test, lead-zinc concentrates are chlorinated in an aqueous slurry resulting in the production of lead chloride, lead sulfate, elemental sulfur, and solubilized metal values (63). Cadmium, silver, and copper eventually report to the leach liquor and then are recovered by fire-refining.

Another Bureau of Mines study entails the inert atmosphere roasting of chalcopyrite prior to selective leaching of iron from the calcined product (114). The leach residue is dissolved in a copper sulfate-sulfuric acid electrolyte, from which high-purity copper is recovered by electrowinning. Sulfur, gold, and silver are recoverable--the first in the elemental form from roasting and leaching and the last two from a silica residue from leaching.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of samples and other information supplied by copper smelters and refiners which account for 92 percent of installed capacity during 1971-74, several conclusions and recommendations can be made.

The content of many minor metals in ores and concentrates is so low that they have not been determined for technologic or economic reasons. Consequently, the total of the inputs of the minor metals is not fully known. As processing proceeds, the byproduct metals are concentrated in calcines, flue dusts, mattes, or in the blister in quantities that can be determined. This study was greatly aided by those plants that provided either samples or assay data with the weight of material represented. In other instances, the samples were not representative or were unavailable.

Some copper concentrates processed were relatively rich in minor metals. For example, copper concentrates from Colorado and Idaho were high in arsenic as were those from Peru and the Philippines. Similarly, concentrates from Nevada, Tennessee, and the Philippines were highest in selenium; and concentrates from Colorado and the Philippines were richest in tellurium. The gold content was greatest in concentrates from Colorado, Nevada, Utah, Canada, and the Philippines; silver was highest in copper concentrates from California, Idaho, Canada, and Peru. Data were scant on the platinum-group metals, but Utah concentrates appeared to be the richest.

Generally, copper precipitates were lower than concentrates in byproduct values, but they did carry values in arsenic and tellurium in two instances.

It was noted that smelting intermediates such as speiss, flue dusts, and sludges became enriched in arsenic, gold, and silver. It was shown that 56 percent of the arsenic, 43 percent of the gold, and 49 percent of the silver in domestic materials fed to roasters was in the intermediates or, as in one case, in an arsenical pyrite. The flue dusts from both roasters and reverberatory smelting furnaces were recycled and thus became further enriched.

Available weights and assays provided various degrees of accuracy in showing inputs and outputs of the minor metals in roasting, reverberatory smelting, and converting. Roaster calcine data received from two plants indicated the calcines contained 83 percent of the known arsenic in the concentrate feed. Recycling and the lack of specific data on dusts and fumes obscured the true picture of minor metals in these materials.

Blister and anode copper are the major feed materials to refineries. The difficulty of correlating widely differing assays with specific feed quantities to the refineries made it difficult to obtain a true picture of overall input or output of minor metals.

Because intermediate products are not weighed, often not assayed, and invariably recycled (sometimes being shipped to other plants for recycling), it becomes difficult to establish metallurgical balances and to measure the point and amount of byproduct recovery or loss.

The detailed analyses of the partial data clearly point out the need to develop a better metallurgical accounting capability. Close perusal of this report with its inadequacies indeed might provide incentive for better practice and the conduct of research to improve the utilization and husbandry of the Nation's mineral resources.

