U.S. Geological Survey Open-File Report 2004-1395

Flows of Selected Materials Associated with World Copper Smelting

By Thomas G. Goonan

Open-File Report 2004–1395

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia 2005

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Abstract

The U.S. Geological Survey collects, analyzes, and disseminates information about the material flows associated with mineral extraction and use. This publication focuses on the flows associated with the smelting of copper concentrates. Copper is one of the core commodities in modern and developing economies. One cost paid for placing it in service is the significant, though manageable, set of environmental effects associated with the smelting process.

Through a detailed assessment of smelting technologies, covering approximately two-thirds of world capacity, this research quantifies the unwanted by-products associated with copper production. The conversion of one kilogram (kg) of copper concentrate from its in-ground condition (ore) into economic service generates an average landscape footprint comprised of 210 kg of mine waste, 113 kg of mill tailings, 2 kg of slag, and 2.3 kg of sulfur-bearing co-product. The corresponding air releases per kg of copper include 0.5 kg of carbon dioxide and 0.2 kg of sulfur dioxide.

Because copper concentrates are a traded worldwide, the ecological footprint described above can be allocated among the countries that smelt and export copper and to the countries that import and use it. This report also highlights the relationship between exporting and importing countries.

Introduction

One of the responsibilities of the U.S. Geological Survey is to collect, analyze, and disseminate information about the material flows associated with mineral extraction and use. This publication focuses on the material flows associated with the technologies being used for smelting of copper concentrates.

Copper concentrates that contain large amounts of sulfur are smelted in refractory-lined furnaces at temperatures sufficiently high to liquefy the smelting products. In the past, copper smelters emitted large amounts of sulfur, mainly to the air. New smelting and sulfur recovery technologies have improved the sulfur-capture performance of copper smelters. This report identifies the remaining gaps to complete sulfur emission control at copper smelters. World copper mine production in 2000 was about 13 million metric tons (Mt) (Edelstein and Porter, 2004). This study covers more than 8 Mt of copper that passed through pyrometallurgical smelters; that is, about 65 percent of such smelter capacity.

Copper smelting generates many types of materials flows. As copper concentrate flows through the smelting process, it leaves behind an altered mine deposit, sometimes mine waste, and mill tailings. Fluxing materials, fuels, oxygen, recyclables, scrap, and water are input to the process. Dust (recycled); gases, which contain carbon dioxide (CO_2) (dissipated); sulfur dioxide (SO_2) (collected); and slag (discarded or sold) are process outputs. This report estimates the flows of these materials for each smelter studied.

This report presents flows from operational practices current as of June 2002. Known near-term plant modifications under development that extend beyond this date are not included. Information was compiled from multiple sources, and the disparate data was conformed to each other by application of metallurgical principles within material balances that represent the 2002 practice for each smelter. The report contains data on at least 65 percent of world copper concentrate smelting capacity operating in 2002.

Smelting Overview

One requires many process steps to obtain 99.99 percent copper metal from *sulfide ores* [1] that contain copper at levels most often below 1 percent. Although chalcopyrite ($CuFeS_2$) is the predominant copper sulfide ore processed, other important copper sulfide ore minerals include bornite (Cu_5FeS_4), chalcocite (Cu_2S), covellite (CuS), and enargite (Cu_3AsS_4). Natural ores undergo *comminution* and separation by *flotation* at copper mining facilities to produce copper *concentrate*. Concentrate can contain from 25 to 35 percent copper; similar levels of iron and *sulfur*; minor percentages of oxides of aluminum, calcium, and silicon; and a small balance of trace metals that depend on the ore source.

Smelters may be integrated with a specific mine or company and process concentrates produced from the ores of that particular mine or from the company's multiple mine holdings. The Chuquicamata smelter in Chile, for example, is solely supplied by the Chuquicamata Mine, which is the world's second largest copper mine. The Miami smelter in Arizona takes concentrates supplied from mines and mills operated by Phelps Dodge Corporation in North America and South America. Other smelters process concentrates from multiple mines located in many countries. For example, the Saganoseki smelter in Japan, which has few copper resources but many of the world's largest smelters, takes and blends concentrates from such countries as Chile, Indonesia, and the Philippines. The charge (concentrate plus other items) to a given smelter is not chemically constant. This study reports what was typical at the time of analysis.

Regardless of how many different flotation concentrates a smelting facility may process, the material supplied to a smelting furnace is generally a blend of materials, which includes concentrate/s, recycle dusts, and products of *slag*-cleaning operations (*mattes*).

Technically, smelting means to melt and fuse. With regard to copper smelting, it means to melt and fuse copper-bearing materials, which include concentrates, dust (circulating load), fluxes (slagmaking materials), and *revert* (circulating load) in a furnace. Heat is required for the melting and fusing and can be generated by several means, such as electric current, fuel combustion, or mineral oxidation. The oxidation of iron and sulfur in copper concentrate generates heat, which aids the melting of the charge. Air and industrial oxygen are important inputs to the modern *primary smelting furnace*. In this report, the term ''smelting'' takes a broader meaning. It includes all the batch-process activities involved in producing a *cast* copper *anode* at the smelting facility, which include (stepwise) primary smelting furnace, converting, *fire-refining*, casting, and slag treatment.

In a flash furnace, finely ground copper-bearing materials (mainly concentrates) are injected with a combination of air and industrial oxygen into the furnace. The oxygen reacts with some of the iron and sulfur to produce sufficient heat to melt and fuse the remaining unreacted mass. The liquefied mass has two immiscible components—matte, which is a mixture of copper and iron sulfides, and slag, which is a mixture of aluminum trioxide, calcium oxide, iron oxide (the product of iron oxidation), and silicon dioxide. As oil floats on water, slag floats on matte. Slag is removed from the melted mass, and the remaining matte is moved to the next processing step. Any sulfur that has reacted with the oxygen forms a hot *sulfur dioxide* (SO_2) gas, which the *gas-handling system* collects and channels to an *acid plant* to recover the sulfur as *sulfuric acid* (H_2SO_4), or to another sulfur fixing plant, to recover the sulfur in a useful product, such as *gypsum*, *oleum*, or sulfur. During the generation of useful sulfur-bearing products from the collected SO_2, a small amount of the total sulfur load in treated gas goes into sludge. These data are not easily accessible and are not included in this study. The result is that the H_2SO_4 production numbers are very slightly overstated. Other trace-metal impurities, such as arsenic (converted to *arsenic trioxide*) and *mercury*, distribute between anode, gas and slag. Part of the gas treatment is the removal of fine particulate (dust), which is continually recycled.

The matte product of the primary furnace contains from 50 to 75 percent copper, the remaining major elements being iron and sulfur and small percentages of residual metals and oxygen. If the remaining element is sulfur, then the material is technically no longer matte, but rather is white metal (C_2S).

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[1] In the section "Smelting Overview" terms in italic appear in Appendix II, Glossary, with further definition.

In a batch process, matte is transferred to a *converter* vessel, which is another brick-lined container where a fluxing agent, either silica or limestone, is added, and the melt is oxidized with air. Furthermore, this processing step is where high-purity copper scrap is added. A two-step process occurs within the converting vessel. Step one is to oxidize the melt until the iron is completely eliminated. This is called the slag-forming step because the oxidized iron reacts with the flux to form an iron silicate slag. The slag, which contains a high percentage of copper, is recycled to either the smelting vessel or a slag-treating step to recover entrained or oxidized copper. The second step in the converting process is to eliminate the remaining sulfur from the Cu_2S by continuing the injection of oxygen (in air) after the iron-bearing slag has been removed. The SO_2, generated during both steps is collected and processed to acid. Coincident dust is collected and recycled. The product of the converting process is *blister* copper, which contains about 99.5 percent copper.

The greater part of blister production is not cooled, but rather transferred hot to a fire refining (anode) furnace. The product of the anode furnace is a copper casting that performs as an anode in an *electrolytic* cell. The electrolytic refining step usually occurs at a different facility. In the anode furnace, the liquid copper, which contains high levels of dissolved gases, is treated with a *reducing agent* — pulverized coal, natural gas, or wooden poles. The reductant reacts with the dissolved oxygen, and the resulting metal can cool without the blistering effect and be cast into a mold where the cooled surface will be flat, which is a desired characteristic for electrolytic processing. The casting process involves pouring hot copper into molds, which are shaped as anodes; each mold is on the circumference of a wheel that turns to present an empty mold as the previously cast mold moves on and cools.

For this study, a typical material balance for each facility covers the primary smelting furnace, the converting process, and the anodemaking process. The electrolytic process is not included. A quantitative estimate for the largest noncopper- or low-copper-bearing material flows at mines and mills that provide concentrates to smelters is made for each smelter studied. Thirty pyrometallurgical smelters, which represents about 65 percent of smelter-rated capacity, were studied. Table 1 shows the weighted average of the *copper-specific* and gross material flows for those smelters, thus the table represents a stylized world smelter.

Table 1. Weighted average annual flows for all smelters studied.
[Total capacity for these smelters was 8.3 Mt cast copper product per year in 2002. Values represent the average of each flow stream (Column 1) for the smelters studied, weighted by smelter capacity, and are expressed alternatively as copper-specific flow (Column 2) and gross flow (Column 3), which has units of thousand metric tons per year, under the assumption of a 92-percent capacity utilization rate.]

Flow streams	Copper-specific flow	Gross flow
Inputs		
Mine ore	116.17	887,000
Concentrate	3.14	24,000
Scrap	.11	808
Fuel	.10	744
Air:		
Smelting	2.16	16,500
Converting	1.78	13,600
90 percent oxygen:		
Smelting	.95	7,290
Converting	.06	426
Flux:		
Smelting	.26	1,950
Converting	.09	709
Limestone	.18	1,410
Water	.49	3,760
Recycling loads		
Revert	.11	873

Table 1. Weighted average annual flows for all smelters studied—Continued.

Flow streams	Copper-specific flow	Gross flow
Dust	.20	1,420
Matte	.13	961
Outputs		
Mine waste	210.42	1,610,000
Mill tailings	113.02	863,000
Slag	1.91	14,600
Sulfuric acid	2.20	16,800
Other sulfur product	.11	815
Sulfur dioxide	.19	1,450
Carbon dioxide	.47	3,570
Copper in anode	1.00	7,580
Percentage of world capacity	64.75	

Figure 1 is a generalized process flow diagram with the table 1 data assigned to process steps. The process steps function mainly to separate copper from the iron and sulfur contained in the concentrate mix and to recover copper and as many useful, even salable, co-products as practicable.

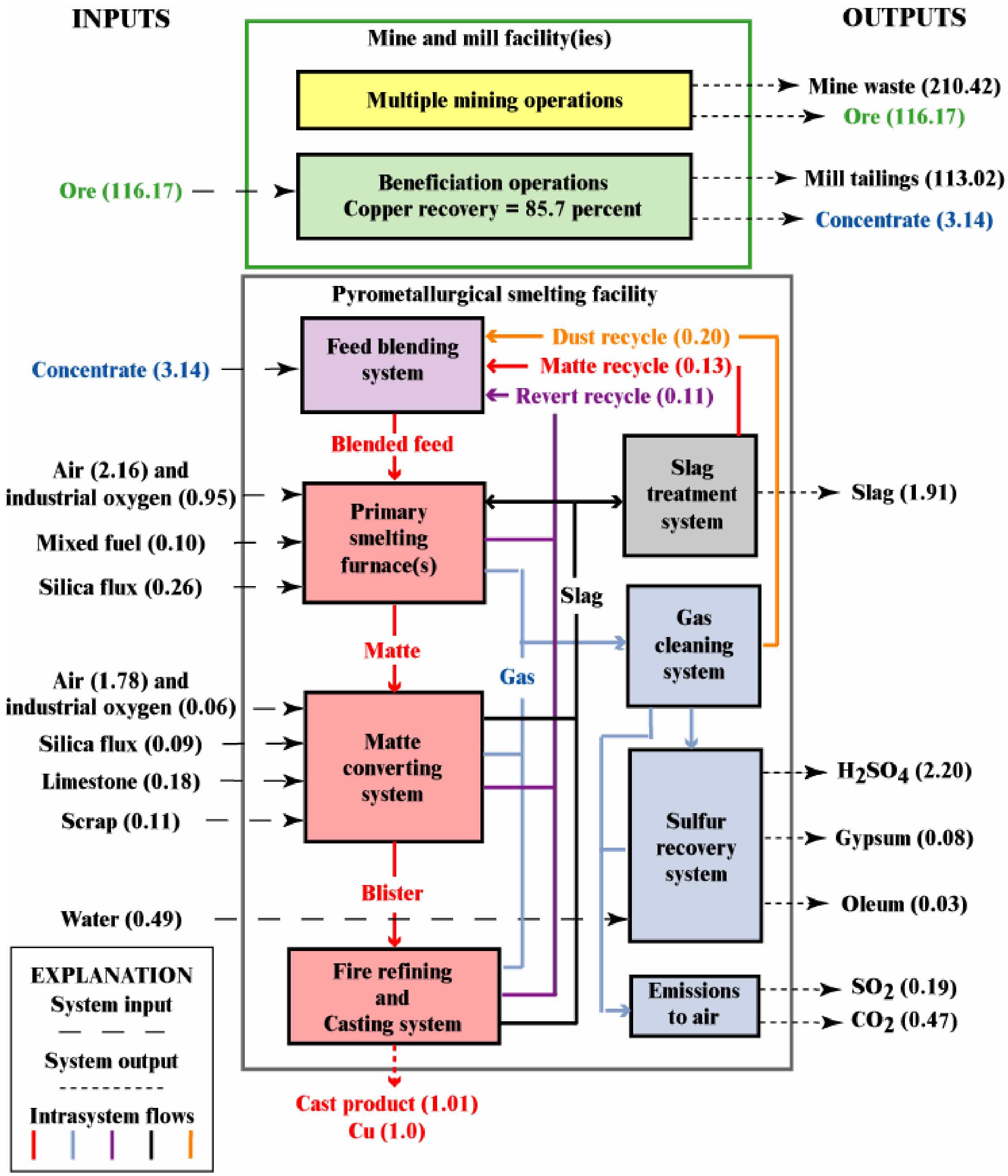

Figure 1. Copper-specific flow diagram of the smelting process.

[Smelting is a separating and value-adding process. The steps—smelting, converting, fire refining, and casting—are taken together as a single process. The data reported in the figure represent the weighted average copper-specific flows for all the smelters studied in this report. The total capacity of the smelters studied was 8.3 mt of cast copper product.]

Selected Analytical Themes

Because the data generated by the material balances for the studied smelters can be grouped into spatially bounded and material categories, many thematic analyses are possible. Table 2 lists the analytical themes selected for this report, by subject.

Table 2. Selected analytical themes, by subject.

Theme Number	Theme
1	Annual material flows associated with smelting in Chile.
2	Annual material flows associated with smelting in Europe.
3	Annual material flows associated with smelting in Japan.
4	Annual material flows associated with smelting in the United States.
5	Annual material flow comparison—Chile, Europe, Japan, and the United States.
6	Carbon dioxide and sulfur dioxide disposition from copper smelters.
7	Technologies for capturing and fixing copper–smelter–generated sulfur.
8	Slag generation at copper smelting facilities, by country/region.
9	Copper–smelter–generated ore demand and ore supply, by country/region.
10	Mine waste generated with attribution to the country that generated the demand for concentrate.
11	Mill tailings generated when serving copper smelter demand for concentrates.

Theme 1. Annual material flows associated with smelting in Chile

The four largest copper smelting organizations in Chile are Anglo American Plc. (Chagres), Corporación Nacional del Cobre de Chile (CODELCO) (Caletones, Chuquicamata, and Potrerillos), Empresa Nacional de Minería de Chile (ENAMI) (Las Ventanas), and Noranda Inc. (Altonorte); CODELCO and ENAMI are state owned corporations, and Anglo American and Noranda are private sector organizations. A summary of the material flows associated with those smelters operating in 2003 is listed in table 3.

Table 3. Annual material flows associated with smelting at 92-percent capacity utilization in Chile.
[Values are expressed in thousand metric tons per year based on 2002 practice. Zero in the "Mine waste" cell indicates an underground mine. Summary columns may not equal the sum of the parts because the summary column represents weighted averages and is separately rounded.]

Flows	Alto-norte	Cale-tones	Chagres	Chuqui-camata	Las Ventanas	Potre-rillos	Total
Plant capacity	290	400	150	500	150	220	1,710
Inputs							
Mine ore	23,300	38,800	12,700	43,500	10,700	22,500	152,000
Concentrate	755	1,170	411	1,210	494	569	4,610
Scrap	0	0	17	42	7	24	90
Fuel and reductants	14	6	2	18	0	1	40
Air							
Smelting	661	707	8	800	315	332	2,820
Converting	498	640	324	874	234	362	2930
90 percent oxygen							
Smelting	229	224	113	216	100	89	971
Converting	0	0	0	0	0	0	0
Flux							
Smelting	0	19	1	16	32	6	74
Converting	11	9	2	7	4	2	34
Limestone	0	0	0	78	0	0	78
Water	131	177	77	212	87	87	771

Table 3. Annual material flows associated with smelting at 92-percent capacity utilization in Chile —Continued.

Flows	Alto-norte	Cale-tones	Chagres	Chuqui-camata	Las Ventanas	Potre-rillos	Total
Recycling loads							
Revert	14	92	21	170	42	57	395
Dust	57	11	28	32	35	47	208
Matte	26	121	33	63	33	99	375
Outputs							
Mine waste	81,500	0	21,600	109,000	24,600	18,600	255,000
Mill tailings	22,500	37,600	12,300	42,300	10,200	22,000	147,000
Slag	311	696	188	607	288	275	2,360
Sulfuric acid	644	721	313	869	357	319	3,220
Sulfur dioxide	32	144	14	106	3	109	407
Carbon dioxide	38	18	6	87	25	8	183
Anode copper	267	368	138	460	138	202	1,570

On a smelter-capacity-weighted-average basis, for every weight unit of copper contained in cast anode produced in Chile, 2.93 weight units of Chilean concentrate is smelted, which yields 168.98 weight units of mine waste, 90.20 weight units (dry) of mill tailings, 2.05 weight units of H_2SO_4, 1.50 weight units of slag, 0.26 weight unit of SO_2, and 0.12 weight unit of CO_2.

Theme 2. Annual material flows associated with smelting in Europe

Four of Europe's largest copper smelters are Glogow I and II (Poland), Huelva (Spain), Norddeutsche Affiniere (Germany), and Ronnskar (Sweden). Norddeutsche Affiniere is unique in that it smelts concentrates imported from all over the world and also has high scrap utilization. A summary of the material flows associated with smelter operation in 2002 is shown in table 4.

Table 4. Annual material flows associated with smelting at 92-percent capacity utilization in Europe.
[Values are expressed in thousand metric tons per year based on 2002 practice. Zero in the "Mine waste" cell indicates underground mine. Summary columns may not equal the sum of the parts because the summary column represents weighted averages and is separately rounded.]

Flows	Glogow I	Glogow II	Huelva	Norddeutsche	Ronnskar	Total
Plant capacity	205	220	330	420	240	1,420
Inputs						
Mine ore	11,800	10,300	27,900	28,700	30,400	109,000
Concentrate	757	698	870	999	596	3,920
Scrap	11	10	43	63	186	313
Fuel	29	25	10	17	6	87
Air						
Smelting	500	70	175	582	355	1,680
Converting	358	17	429	631	66	1500
90 percent oxygen						
Smelting	0	456	337	436	303	1,530
Converting	0	0	45	7	0	52
Flux						
Smelting	0	0	7	134	44	185
Converting	25	14	15	26	17	96
Limestone	0	80	0	30	0	110
Water	43	44	149	190	98	523

Table 4. Annual material flows associated with smelting at 92-percent capacity utilization in Europe—Continued.

Flows	Glogow I	Glogow II	Huelva	Norddeutsche	Ronnskar	Total
Recycling loads						
Revert	11	6	6	29	n.a.	52
Dust	21	97	66	77	31	292
Matte	0	87	36	12	34	168
Outputs						
Mine waste	0	0	45,200	67,100	46,400	159,000
Mill tailings	11,000	9,580	27,000	27,700	29,800	105,000
Slag	385	335	445	607	372	2,140
Sulfuric acid	209	215	731	950	506	2,610
Sulfur dioxide	4	6	12	3	8	33
Carbon dioxide	357	410	32	66	19	885
Anode	189	202	304	386	221	1,300

On a smelter-capacity-weighted-average basis, for every weight unit of copper anode produced in Europe, 3.01 weight units of concentrate is smelted, some of which is of extra-European origin that yields 97.88 weight units of mine waste, and 71.85 weight units (dry) of mill tailings, 2.01 weight units of H_2SO_4, 1.65 weight units of slag, 0.68 weight unit of CO_2, and 0.03 weight unit of SO_2.

Theme 3. Annual material flows associated with smelting in Japan

Japan's five copper smelters are Onahama, Naoshima, Saganoseki, Tamano, and Toyo. Although Japan is not a large copper ore producer, it is one of the world's largest copper smelting states. Japan's copper companies, Dowa Mining Co. Ltd., The Furukawa Electric Company Limited, Mitsubishi Materials Corporation, Mitsui Mining & Smelting Co. Ltd., and Sumitomo Metal Mining Co. Ltd., have created many concentrate-buying partnerships and have invested in foreign copper mining and smelting joint ventures such that concentrates are imported from all over the world. Table 5 shows a summary of the material flows associated with Japanese smelters operating in 2002.

Table 5. Annual material flows associated with smelting at 92-percent capacity utilization in Japan.
[Values are expressed in thousand metric tons per year based on 2002 practice. Zero in the "Mine waste" cell indicates an underground mine. Summary columns may not equal the sum of the parts because the summary column represents weighted averages and is separately rounded.]

Flows	Naoshima	Onahama	Saganoseki	Tamano	Toyo	Total
Plant capacity	270	258	470	263	300	1,560
Inputs						
Mine ore	19,900	29,900	63,900	32,900	42,600	189,000
Concentrate	669	576	1,220	634	756	3,850
Scrap	62	49	25	36	38	210
Fuel	19	159	19	20	9	226
Air						
Smelting	259	2,590	126	321	509	3,800
Converting	298	756	931	558	566	3110
90 percent oxygen						
Smelting	272	0	339	256	264	1,130
Converting	65	0	0	0	0	65
Flux						
Smelting	83	26	87	76	147	419
Converting	0	26	38	28	28	120

Table 5. Annual material flows associated with smelting at 92-percent capacity utilization in Japan—Continued.

Flows	Naoshima	Onahama	Saganoseki	Tamano	Toyo	Total
Limestone	42	145	0	16	38	241
Water	112	207	220	126	139	804
Recycling loads						
Revert	NA	7	63	4	12	85
Dust	60	25	87	56	39	267
Matte	5	0	89	25	17	136
Outputs						
Mine waste	39,700	61,100	128,000	67,200	77,300	373,000
Mill tailings	19,300	29,300	62,700	32,300	41,800	185,000
Slag	381	343	625	383	508	2,240
Sulfuric acid	510	393	916	581	671	3,070
Other sulfur product	114	324	0	16	25	480
Sulfur dioxide	0	1	6	0	1	8
Carbon dioxide	76	531	55	68	57	787
Anode	248	237	432	242	276	1,440

On a smelter-capacity-weighted-average basis, for every weight unit of copper anode produced in Japan, 2.68 weight units of concentrate is smelted, most of which is of extra-Japanese (Australia, Chile, Indonesia, United States) origin, that yields 213.63 weight units of mine waste, and 96.94 weight units (dry) of mill tailings, 2.14 weight units of H_2SO_4, 1.56 weight units of slag, 0.55 weight unit of CO_2, and 0.01 weight unit of SO_2.

The impact of mine and mill waste occurs in the countries from which concentrate is imported. Figure 2 shows the percentage of Japanese copper concentrate imports for 2001, by source (Wu, 2002, p. 13.6).

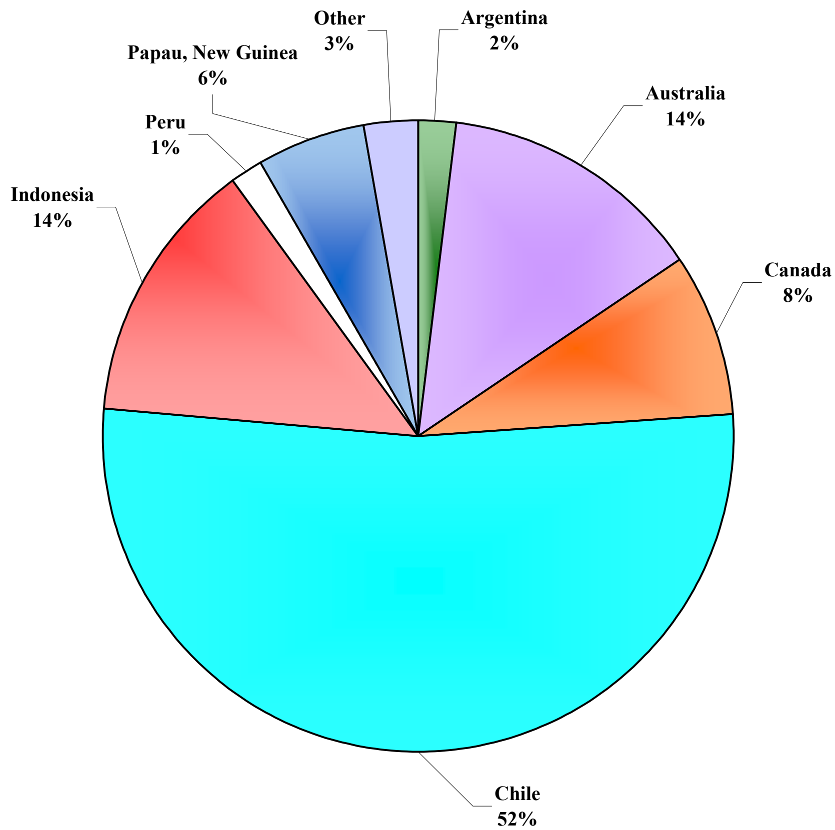

Figure 2. Japanese copper concentrate imports for 2001, by source.

Theme 4. Annual material flows associated with smelting in the United States

Four large smelters in the United States are not operating (standby) pending higher copper prices. Chino and Hidalgo are owned by Phelps Dodge Corp.; El Paso by Grupo Mexico S.A. de C.V.); and San Manuel by BHP Billiton Ltd. Garfield (Rio Tinto plc), Hayden (Grupo Mexico), and Miami (Phelps Dodge) are still (2005) operating. A summary of the material flows associated with these three operating smelters is shown in table 6.

Table 6. Annual material flows associated with smelting at 92-percent capacity utilization in the United States.
[Values are expressed in thousand metric tons per year based on 2002 practice. Zero in the ''Mine waste'' cell indicates underground mine. Summary columns may not equal the sum of the parts because the summary column represents weighted averages and is separately rounded.]

Flows	Garfield	Hayden	Miami	Total
Plant capacity	320	210	180	710
Inputs				
Mine ore	49,200	38,500	38,800	127,000
Concentrate	981	708	592	2,280
Scrap	34	1	13	48
Fuel	1	0	1	2

Table 6. Annual material flows associated with smelting at 92-percent capacity utilization in the United States—Continued.

Flows	Garfield	Hayden	Miami	Total
Air				
Smelting	29	0	117	146
Converting	143	450	402	995
90 percent oxygen				
Smelting	266	58	131	554
Converting	97	0	0	97
Flux				
Smelting	110	84	64	259
Converting	5	37	26	68
Limestone	52	0	9	61
Water	190	107	120	417
Recycling loads				
Revert	16	22	27	66
Dust	86	24	2	112
Matte	31	8	8	47
Outputs				
Mine waste	74,300	84,200	54,200	213,000
Mill tailings	48,200	37,800	38,200	124,000
Slag	560	475	271	1,310
Sulfuric acid	751	439	407	1,600
Sulfur dioxide	1	17	6	24
Carbon dioxide	24	0	6	30
Anode copper	294	193	166	653

On a smelter-capacity-weighted-average basis, for every weight unit of copper anode produced in the United States, 3.49 weight units of concentrate is smelted, most of which is from U.S. mines, that yields 371.62 weight units of mine waste, and 206.27 weight units (dry) of mill tailings, 2.44 weight units of H_2SO_4, 2.00 weight units of slag, 0.05 weight unit of CO_2, and 0.04 weight unit of SO_2.

Theme 5. Annual material flow comparison—Chile, Europe, Japan, and the United States

A comparison of smelting-related material flows in Chile, Europe, Japan, and the United States is shown in table 7.

Table 7. Annual material flows associated with smelting at 92-percent capacity utilization in Chile, Europe, Japan, and the United States.
[Values are expressed in thousand metric tons per year based on 2002 practice.]

Flows	Chile	Europe	Japan	United States
Plant capacity	1,710	1,420	1,560	710
Inputs				
Mine ore	152,000	109,000	189,000	127,000
Concentrate	4,610	3,920	3,850	2,280
Scrap	90	314	210	49

Table 7. Annual material flows associated with smelting at 92-percent capacity utilization in Chile, Europe, Japan, and the United States—Continued.

Flows	Chile	Europe	Japan	United States
Fuel	40	847	226	1
Air				
Smelting	2,820	1,680	3,800	146
Converting	2,930	1,500	3,110	995
90 percent oxygen				
Smelting	971	1,530	1,130	554
Converting	0	52	65	97
Flux				
Smelting	74	185	419	259
Converting	34	96	120	68
Limestone	78	110	241	61
Water	771	523	804	416
Recycling loads				
Revert	395	52	85	66
Dust	208	292	267	112
Matte	375	168	136	47
Outputs				
Mine waste	255,000	159,000	373,000	213,000
Mill waste (tails)	147,000	105,000	185,000	124,000
Slag	2,360	2,140	2,240	1,310
Sulfuric acid	3,220	2,610	3,070	1,600
Other sulfur product	0	92	480	0
Sulfur dioxide	407	33	8	24
Carbon dioxide	183	885	787	30
Anode copper	1,570	1,310	1,440	653

Theme 6. Carbon dioxide and sulfur dioxide disposition from copper smelters

CO_2 emissions derive from various sources within the smelting-casting system; these include, oxidation of carbon in the charge and in fuels, and decomposition of limestone used in fluxing and gas scrubbing operations. Anthropogenic CO_2 emissions have become an environmental issue, so they are reported here for the smelters studied.