BIBLIOGRAPHY

1. Ageton, R. W. Selenium. Ch. in Mineral Facts and Problems. BuMines Bull. 650, 1970, pp. 713-726.
2. Ageton, R. W., and J. P. Ryan. Platinum-Group Metals. Ch. in Mineral Facts and Problems. BuMines Bull. 650, 1970, pp. 653-669.
3. American Bureau of Metal Statistics. Yearbook 1971. Issued June 1972, New York, 148 pp.
4. _____. Yearbook 1973. Issued June 1974, New York, 152 pp.
5. American Smelting and Refinishing Co. 1974 Annual Report.
6. _____. 1975 Annual Report.
7. _____. 1976 Annual Report.
8. The Anaconda Co. 1973 Annual Report.
9. _____. 1974 Annual Report.
10. _____. 1975 Annual Report.
11. Anderson, C. A. Copper. Ch. in Mineral and Water Resources of Arizona. Report prepared by the U.S. Geological Survey, Arizona Bureau of Mines, and U.S. Bureau of Reclamation for the Committee on Interior and Insular Affairs. U.S. Senate, 90th Cong., 2d sess., 1969, pp. 117-156.
12. _____. Alteration and Metallization in the Bagdad Porphyry Copper Deposit, Arizona. Econ. Geol., v. 45, No. 7, November 1950, pp. 609-628.
13. _____. Arizona and Adjacent New Mexico. Ch. 56 in Ore Deposits of the United States, v. 2, 1968, pp. 1163-1190.
14. Anderson, E. C. The Metal Resources of New Mexico and Their Economic Features Through 1954. New Mexico Bureau of Mines and Mineral Resources, Bull. 39, 1957, 183 pp.
15. Babitzke, H. R., W. D. Hardeman, and R. E. Hershey. The Mineral Industry of Tennessee. BuMines Minerals Yearbook 1971, v. 2, 1973, pp. 673-678.
16. _____. The Mineral Industry of Tennessee. BuMines Minerals Yearbook 1972, v. 2, 1974, pp. 661-677.
17. Baier, R., and M. B. Kushma. Anode Furnace Refining. Ch. 5 in Copper, the Science and Technology of the Metal, Its Alloys and Compounds, ed. by A. Butts. Reinhold Publishing Corp., New York, 1954, pp. 119-137.

18. Batty, J. V., and B. F. Andrew. Leach-Precipitation-Flotation Studies on Red Bed Copper Ore Using Controlled Atmosphere. BuMines RI 7375, 1970, 9 pp.
19. Beall, J. V. Copper Paces Mining Expansion in the Philippines. Min. Eng., v. 21, No. 4, April 1969, pp. 63-72.
20. Bray, J. L. Non-Ferrous Production Metallurgy. John Wiley & Sons, Inc., New York, 1941, 430 pp.
21. British Columbia Department of Mines and Petroleum Resources. Geology, Exploration, and Mining in British Columbia 1970, 561 pp.
22. Brobst, D. A., and W. P. Pratt (ed. by). United States Mineral Resources. U.S. Geol. Survey Prof. Paper 820, 1973, 722 pp.
23. Brown, B. C. The Mineral Industry of the Philippines. BuMines Minerals Yearbook 1971, v. 3, 1973, pp. 661-667.
24. Bryant, D. G., and H. E. Metz. Geology and Ore Deposits of the Warren Mining District. Ch. in Geology of the Porphyry Copper Deposits, Southwestern North America, ed. by S. R. Titley and C. L. Hicks. The Univ. of Arizona Press, Tucson, Ariz., 1969, pp. 189-203.
25. Butts, A. Copper. The Science and Technology of the Metal, Its Alloys and Compounds. Reinhold Publishing Corp., New York, 1954, 936 pp.
26. Cammarota, V. A., Jr. The Mineral Industry of Nevada. BuMines Minerals Yearbook 1970, v. 2, 1972, pp. 455-469.
27. _____. The Mineral Industry of Nevada. BuMines Minerals Yearbook 1971, v. 2, 1973, pp. 465-478.
28. Carrillo, F. V., M. A. McComb, and N. S. Petersen. The Mineral Industry of Idaho. BuMines Minerals Yearbook 1969, v. 3, 1973, pp. 239-254.
29. Carter, F. E. Gold and Gold Alloys. Ch. in Encyclopedia of Chemical Technology, ed. by R. E. Kirk and D. F. Othmer. The Interscience Encyclopedia, Inc., New York, v. 7, 1951, pp. 274-284.
30. Cities Service Co. Annual Report 1975.
31. Clark, C. W., and J. H. Schloen. Recovery of Precious Metals and Production of Selenium and Tellurium at Montreal East. Trans. AIME, v. 159, Reduction and Refining of Nonferrous Metals, 1944, pp. 495-520.
32. Clarke, T. G. Silver. BuMines Minerals Yearbook 1974, v. 1, 1976, pp. 1181-1199.
33. Coakley, G. J. Selenium. Ch. in Mineral Facts and Problems. BuMines Bull. 667, 1976, pp. 955-961.