Roughly one-third of the copper concentrate input to copper smelters is sulfur that must be separated from the desired copper metal by the end of the step-wise process. The process chemically combines the sulfur in the charge with oxygen from, air, industrial oxygen, or a mix of both, and the resulting product is SO_2 gas. During the past 30 years, a large degree of technological focus was towards the control of SO_2 emissions to the air. Most of the world's large capacity smelters are capturing SO_2 at levels above 95 percent. Those that are not are under legal orders to do so with near-term time commitments.

Figure 3 shows the annual flow of CO_2 and SO_2 emissions generated by the studied copper smelters, by country. In terms of gross flows, one may compare these data with information about non-smelter sources of CO_2 and SO_2 emissions for the countries indicated.

Australia and Chile are committed to investments in new smelting and pollution control technologies, which will reduce SO_2 further. Southern Peru Copper Company is phasing in new technology and will reduce its large contribution of SO_2 emissions shortly.

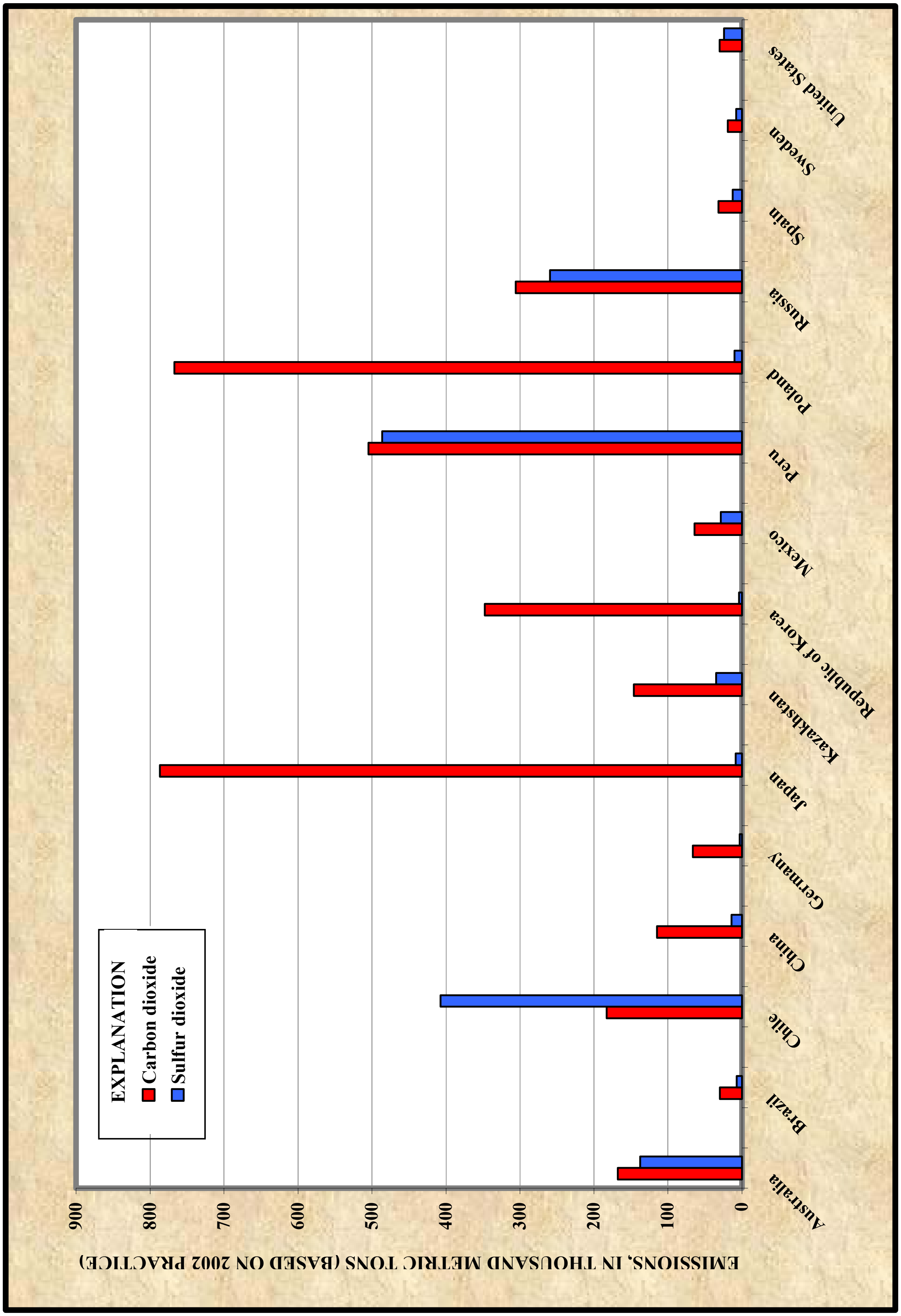

Figure 3. Annual gross flow of carbon dioxide and sulfur dioxide emissions from copper smelters, by country.

Figure 4 shows the same information, however, in copper-specific terms. These data are more suggestive of the relative efficiencies of collection and control of CO2 and SO2 by the technologies used in the indicated countries for copper smelting. By implication, countries with the shortest bars are more efficient with respect to collecting and controlling emissions of CO2 and SO2.

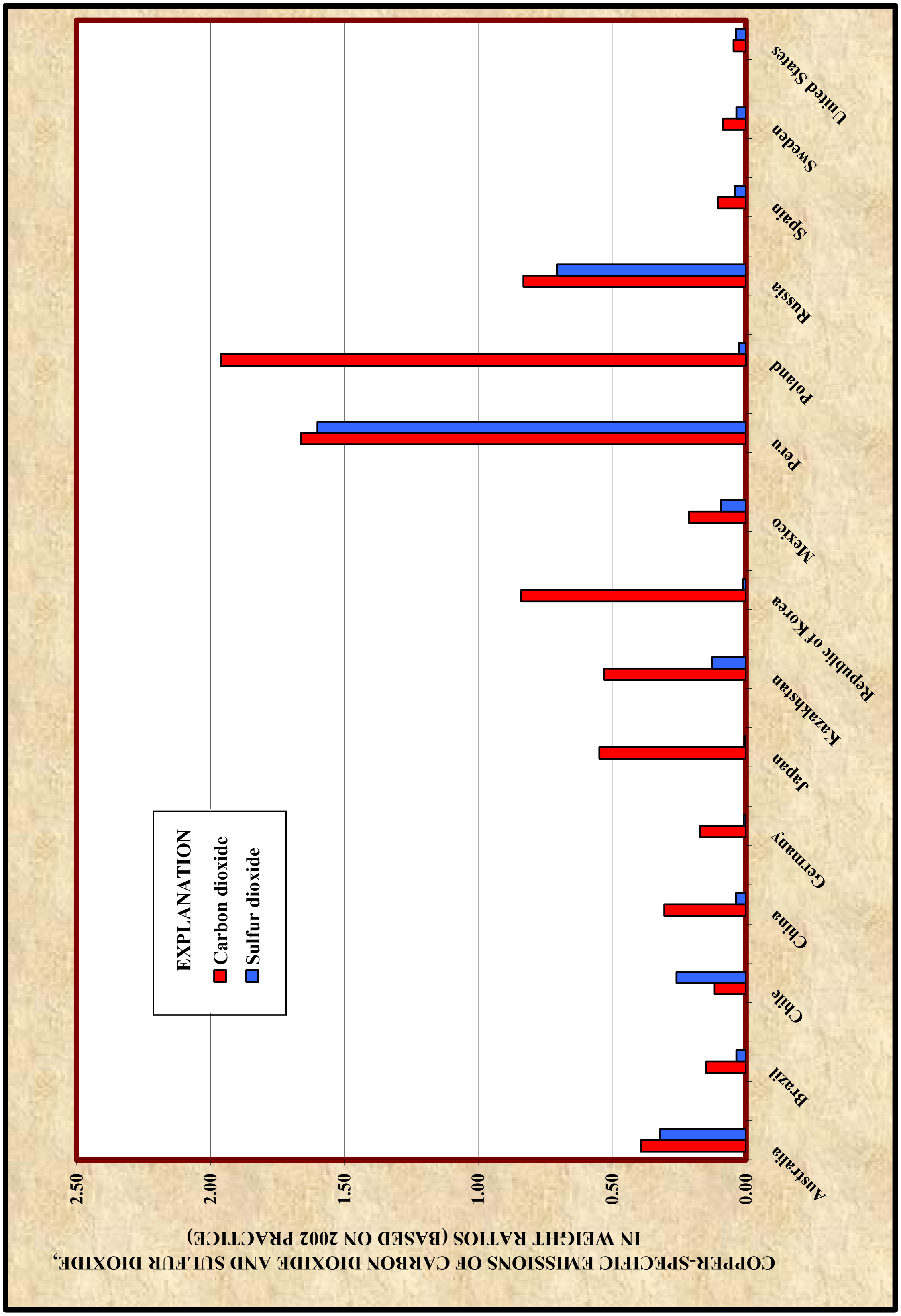

Figure 4. Annual copper–specific flow of carbon dioxide and sulfur dioxide emissions from copper smelters, by country.

Theme 7. Technologies for capturing and fixing copper–smelter–generated sulfur

Before modern flash smelting technologies became common, the primary smelting furnace was generally a reverberatory furnace, which generated a high-volume gas stream with a low concentration of SO_2 (3-5 percent). This gas was discharged from tall stacks to disperse the SO_2 as widely as possible to avoid local contamination. Low-percentage SO_2 gas streams are not amenable to treatment in sulfuric acid plants, which is the most acceptable and used method for fixing sulfur in current practice. Flash furnace technologies, regardless of the type, combine finely divided concentrate with a mixture of air and industrial oxygen within the smelting furnace. This practice oxidizes the sulfur directly, which yields heat for melting the charge and high-percentage (> 25 percent) SO_2 gas streams. The gas, after cleaning for particulate, and treating for consistency of SO_2 concentration and temperature, usually flows directly to acid plants for conversion to sulfuric acid. Sulfuric acid is a useful product that is easily transportable, and is used either on site or marketed.

Japan selected to control SO_2 emissions as completely as possible. They developed scrubbing technologies to treat low-percentage SO_2-containing gases. Scrubber products are generally forms of gypsum, or alkali-sulfite salts that have market value. These technologies capture more that 99 percent of the SO_2 generated by pyrometallurgical smelters. The Republic of Korea (South Korea) heavily uses Japanese technology and produces similar products. Most other countries seem satisfied with 97-99 percent capture rates and are prodding non-achievers to comply quickly.

Figure 5 shows how, and how much, sulfur is fixed in the countries where the studied smelters are located.

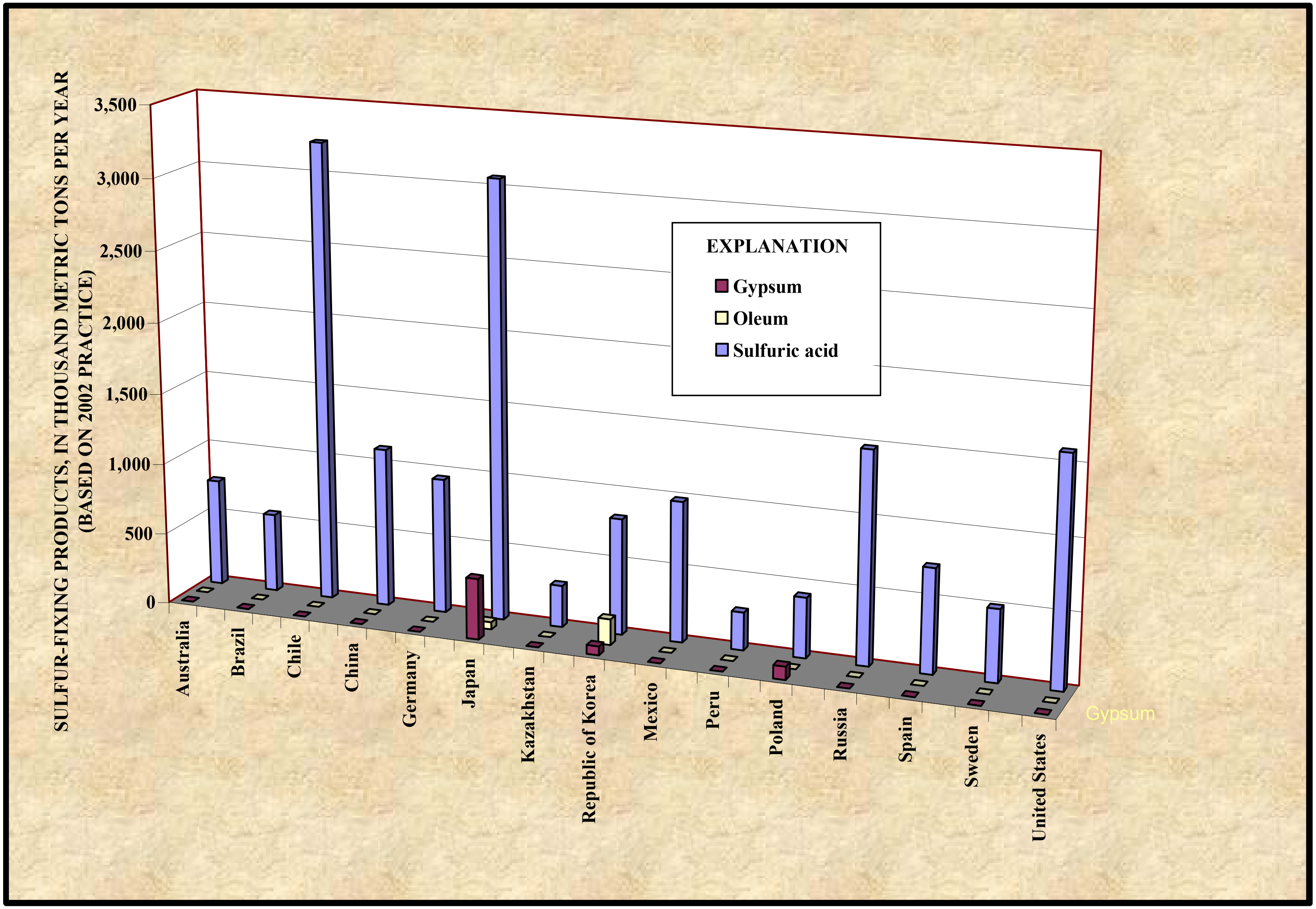

Figure 5. Annual quantity of sulfur–fixing products, by product type and country.

Theme 8. Slag generation at copper smelting facilities, by country/region

Reaction of copper concentrate with oxygen separates the sulfur from the concentrate and directs it into the gas stream. Oxygen also reacts with the iron in the concentrate to form various iron oxide compounds and these react with fluxing materials [light-metal oxides, such as alumina (Al_2O_3), lime (CaO), and sand (SiO_2)]. The minerals formed from the combination of iron oxides and light-metal oxides have relatively low melting points. This results in molten slag, which floats on top of the remaining liquid copper metal effectively separating iron from the desired copper.

A continually recycling load within the copper smelting process is set up when slag materials, which contain entrained copper, are reprocessed. After any reprocessing, a large amount of residual material must either be used in a valued application like road base, or be discarded in a landfill. Figure 6 shows the annual amount of slag generated by the studied smelters, by country. The amount of slag generated in a country is about two times the rated capacity of operating copper smelters in that country (table 1.)

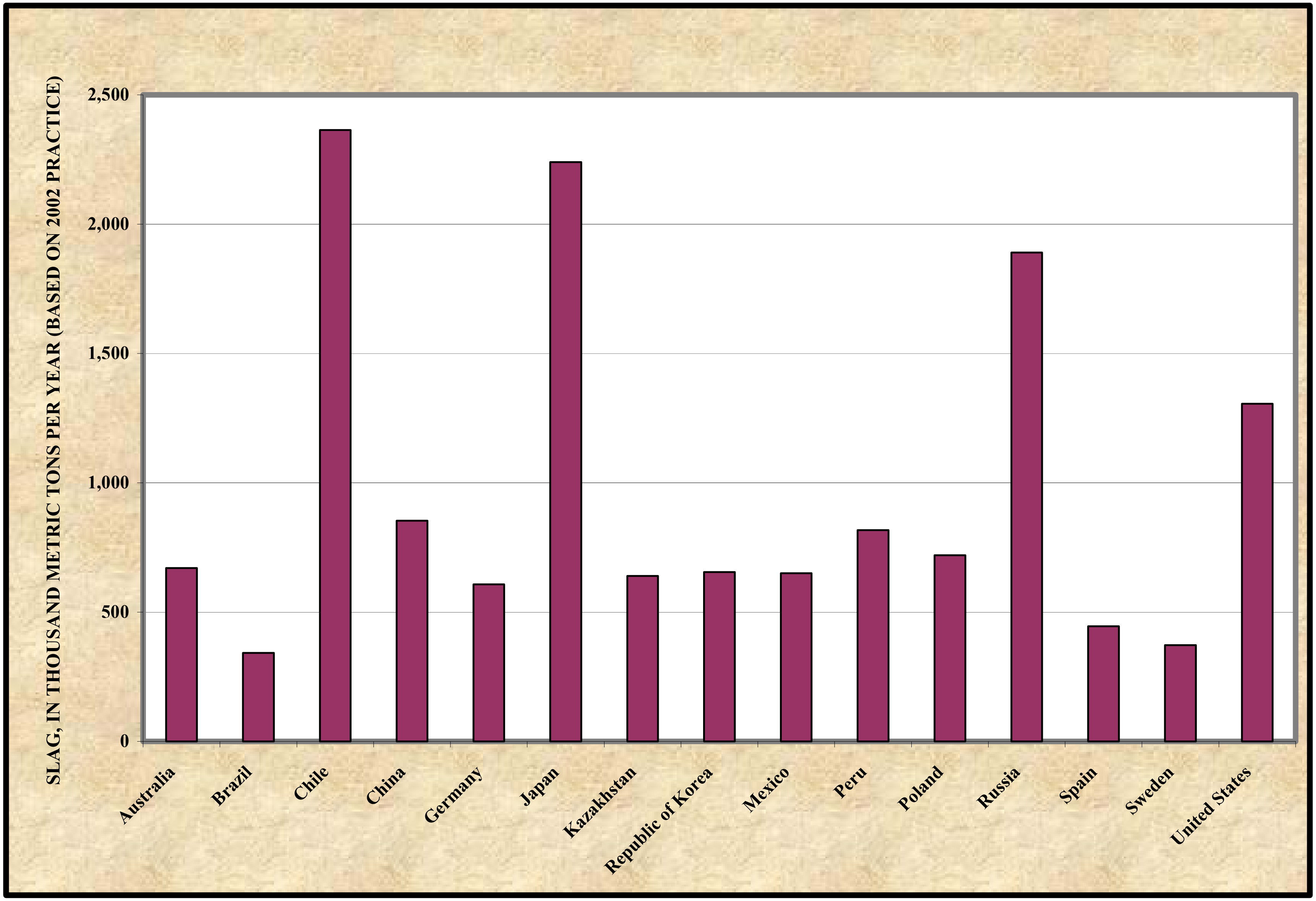

Figure 6. Annual quantity of slag generated by copper smelters, by country.

Theme 9. Copper–smelter–generated ore demand and ore supply, by country/region

Copper smelters process copper concentrate, which is a derived product from copper ore. The demand for concentrate generated by the pyrometallurgical smelters translates into a demand for ore at the mine. In this study, the quantity of ore to support a given smelter's known copper output flow was estimated from information about the mines that supply a smelter and the process characteristics of the milling step. Figure 7 shows the annual quantity of ore required by the smelters studied, by country.

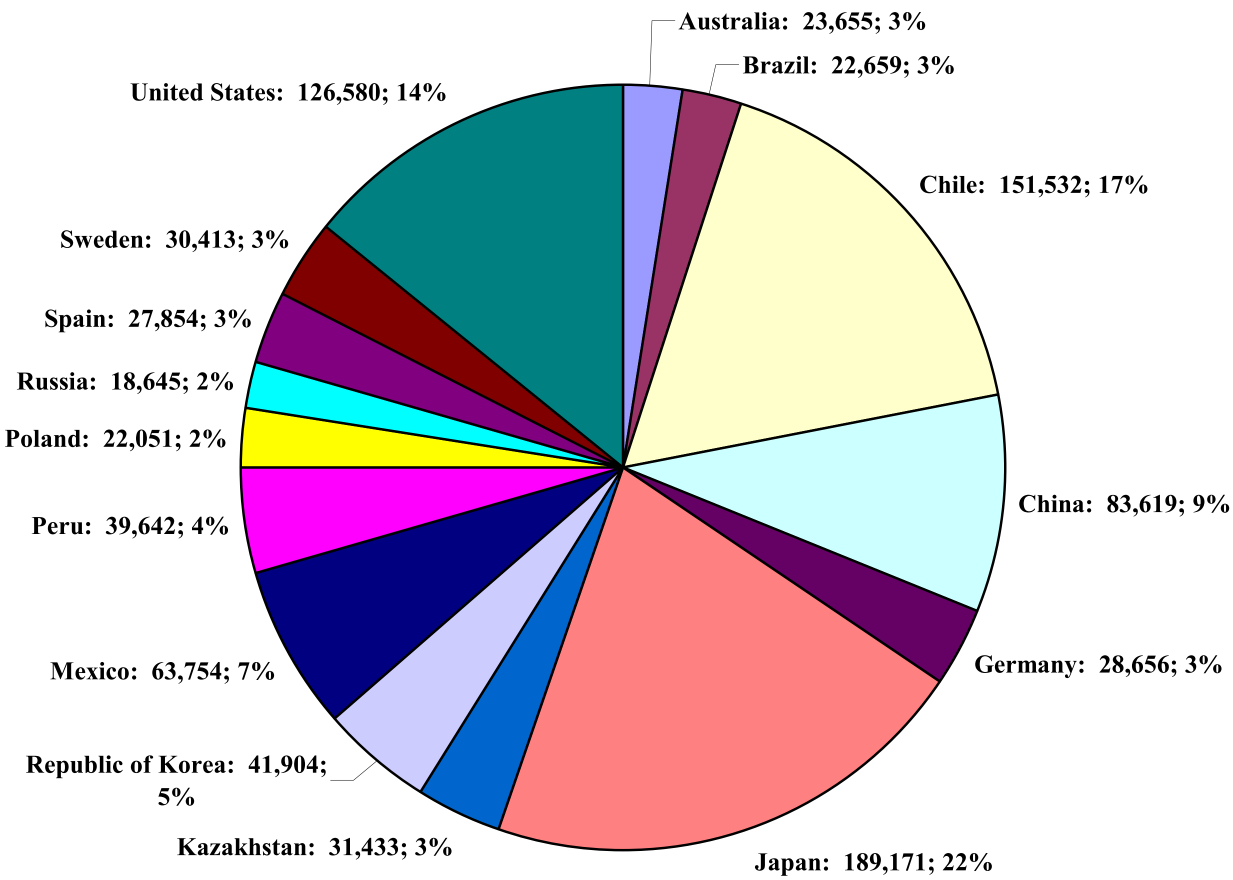

Figure 7. Annual quantity of copper ore demand generated by copper smelters, by country.
[Values are expressed in thousand metric tons per year of ore (based on 2002 practice) and by percentage of total.]

Figure 8 shows the sources that satisfy the demanded quantity of ore; that is, the supply, by country.

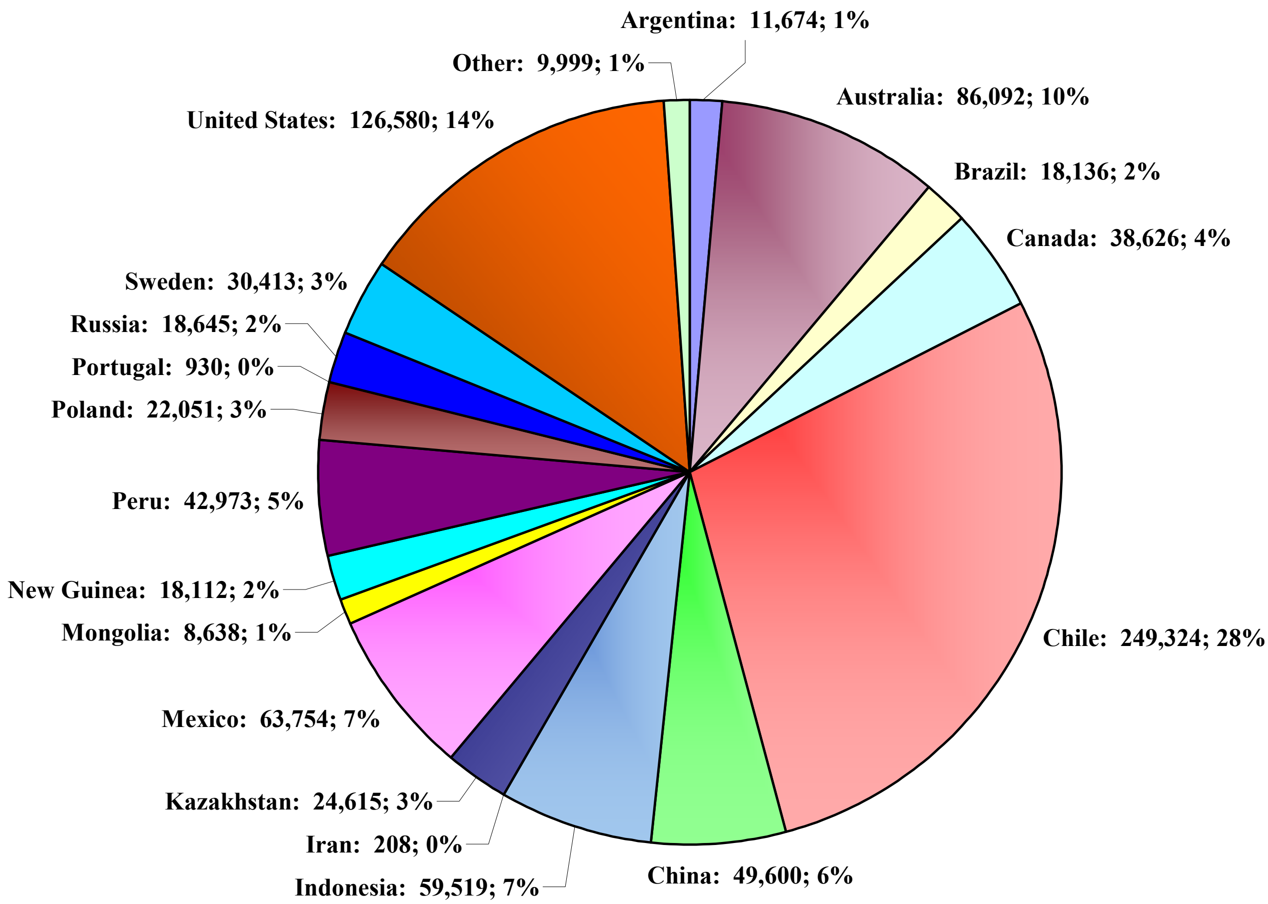

Figure 8. Annual quantity of copper ore supply for copper smelters, by country.
[Values are expressed in thousand of metric tons per year of ore (based on 2002 practice) and by percentage of total.]

Figure 9 shows the distribution of Chilean ore, by country.

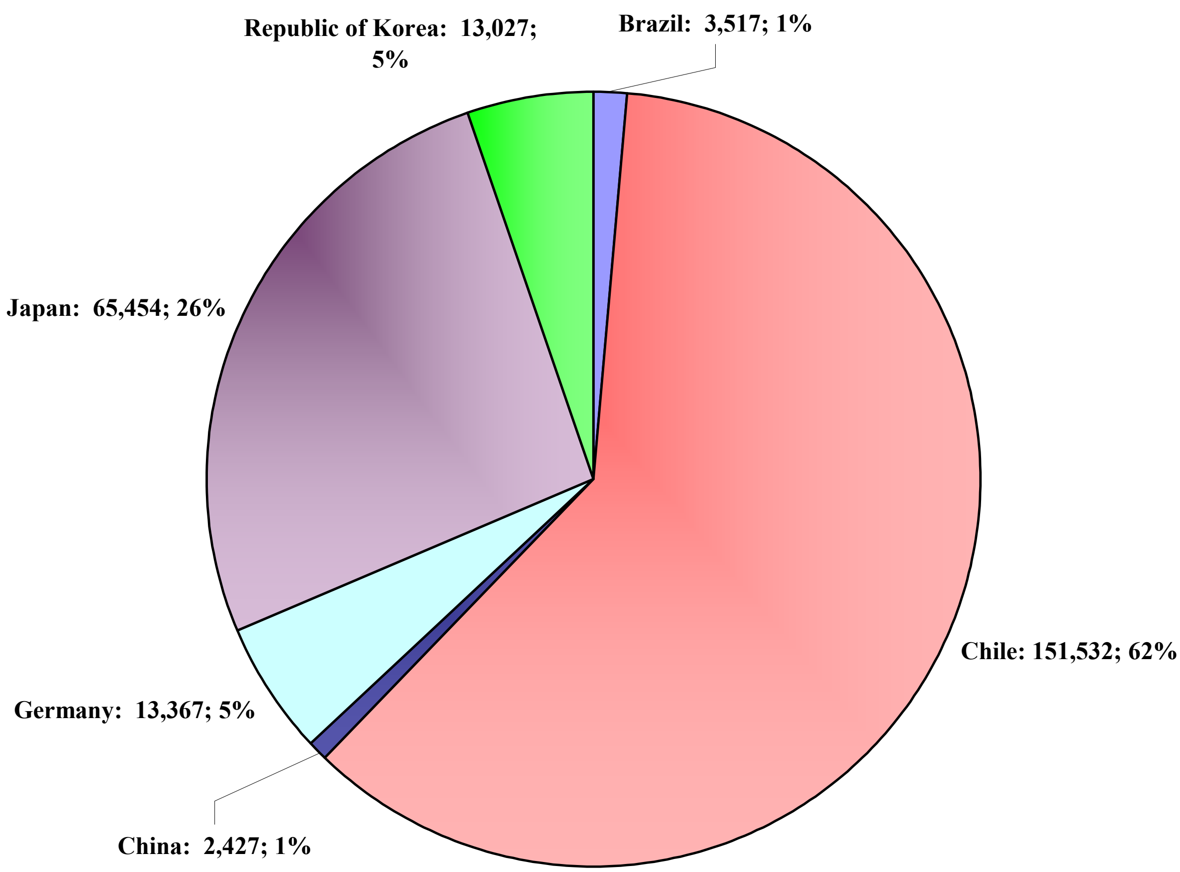

Figure 9. Annual quantity of Chilean copper ore distributed to copper smelters, by country.
[Values are expressed in thousand of metric tons per year of ore (based on 2002 practice) and by percentage of total.]