34. Cox, D. P., R. G. Schmidt, J. D. Vine, H. Kirkemo, E. B. Tourtelot, and M. Fleischer. Copper. Ch. in United States Mineral Resources, U.S. Geol. Survey Prof. Paper 820, 1973, pp. 163-190.
35. Davidson, D. F., and H. W. Lakin. Tellurium. Ch. in United States Mineral Resources, U.S. Geol. Survey Prof. Paper 820, 1973, pp. 627-630.
36. Davis, L. E., and J. G. Bond. The Mineral Industry of Idaho. BuMines Minerals Yearbook 1974, v. 2, 1977, pp. 213-224.
37. Dayton, S., and D. Jackson, Jr. Mining Program Aims at Growth Opportunities, Pt. 2. Inspiration Copper (Ore to Rod). Eng. and Min. J., v. 175, No. 8, August 1974, pp. 63-74.
38. Dennis, W. H. Metallurgy of the Non-Ferrous Metals. Sir Isaac Pitman & Sons, Ltd., London, 2d ed., 1961, 711 pp.
39. Drescher, W. H. Chemical Processing. Min. Eng., v. 27, No. 2, February 1975, pp. 58-60.
40. Eastlick, J. T. Geology of the Christmas Mine and Vicinity. Banner Mining District, Arizona. Ch. 57 in Ore Deposits of the United States, v. 2, 1968, pp. 1191-1210.
41. Eichrodt, C. W., and J. H. Schloen. Electrolytic Copper Refining. Ch. 8 in Copper. The Science and Technology of the Metal, Its Alloys and Compounds, ed. by A. Butts. Reinhold Publishing Corp., New York, 1954, pp. 165-222.
42. Elkin, E. M. Tellurium and Tellurium Compounds. Ch. in Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc., New York, v. 19, 2d ed., 1969, pp. 756-774.
43. Elkin, E. M., and J. L. Margrave. Selenium and Selenium Compounds. Ch. in Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc., New York, v. 17, 2d ed., 1968, pp. 809-833.
44. Engineering and Mining Journal. International Directory of Mining and Mineral Processing Operations. McGraw-Hill Book Co., Inc., New York, 1976.
45. _____. How White Pine Filters Fine, Slimy Copper Pulp. V. 159, No. 12, December 1958, pp. 104-105.
46. Ensign, C. O., Jr., W. S. White, J. C. Wright, J. L. Patrick, R. J. Leone, D. J. Hathaway, J. W. Trammell, J. J. Fritts, and T. L. Wright. Copper Deposits in the None-Such Shale, White Pine, Michigan. Ch. 22 in Ore Deposits of the United States, v. 1, 1968, pp. 460-488.
47. Everett, F. The Mineral Industry of Arizona. BuMines Minerals Yearbook 1974, v. 2, 1977, pp. 73-92.

48. Fielder, F. M. (ed. by). Canadian Mines Handbook, 1971-1972. Northern Miner Press, Ltd., July 1971, 476 pp.
49. The Financial Times, Ltd. (London). Walter R. Skinner's Mining International Yearbook, 1973-1974, 726 pp.
50. Forward, F. A., and V. N. Mackiw. Chemistry of the Ammonia Pressure Process for Leaching Ni, Cu, and Co From Sherritt Gordon Sulphide Concentrates. *J. Metals*, v. 203, March 1955, pp. 457-463.
51. Gray, R. F., V. J. Hoffman, R. J. Bagan, and H. L. McKinley. Bishop Tungsten District, California. Ch. 73 in *Ore Deposits of the United States*, v. 2, 1968, pp. 1531-1554.
52. Grunenfelder, J. G. The Hydrometallurgy of Copper. Ch. 13 in *Copper. The Science and Technology of the Metal, Its Alloys and Compounds*, ed. by A. Butts. Reinhold Publishing Corp., New York, 1954, pp. 300-336.
53. Gualtieri, J. L. Arsenic. Ch. in *United States Mineral Resources*, U.S. Geol. Survey Prof. Paper 820, 1973, pp. 51-61.
54. Hammer, D. F., and D. W. Peterson. Geology of the Magma Mine Area, Arizona. Ch. 61 in *Ore Deposits of the United States*, v. 2, 1968, pp. 1282-1310.
55. Hardwick, W. R., and W. C. Henkes. The Mineral Industry of Arizona. *BuMines Minerals Yearbook 1969*, v. 3, 1971, pp. 89-111.
56. Hayward, C. R. *An Outline of Metallurgical Practice*. D. Van Nostrand Co., Inc., New York, 3d ed., 1952, 728 pp.
57. _____. Copper Slags and Mattes. Ch. 6 in *Copper. The Science and Technology of the Metal, Its Alloys and Compounds*, ed. by A. Butts. Reinhold Publishing Corp., New York, 1954, pp. 138-148.
58. Heyl, A. V., W. E. Hall, A. E. Weissenborn, H. K. Stager, W. P. Puffett, and B. L. Reed. Silver. Ch. in *United States Mineral Resources*, U.S. Geol. Survey Prof. Paper 820, 1973, pp. 581-603.
59. Hillebrand, J. R. The Idarado Mine. Ch. in *New Mexico Geological Society Guidebook of Southwestern San Juan Mountain, Colorado*; 8th Field Conference, Sept. 5-7, 1957, pp. 176-188.
60. Hobbs, S. W., and V. C. Fryklund, Jr. The Coeur d'Alene District, Idaho. Ch. 66 in *Ore Deposits of the United States*, v. 2, 1968, pp. 1417-1435.
61. Hubbell, D. S. Cupreous Powder and Its Applications. Ch. 41 in *Copper. The Science and Technology of the Metal, Its Alloys and Compounds*, ed. by A. Butts. Reinhold Publishing Corp., New York, 1954, pp. 825-833.

62. Jones, W. R. Copper. Ch. in Mineral and Water Resources of New Mexico. Report prepared by the U.S. Geological Survey in cooperation with the New Mexico Bureau of Mines and Mineral Resources, the New Mexico State Engineer Office, and the New Mexico Oil Conservation Commission. Committee on Interior and Insular Affairs. U.S. Senate, 89th Cong., 1st sess., 1965, pp. 160-176.
63. Kirby, R. C., and J. A. Barclay. Extraction Processes for Low-Grade Ores. Min. Eng., v. 27, No. 6, June 1975, pp. 42-47.
64. Kirk, R. C., and D. F. Othmer (ed. by). Encyclopedia of Chemical Technology. The Interscience Encyclopedia, Inc., New York, 1947-1956, with supplemental volumes, 1957 and 1960.
65. _____. Encyclopedia of Chemical Technology. John Wiley & Sons, Inc., New York, 1963-1970, with index and supplemental volume, 1971.
66. Kirkemo, H. Copper. Ch. in Mineral and Water Resources of Nevada. Report of the U.S. Geological Survey in cooperation with the Nevada Bureau of Mines. 88th Cong., 2d sess., 1964, pp. 81-87.
67. Kruesi, P. R., E. S. Allen, and J. L. Lake. Cymet Process--Hydrometallurgical Conversion of Base-Metal Sulfides to Pure Metals. Can. Min. and Met. Bull., v. 66, No. 734, June 1973, pp. 81-87.
68. Kuhn, M. C., and N. Arbiter. Physical and Chemical Separation via the Arbiter Process. Proc. 11th Internat. Min. Processing Cong., Cagliari, Italy, Apr. 21-26, 1975, pp. 831-847.
69. Kuhn, M. C., N. Arbiter, and H. Kling. Anaconda's Arbiter Process for Copper. Can. Min. and Met. Bull., v. 67, No. 742, February 1974, pp. 62-73.
70. Kuklis, A. The Mineral Industry of Colorado. BuMines Minerals Yearbook 1971, v. 2, 1973, pp. 169-195.
71. _____. The Mineral Industry of Colorado. BuMines Minerals Yearbook 1972, v. 2, 1974, pp. 145-172.
72. Lakin, H. W., and D. F. Davidson. Selenium. Ch. in United States Mineral Resources, U.S. Geol. Survey Prof. Paper 820, 1973, pp. 573-576.
73. Lanier, H. Copper. Ch. in Kirk-Othmer Encyclopedia of Chemical Technology. New York Interscience Publishing Inc., John Wiley & Sons, Inc., New York, v. 6, 2d ed., 1967, pp. 131-181.
74. Lansche, A. M. Selenium and Tellurium. A Materials Survey. BuMines IC 8340, 1967, 56 pp.