Figure 10 shows the distribution of Australian ore, by country.

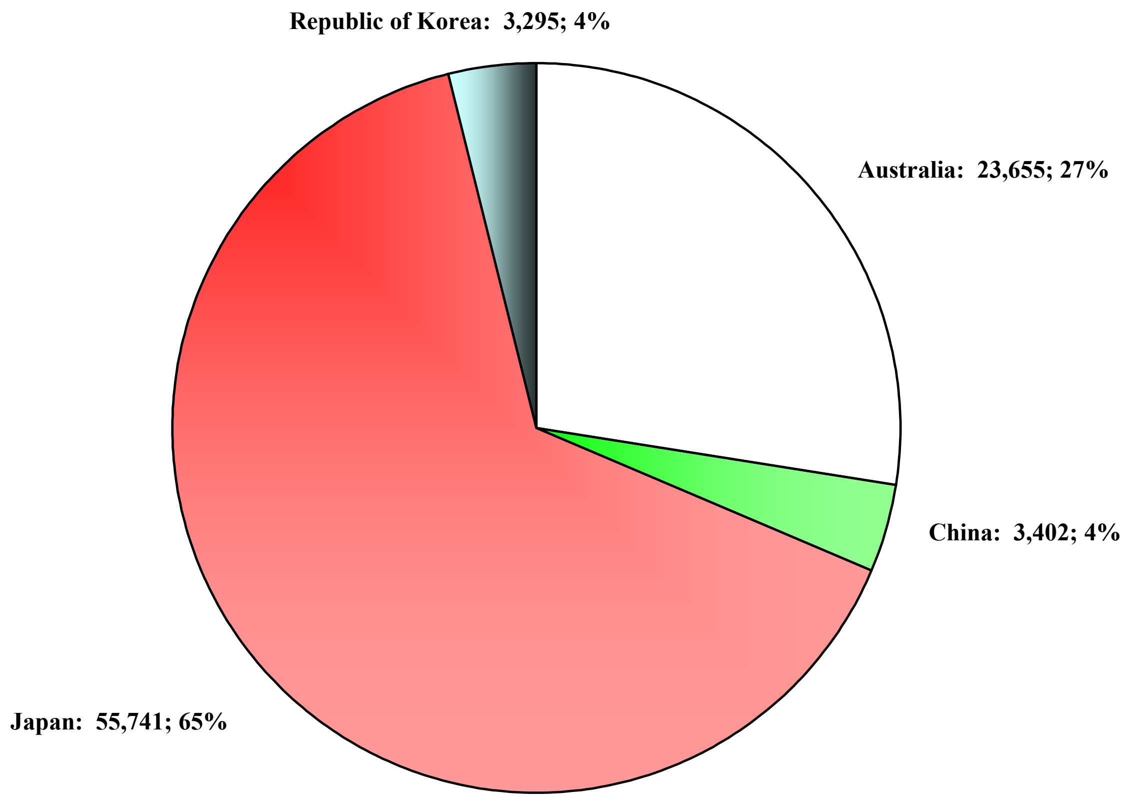

Figure 10. Annual quantity of Australian copper ore distributed to copper smelters, by country.
[Values are expressed in thousand metric tons per year of ore (based on 2002 practice) and by percentage of total.]

By comparing figures 7 and 8, one can see the importance of Chile and Australia as producers of mine and smelter copper product. Germany, Japan, and the Republic of Korea are large smelter product producers but import almost all the concentrate charged into their furnaces.

Theme 10. Mine waste generated with attribution to country that generated the demand for concentrate

As demand for copper concentrates generates a demand for copper ore, the mining of that ore, which depends on the type of mine and the characteristics of the mine, generates mine waste. This makes it possible to estimate the quantity of open-pit mine waste that derives from copper smelter demand for concentrate and to attribute mine waste generated within the country where the ore originates to the country where the smelting occurs. Underground mines do create mine waste but generally in much smaller and often unreported quantities.

Figure 11A shows the annual quantity (the height of the bar) of open-pit mine waste produced in a concentrate supplying country (X axis), and the attribution of the mine waste to the smelting countries (the color splits within the bars).

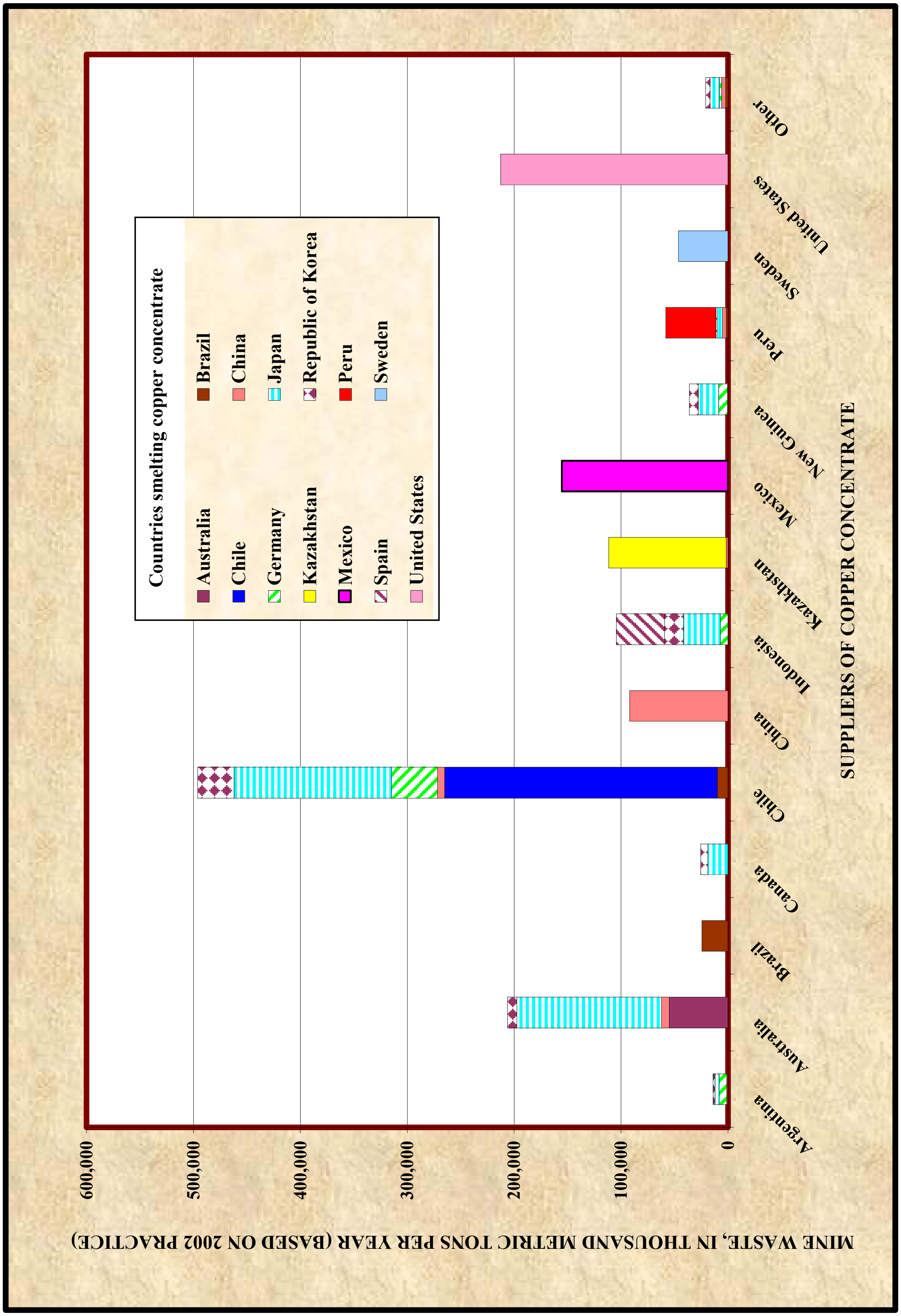

Figure 11A. Annual quantity of open-pit mine waste produced, by country; and attribution to copper smelters, by country.
[Values are expressed in thousand metric tons per year of mine waste (based on year 2002 practice).]

Figure 11B is derived from the same data as figure 11A but is arranged to show the attribution of open-pit mine waste from the viewpoint of the smelting countries (X axis).

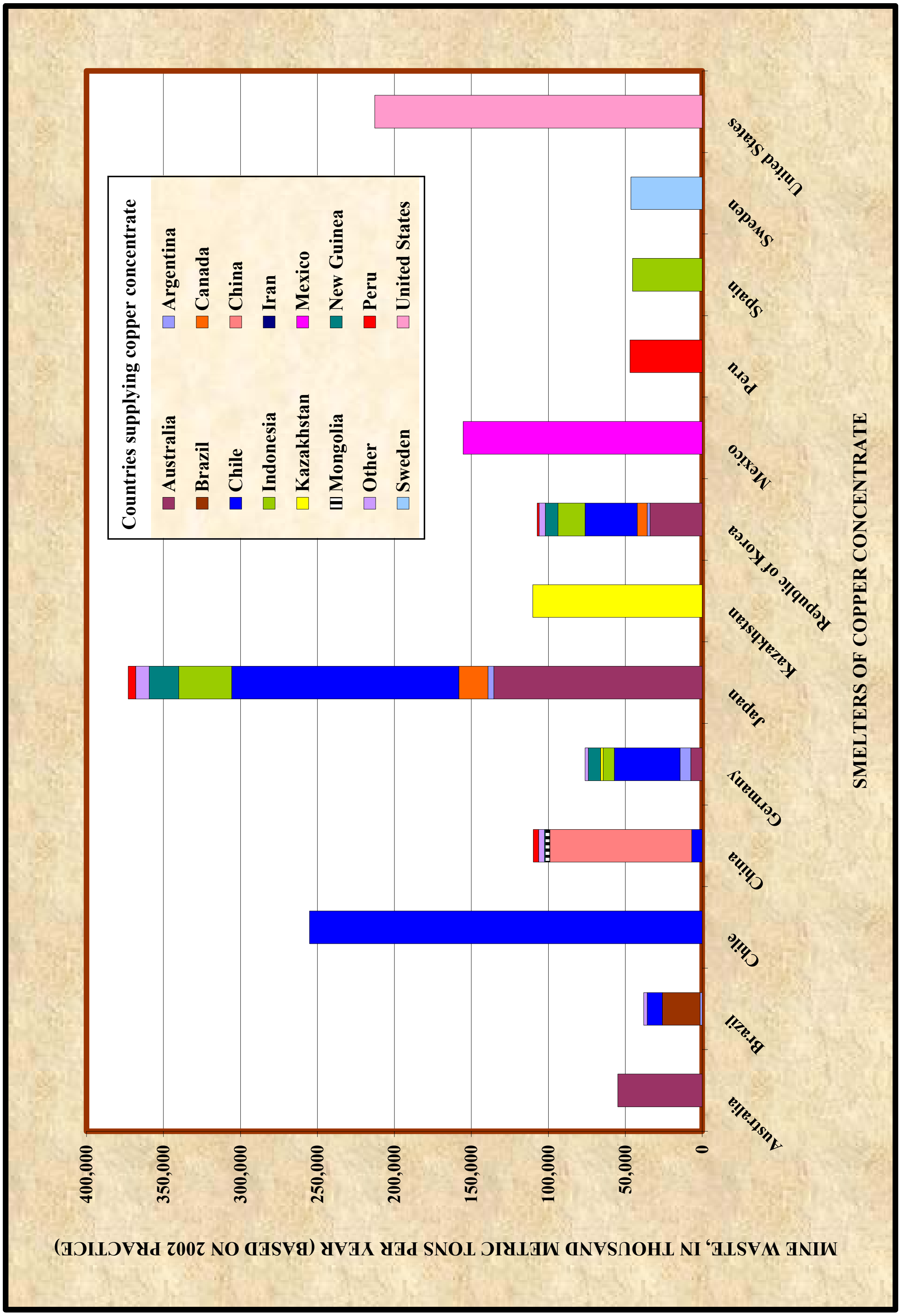

Figure 11B. Annual quantity of open-pit mine waste produced, by country; and attribution to copper smelters, by country.
[Values are expressed in thousand metric tons per year of mine waste (based on year 2002 practice).]

Even though Chile exports about 38 percent of its ore as concentrate, about 50 percent of the mine waste burden in Chile is attributable to the smelting of that concentrate in other countries (figures 9, 11). This apparent anomaly is accounted by the fact that the exported concentrate is from open-pit mines where mine waste is generated in larger quantities. For Australia, about 75 percent of its mine waste burden is attributable to smelting in other countries.

Theme 11. Mill tailings generated when serving copper smelter demand for concentrates

Copper ore is finely ground and mixed with water and organic chemicals. The mix is aerated, which causes the sulfide minerals to adhere to the bubbles formed and float. The floating sulfide minerals are skimmed and are further processed into copper concentrate. The much larger fraction (greater than 95 percent) of the remaining material is flotation tailings and is usually reposed into and behind a tailings dam. The dry weight of these tailings was estimated for the smelters studied. Tailings contain associated water of up to 50 percent.

Figure 12 shows the annual quantity of tailings (dry weight basis) generated in the production of the concentrate charged to the smelters studied, by country of concentrate origin.