75. Little, Arthur D., Inc. (Cambridge, Mass.). Economic Impact of New Source Performance Standards on the Primary Copper Industry: An Assessment. Final Report to U.S. Environmental Protection Agency. EPA Contract No. 68-02-1349-Task 2, October 1974, 59 pp.
76. McMahon, A. D. Copper. A Materials Survey. BuMines IC 8225, 1965, 340 pp.
77. Magee, M. Geology and Ore Deposits of the Ducktown District, Tennessee. Ch. 12 in Ore Deposits of the United States, v. 1, 1968, pp. 207-241.
78. Mantell, C. L. Electrochemical Engineering. McGraw-Hill Book Co., Inc., New York, 4th ed., 1960, 680 pp.
79. Meyer, C., E. P. Shea, C. C. Goodard, Jr., and Staff. Ore Deposits at Butte, Mont. Ch. 65 in Ore Deposits of the United States, v. 2, 1968, pp. 1373-1416.
80. Miller, H. J. The Fire Refining of Copper. Ch. 12 in Copper. The Science and Technology of the Metal, Its Alloys and Compounds, ed. by A. Butts. Reinhold Publishing Corp., New York, 1954, pp. 290-299.
81. Mitko, F. C., and J. A. Stock. The Mineral Industry of California. BuMines Minerals Yearbook 1970, v. 2, 1972, pp. 121-157.
82. Moore, L. The Mineral Industry of Arizona. BuMines Minerals Yearbook 1971, v. 2, 1973, pp. 85-104.
83. _____. The Mineral Industry of Arizona. BuMines Minerals Yearbook 1972, v. 2, 1974, pp. 71-95.
84. Murray, G., and H. H. Bein. Rebuilding Lepanto--The Far East's Largest Producer of Copper. Eng. and Min. J., v. 152, No. 3, March 1951, pp. 72, 75.
85. _____. Rebuilding Lepanto--The Far East's Largest Producer of Copper, Pt. 2. Eng. and Min. J., v. 152, No. 4, April 1951, pp. 110-113.
86. Newton, J., and C. L. Wilson. Metallurgy of Copper. John Wiley & Sons, Inc., New York, 1942, 518 pp.
87. Pearson, E. W. A New Pollution-Free Copper Process via Simultaneous Leaching and Electrowinning. Min. Eng., v. 26, No. 12, December 1974, pp. 40-41.
88. Peters, W. C., A. H. James, and C. W. Field. Geology of the Bingham Canyon Porphyry Copper Deposit, Utah. Ch. in Geology of the Porphyry Copper Deposits, Southwestern North America, ed. by S. R. Titley and C. L. Hicks. Univ. of Ariz. Press, Tucson, Ariz., 1969, pp. 165-175.

89. Petrick, A., Jr., H. J. Bennett, K. E. Starch, and R. C. Weisner. The Economics of Byproduct Metals (In Two Parts). 1. Copper System. BuMines IC 8569, 1973, 105 pp.
90. Phelps Dodge Annual Report 1974.
91. _____. Annual Report 1975.
92. _____. Annual Report 1976.
93. Phillips, A. J. The World's Most Complex Metallurgy (Copper, Lead, and Zinc). Trans. Met. Soc., AIME, v. 224, August 1962, pp. 657-668.
94. Price, F. C. Copper Technology on the Move. Eng. and Min. J., v. 174, No. 4, April 1973, pp. RR-ZZ.
95. Ridge, J. D. (ed. by). Ore Deposits of the United States 1933/1967 (In Two Volumes). The Graton-Sales Volume, AIME, New York, 1968, 1880 pp.
96. _____. Annotated Bibliography of Mineral Deposits in the Western Hemisphere. GSA Memoir 131, 1972, 681 pp.
97. Roberts, R. J. Copper. Ch. in Mineral and Water Resources of Utah. Report of the U.S. Geological Survey in cooperation with the Utah Geological and Mineral Survey and the Utah Water and Power Board. Committee on Interior and Insular Affairs. U.S. Senate, 88th Cong., 2d sess., 1964, pp. 75-83.
98. Rose, A. W., and W. W. Baltosser. The Porphyry Copper Deposit at Santa Rita, New Mexico. Ch. in Geology of the Porphyry Copper Deposits, Southwestern North America, ed. by S. R. Titley and C. L. Hicks, Univ. of Ariz. Press, Tucson, Ariz., 1969, pp. 205-220.
99. Schroeder, H. J. Copper. BuMines Minerals Yearbook 1972, v. 1, 1974, pp. 473-509.
100. Schroeder, H. J., and J. W. Cole. Copper. BuMines Minerals Yearbook 1970, v. 1, 1972, pp. 467-500.
101. Securities and Exchange Commission. El Paso Natural Gas Co. Form 10 K, Dec. 31, 1976, 88 pp.
102. Sheffer, H. W., and L. G. Evans. Copper Leaching Practices in the Western United States. BuMines IC 8341, 1968, 57 pp.
103. Simons, F. S., and W. C. Prinz. Gold. Ch. in United States Mineral Resources, U.S. Geol. Survey Prof. Paper 820, 1973, pp. 263-275.
104. Smith, R. B. The Mineral Industry of New Mexico. BuMines Minerals Yearbook 1970, v. 2, 1972, pp. 483-507.