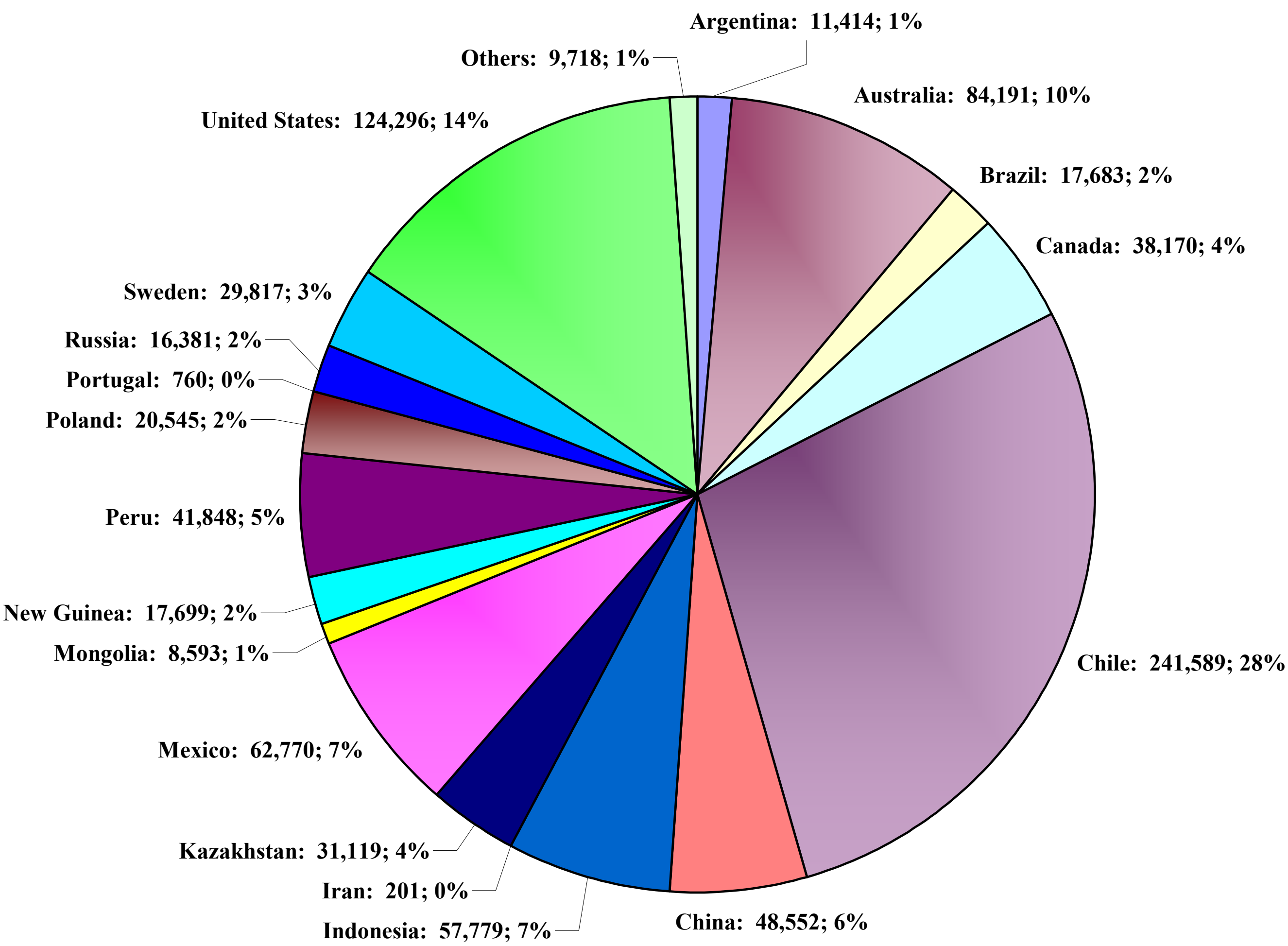

Figure 12. Annual quantity of flotation mill tailings, by country. Values are expressed in thousand metric tons (dry weight) per year of tailings (based on year 2002 practice), and percentage of total.

Figure 13 shows the attribution of tailings generated in concentrate supplying countries to smelting countries. For example, examination of the ‘‘Chile’’ bar in figure 13 shows that 26 percent of the tailings generated in Chile are attributable to smelting of concentrate in Japan.

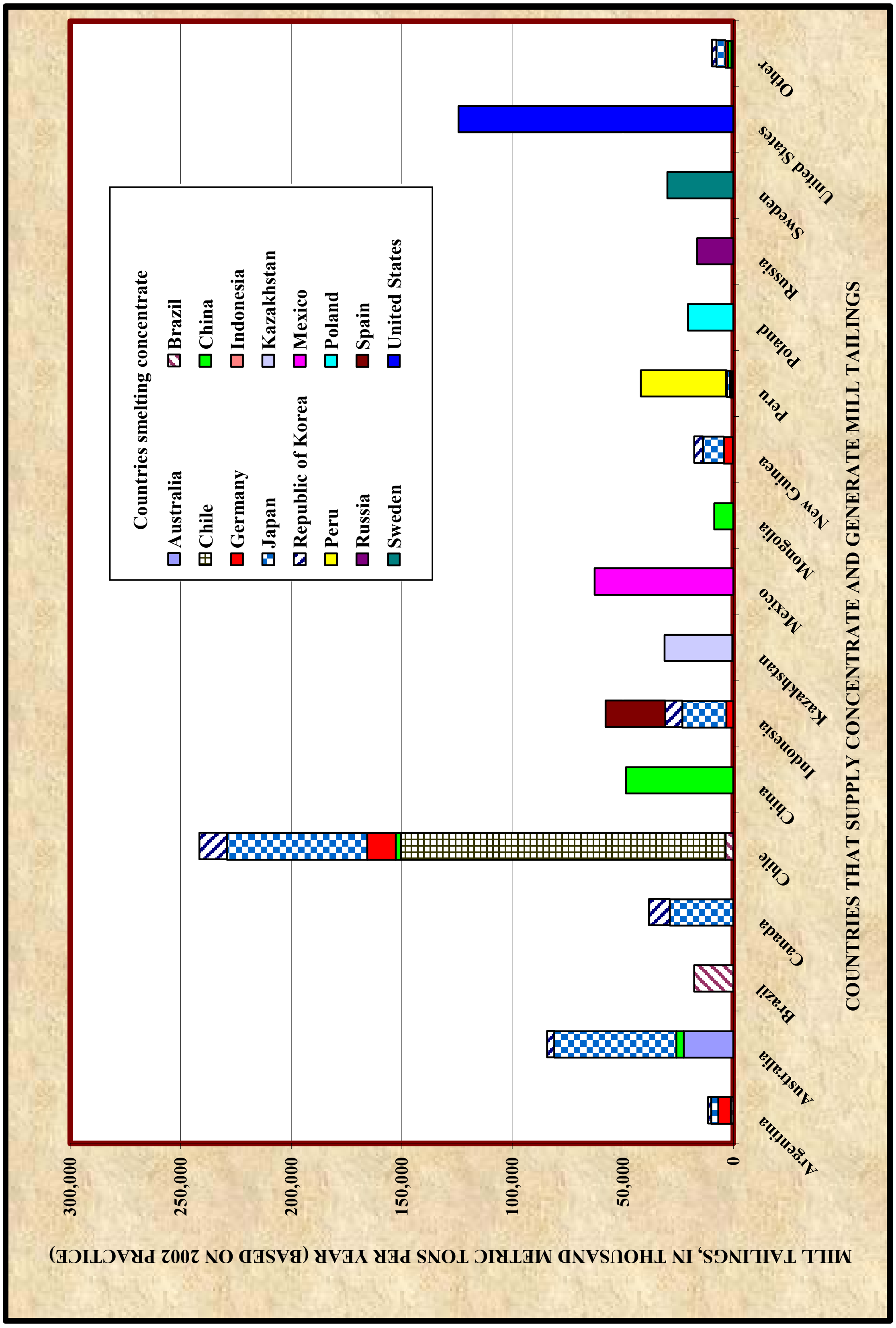

Figure 13. Annual quantity of mill tailings produced, by country, and attribution to copper smelters, by country.
[Values are expressed in thousand metric tons per year of mill tailings (based on year 2002 practice).]

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Kelly, T.D., Buckingham, D.A., DiFrancesco, C.A., Porter, K.E., Goonan, T.G., Szonpek, J.L., Berry, C., and Crane, M., 2002, Historical statistics for mineral commodities in the united States: U.S. Geological Survey Open-File Report 01-006, [Web site accessed August 23, 2004, at URL http://minerals.usgs.gov/minerals/pubs/ofo1-006/.

Wu, John C., 2002, The mineral industry of Japan, in Area reports—International—Asia and the Pacific: U.S. Geological Survey Minerals Yearbook 2000, v. III, p.13.1-13.34, accessible on–line at URL http://minerals.usgs.gov/minerals/pubs/country/2002/jamyb02.pdf.

Appendix I

Smelter Materials Flow Diagrams

Introduction

Table 8 lists the studied smelters, by country, and orders them within countries by descending capacity.

Table 8. Copper smelters, by country.

Country	Smelter (Common name)	Technology (Primary smelting furnace)	Capacity Thousand metric tons of anode
Australia	Mount Isa	Isamelt/Reverberatory	250
	Olympic Dam	Outokumpu	200
Brazil	Camacari	Outokumpu	220
Chile	Chuquicamata	Outokumpu/Teniente	500
	Caletones	Teniente	400
	Altonorte	Noranda	290
	Potrerillos	Teniente	220
	Chagres	Outokumpu	150
	Las Ventanas	Teniente	150
China	Guixi	Outokumpu	250
	Kunming	Isasmelt	160
Germany	Norddeutsche	Outokumpu/Contimelt	420
Japan	Saganoseki	Outokumpu	470
	Onahama	Reverberatory	348
	Toyo (Besshi)	Outokumpu	300
	Naoshima	Mitsubishi (continuous)	270
	Tamano	Outokumpu	263
Kazakhstan	Dzeshkazgan	Electric/Reverberatory	215
Republic of Korea	Onsan II	Mitsubishi (continuous)	240
	Onsan I	Outokumpu	210
Mexico	Nacozari	Outokumpu/Teniente	300
Peru	Ilo	Reverberatory/Teniente	300
Poland	Glogow I	Blast furnace	205
	Glogow II	Outokumpu	220
Russia	Norilsk	Vanyukov	300
Spain	Huelva	Outokumpu	320
Sweden	Ronnskar	Electric (TBRC)	240

Table 8. Copper smelters, by country—Continued.

Country	Smelter (Common name)	Technology (Primary smelting furnace)	Capacity Thousand metric tons of anode
United States	Garfield	Kennecott/Outokumpu	320
	Hayden	Inco	210
	Miami	Isamelt/Electric	180

There are two graphics for each smelter studied—one that shows copper-specific material flows and the other that shows gross material flows at an assumed operating rate of 92-percent of rated plant capacity. Because the graphic depiction of inputs and outputs is focused only on those flows of greatest interest to engineers and scientists, the inputs and outputs do not balance. Excess air, nitrogen associated with input air and industrial oxygen, and water derived from chemical reactions during hydroxide scrubbing, combustion of fuels, and evaporation from charge materials are accounted in the underlying material balances, but are not graphically depicted to simplify the graphics.

Disclaimer: The selection of two significant decimal places for copper-specific flows, and three significant figures for thousand metric tons per year gross flow is arbitrary and is not meant to imply unwarranted accuracy or quality of the original data.

Smelter-Specific Materials Flow Diagrams

Altonorte

Figures 14 and 15 show selected material flows for the Altonorte smelter in Chile. The smelter is located in La Negra, Chile (lat 23.80°S., long 70.33°W.). It is owned and operated by Noranda Inc. of Toronto, Ontario, Canada. It smelts Chilean concentrate from various sources and its annual capacity is rated at 290,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the Altonorte graphics were extracted from the following sources: Biswas, and Davenport, 1980; CIPMA, 2002; Chilean Copper Comission, 2000; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, Stefan, 2001; Mast, Arrian, and Benavides, 1999 Mechanical Engineer's Handbook, 5th edition1951; Mineria Chilena, 2003; Noranda, 2003a, b, c; Noranda Reactor, 2003; NTIS, 1989; Sanchez, and Castro, 2002; Sonami, 2002; Tan, and Zhang, 1996; Valenzuela–Jara, Palacios, Cordero, and Sanchez, 2002; –Velasco, 2000; and World Mine Cost Data Exchange, 2004.

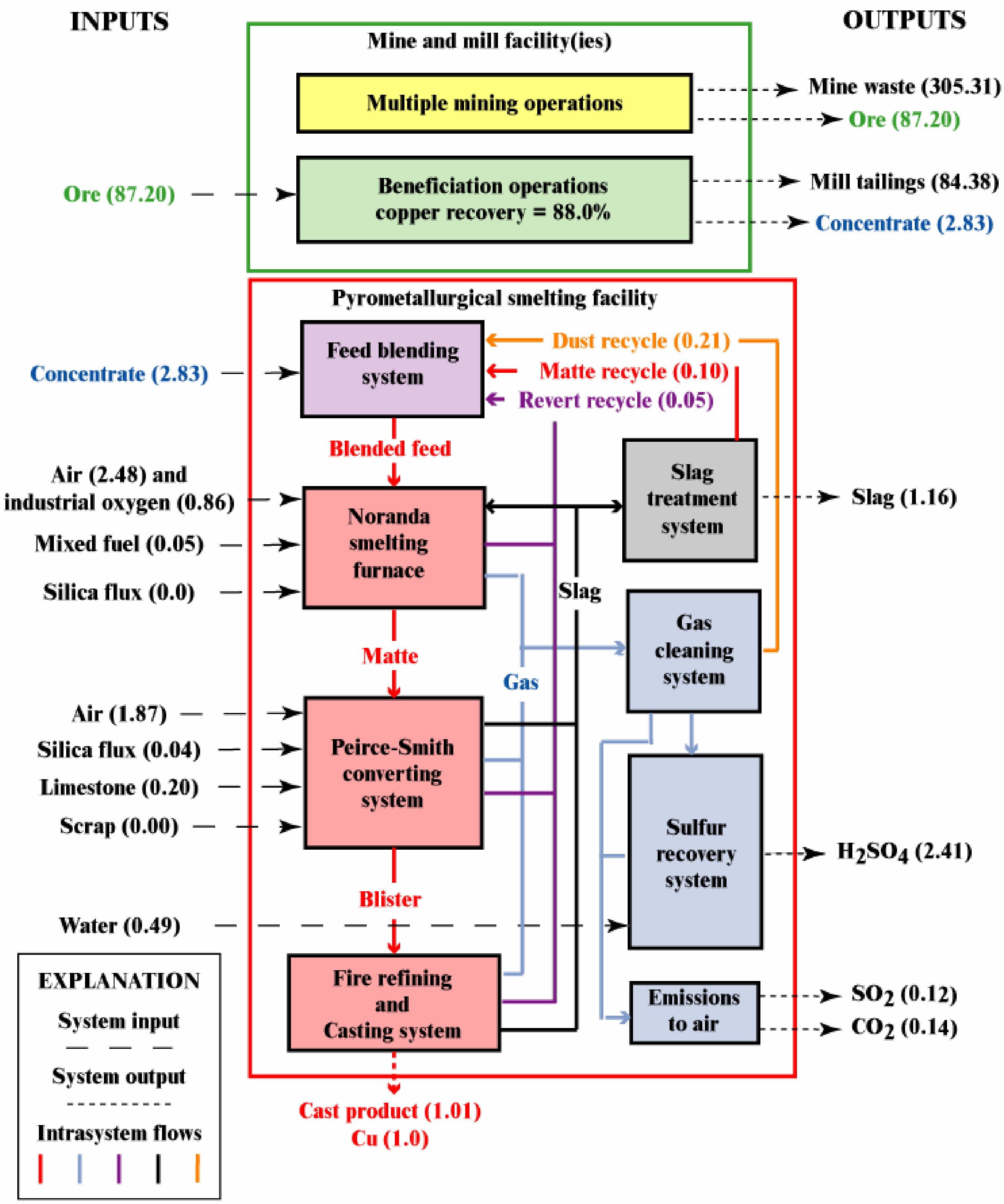

Figure 14. Copper-specific flow diagram of the Altonorte smelter.