105. Snyder, F. G. Geology and Mineral Deposits, Midcontinental United States. Ch. 14 in Ore Deposits of the United States, v. 1, 1968, pp. 257-286.
106. Snyder, F. G., and P. E. Gerdemann. Geology of the Southeast Missouri Lead District. Ch. 17 in Ore Deposits of the United States, v. 1, 1968, pp. 326-358.
107. Sondermayer, R. V. The Mineral Industry of New Mexico. BuMines Minerals Yearbook 1971, v. 2, 1973, pp. 491-510.
108. _____. The Mineral Industry of New Mexico. BuMines Minerals Yearbook 1972, v. 2, 1974, pp. 473-493.
109. Southard, L. G., K. S. Johnson, and J. F. Roberts. The Mineral Industry of Oklahoma. BuMines Minerals Yearbook 1970, v. 2, 1972, pp. 569-584.
110. _____. The Mineral Industry of Oklahoma. BuMines Minerals Yearbook 1972, v. 2, 1974, pp. 549-563.
111. Stroud, R. B., A. B. McMahan, R. K. Stroup, and M. H. Hibpshman. Production Potential of Copper Deposits Associated With Permian Red Bed Formations in Texas, Oklahoma, and Kansas. BuMines RI 7422, 1970, 103 pp.
112. Titley, S. R., and C. L. Hicks (ed. by). Geology of the Porphyry Copper Deposits, Southwestern North America. Univ. of Ariz. Press, Tucson, Ariz., 1969, 287 pp.
113. Treilhard, D. G. Copper. State of the Art. Eng. and Min. J., v. 174, No. 4, April 1973, pp. P-Z.
114. U.S. Bureau of Mines. Copper From Chalcopyrite Without Environmental Degradation. Mineral Research and Data Analysis Highlights, v. 1, No. 3, November 1974, p. 10.
115. Weissenborn, A. E. Copper. Ch. in Mineral and Water Resources of Montana. Report of the U.S. Geological Survey in cooperation with the Montana Bureau of Mines and Geology. Committee on Interior and Insular Affairs. U.S. Senate, 88th Cong., 1st sess., 1963, pp. 62-65.
116. West, J. M. Gold. BuMines Minerals Yearbook 1973, v. 1, 1975, pp. 557-581.
117. Wharton, H. M., J. A. Martin, A. W. Rueff, C. E. Robertson, J. S. Wells, and E. B. Kisvarsanyi. Missouri Minerals-Resources, Production, and Forecasts. Missouri Geological Survey and Water Resources, Rolla, Mo., Spec. Pub. No. 1, December 1969, 303 pp.
118. Wilson, J. R. Geology of the Yerington Mine. Min. Cong. J., v. 49, No. 6, June 1963, pp. 30-34.

119. Wolfe, J. A. Copper Industry in the Philippines Shows Growth in Production and Potential. Min. Eng., v. 19, No. 4, April 1967, pp. 74-75.
120. World Mining. World Mines Register, 1976-77. San Francisco, Calif., 1976, 358 pp.