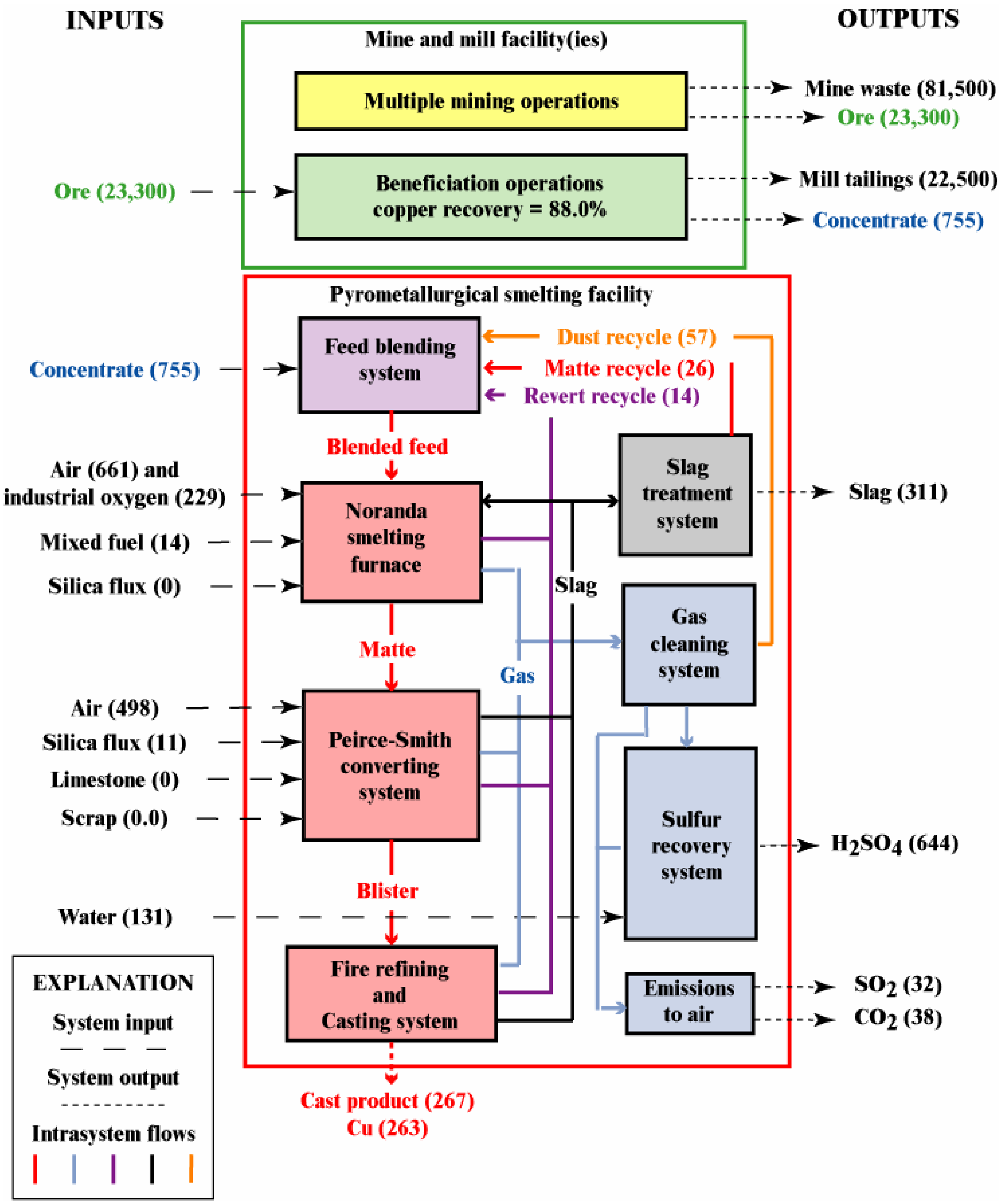

Figure 15. Gross flow diagram of the Altonorte smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Caletones

Figures 16 and 17 show selected material flows for the Caletones smelter in Chile. The smelter is located in El Teniente, Chile (lat 34.10°S., long 70.33°W.). It is owned and operated by Corporación Nacional del Cobre de Chile (CODELCO) of Santiago, Chile. As part of the Teniente Division of CODELCO, it smelts concentrate from the underground El Teniente Mine and annual capacity is rated at 400,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Caletones smelter were extracted from the following sources: Achurra, Chacana, Buchi, and Condore, 2003; Acuna, and Yazawa, 1997; Acuna, Zuniga, Guibout, and Ruz, 1999; Alvaredo, Archurra, and Mac Kay, 1998; Alvaredo, and Godoy, 1999; Biswas, and Davenport, 1980; CODELCO, 1999; CODELCO, 2000; CODELCO, undated a, b; Chilean Copper Commission, 2000; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, Stefan, 2001; Imris, Rebollodo, Sanchez, Castro, Achurra, and Hernandez, 1999; Mechanical Engineer's Handbook, 5th edition, 1951; Montenegro, Fujisawa, Warczuk, and Rivero, 2003; Morales, and Mac-Kay, 1999; O'Ryan, and Diaz, 1998; Sanchez, and Castro, 2002; Valenzuela–Jara, 2002; Valenzuela–Jara, Palacios, Cordero, and Sanchez, 2003; Velasco, 2000; and World Mine Cost Data Exchange, 2004.

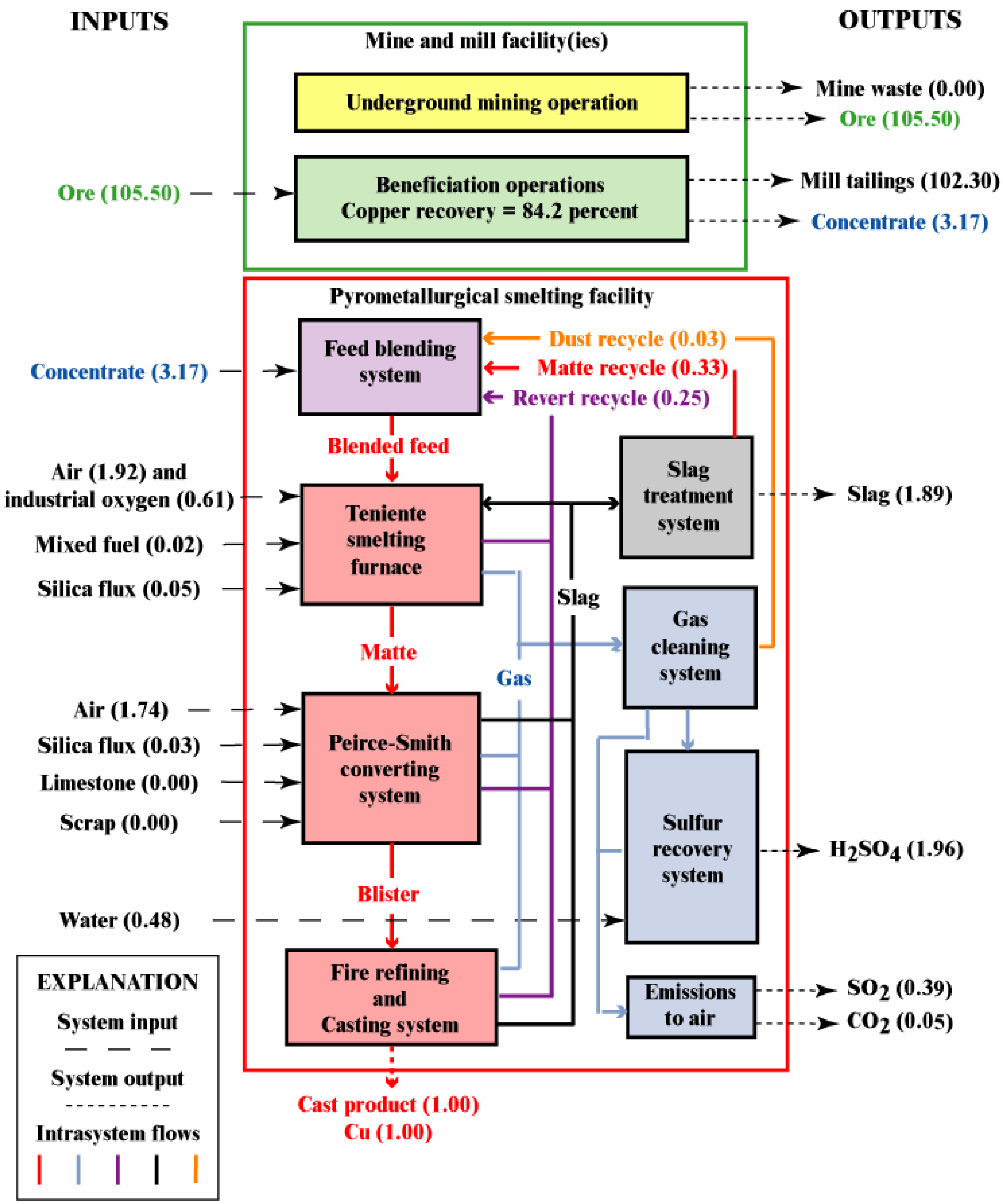

Figure 16. Copper-specific flow diagram of the Caletones smelter.

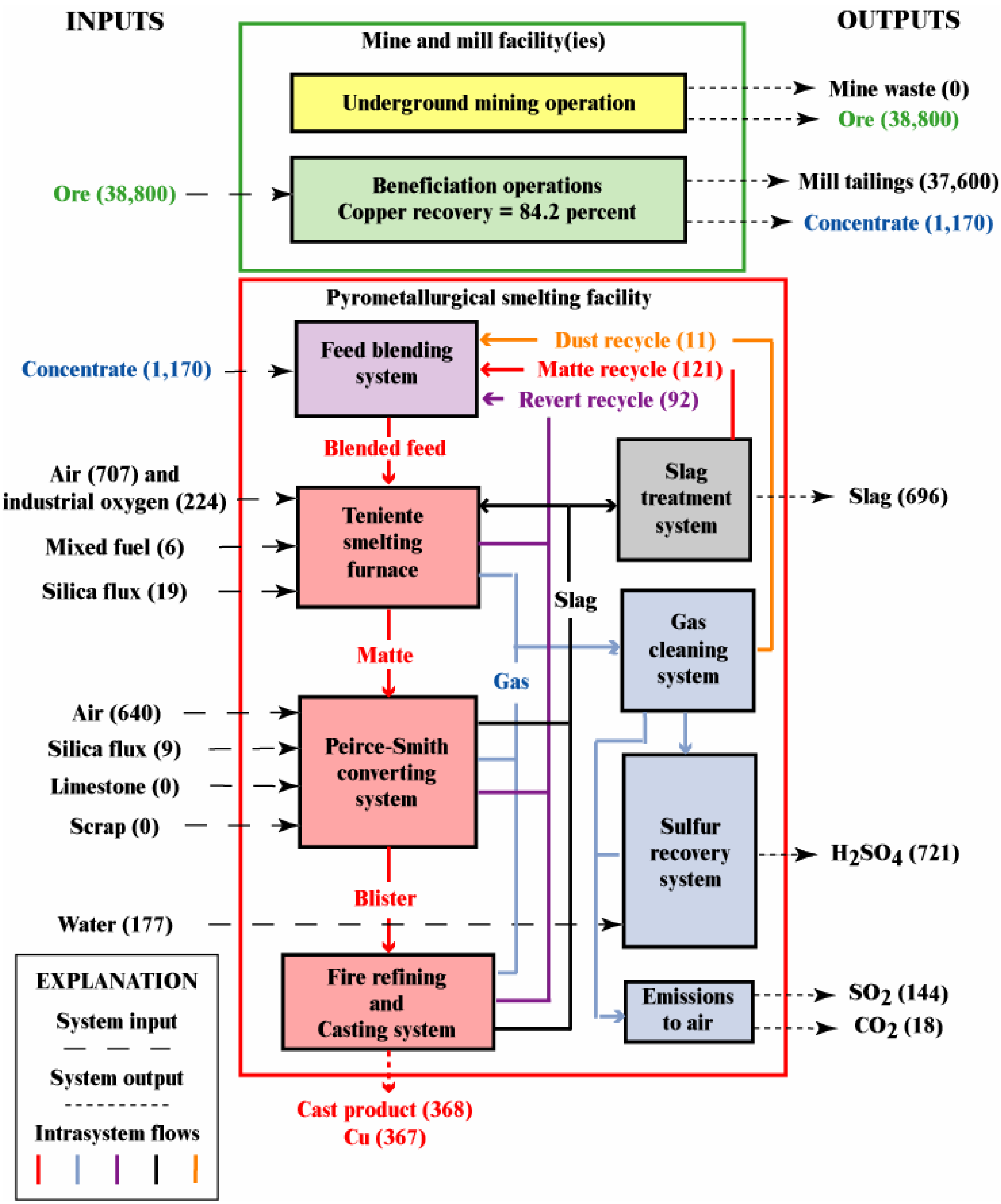

Figure 17. Gross flow diagram of the Caletones smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Camacari

Figures 18 and 19 show selected material flows for the Camacari smelter in Brazil. The smelter is located in Camacari, Brazil (lat 12.68°S., long 38.33°W.). It is owned by Paranapanema Group of Rio de Janiero, Brazil and is operated by Caraiba Metais S.A. Ind. E Com. of Dias D'Avila, Brazil. It smelts concentrate from local Brazilian mines and imports concentrate from other South American countries and the plant's annual capacity is rated at 220,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Camacari smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Branco, and Ribiero, 2002; Canadian Institute of Mining, Metallurgy and Petroleum, Hydrometallurgy Section, 2001; Chilean Copper Comission, 2000; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Gurmendi, 2002; Mechanical Engineer's Handbook, 5th edition, 1951; Porter Geoconsultancy, 2000; Reuters, 2004; and World Mine Cost Data Exchange, 2004.

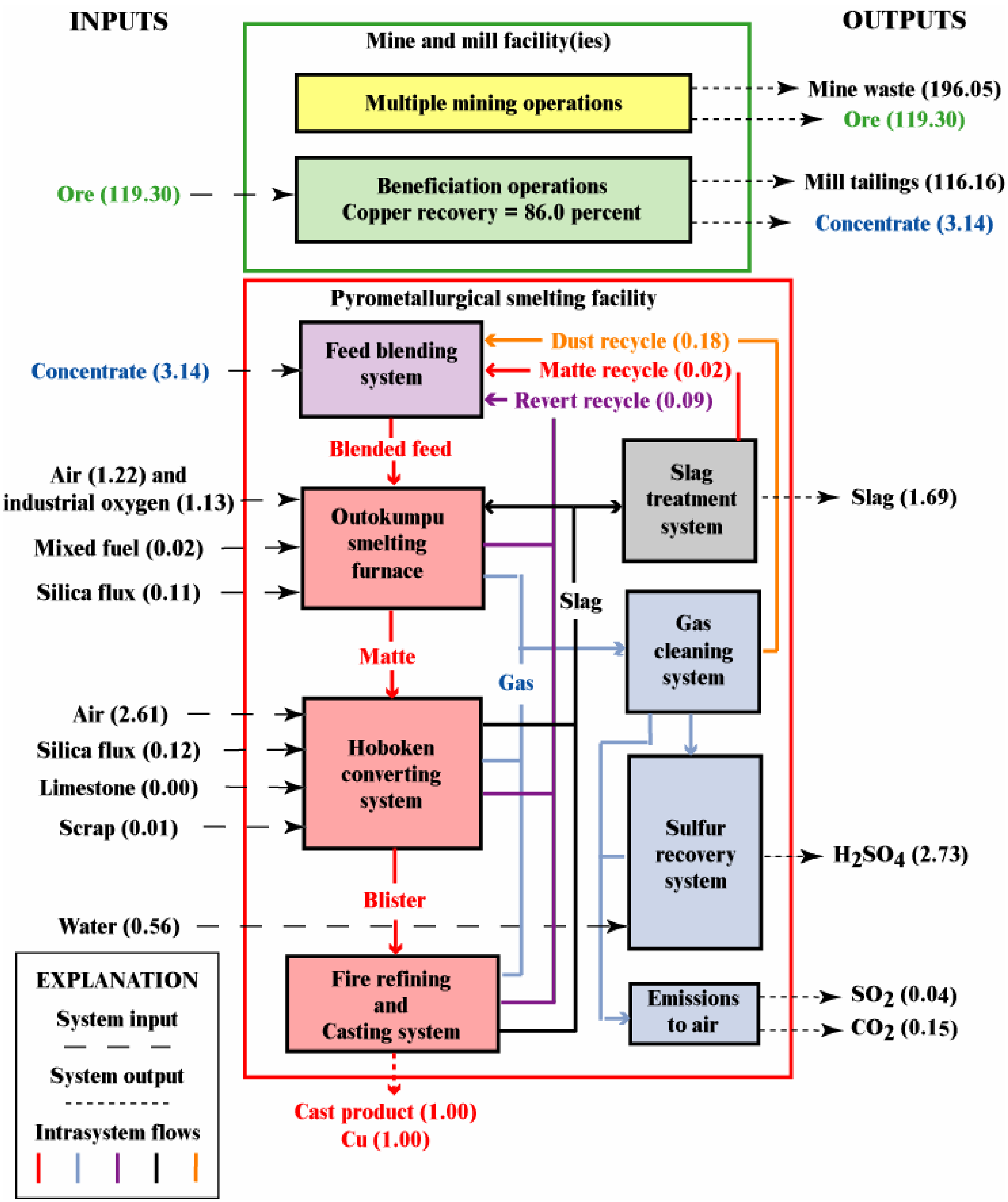

Figure 18. Copper-specific flow diagram of the Camacari smelter.

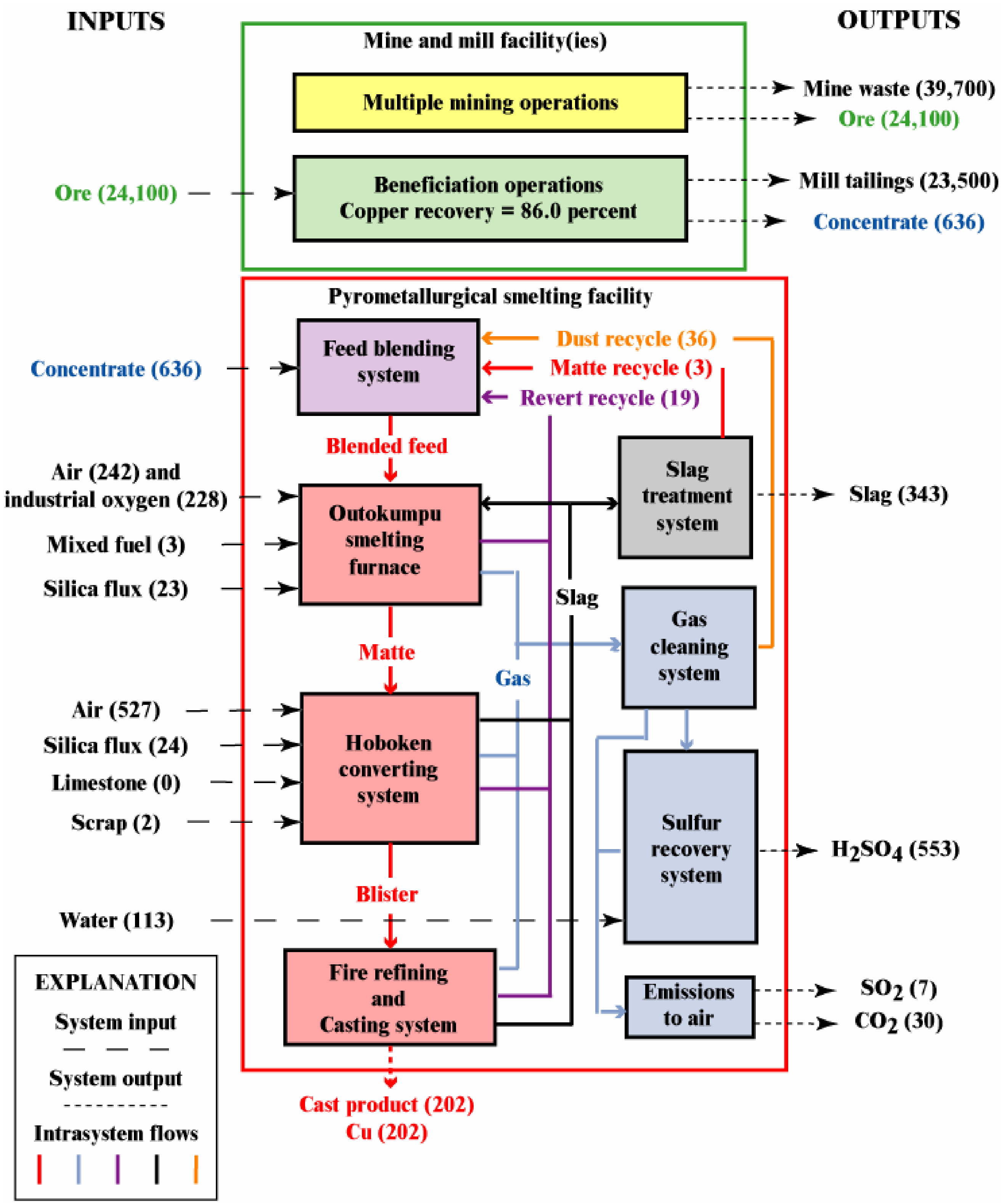

Figure 19. Gross flow diagram of the Camacari smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Chagres

Figures 20 and 21 show selected material flows for the Chagres smelter in Chile. The smelter is located in Chagres, Chile (lat 32.80°S., long 70.97°W.). It is owned by Anglo American plc of Johannesburg, South Africa and is operated by Anglo American Chile Ltda. of Santiago, Chile. The plant receives concentrate from the Chilean mines El Soldado and Los Bronces and its annual capacity is rated at 150,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Chagres smelter were extracted from the following sources: Acuna, Zuniga, Guibout, and Ruz, 1999; AME Mineral Economics, 2001; Anglo American plc, 2002; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; E &MJ, 2002; Gossling, 2001; Mackey, and Weddick, 1999; Mechanical Engineer's Handbook, 5th edition, 1951; Northern Miner, June 2002; Sanchez, and Castro, 2002; Sociedad Nacional de Mineria de Chile, 2002; Valenzuela–Jara, Palacios, Cordero, and Sanchez, 2002; Velasco, 2000; and World Mine Cost Data Exchange, 2004.

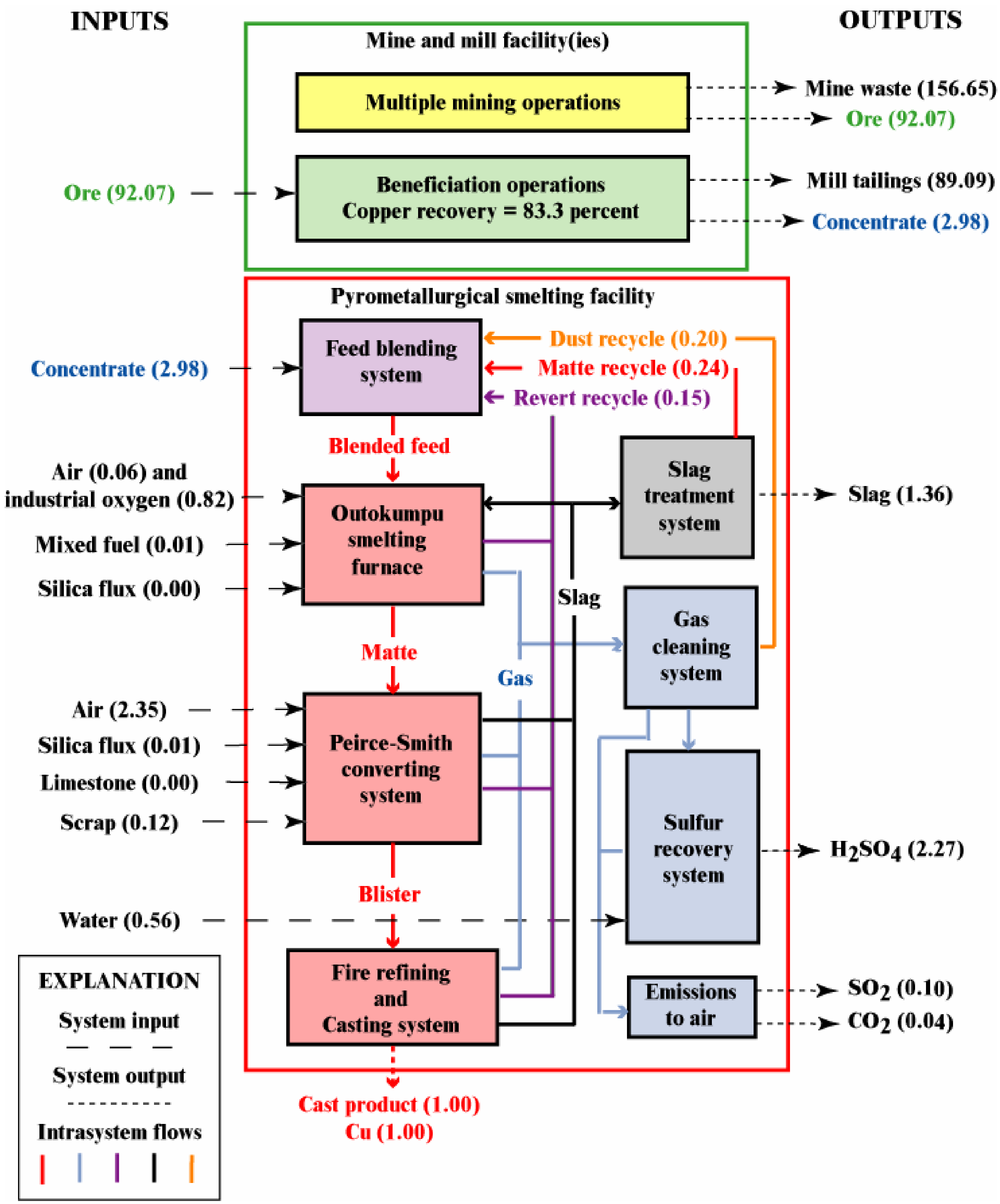

Figure 20. Copper-specific flow diagram of the Chagres smelter.

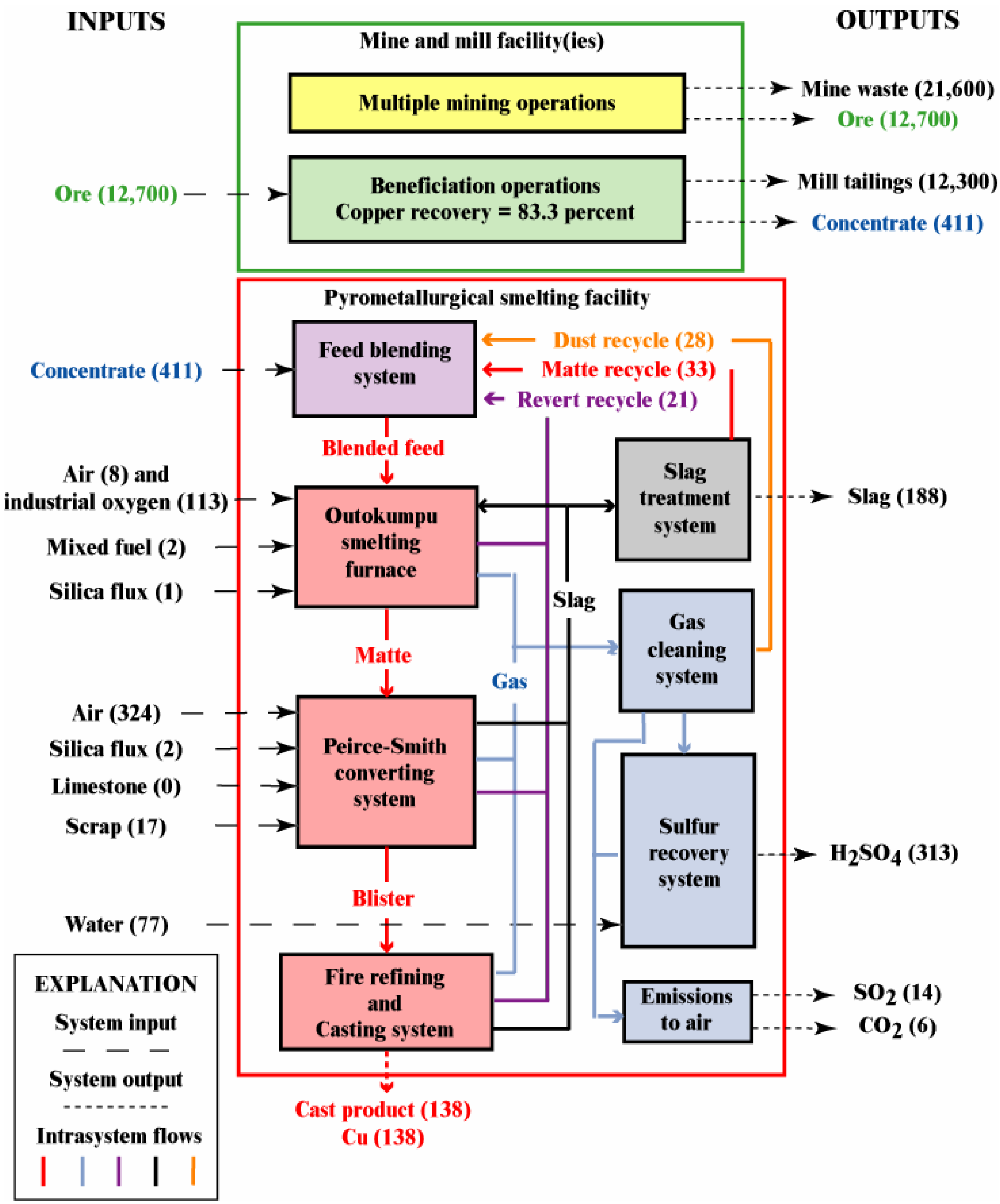

Figure 21. Gross flow diagram of the Chagres smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Chuquicamata

Figures 22 and 23 show selected material flows for the Chuquicamata smelter in Chile. The smelter is located in Chuquicamata, Chile (lat 22.32°S., long 68.93°W.). It is owned and operated by Corporación Nacional del Cobre de Chile (CODELCO) of Santiago, Chile. As part of the Chuquicamata Division of CODELCO, it smelts concentrate from the Chuquicamata Mine and annual capacity is rated at 500,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Chuquicamata smelter were extracted from the following sources: Acuna, and Yazawa, 1997; Acuna, Zuniga, Guibout, and Ruz, 1999; Alvaredo, Archurra, and Mac Kay, 1998; Alvaredo, and Godoy, 1999; AME Mineral Economics, 2001; Biswas, and Davenport, 1980; CIPMA, 2002; CODELCO, 1999, 2000, undated a, b; Chilean Copper Comission, 2000; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Imris, Rebollodo, Sanchez, Castro, Achurra, and Hernandez, 1999; Mechanical Engineer's Handbook, 5th edition, 1951; Morales, and Mac-Kay, 1999; O'Ryan, and Diaz, 1998; Sanchez, and Castro, 2002; Sociedad Nacional de Mineria de Chile, 2002; Valenzuela–Jara, 2002; Valenzuela-Jara, Palacios, Cordero, and Sanchez 2002; Velasco, 2000; and World Mine Cost Data Exchange, 2004.

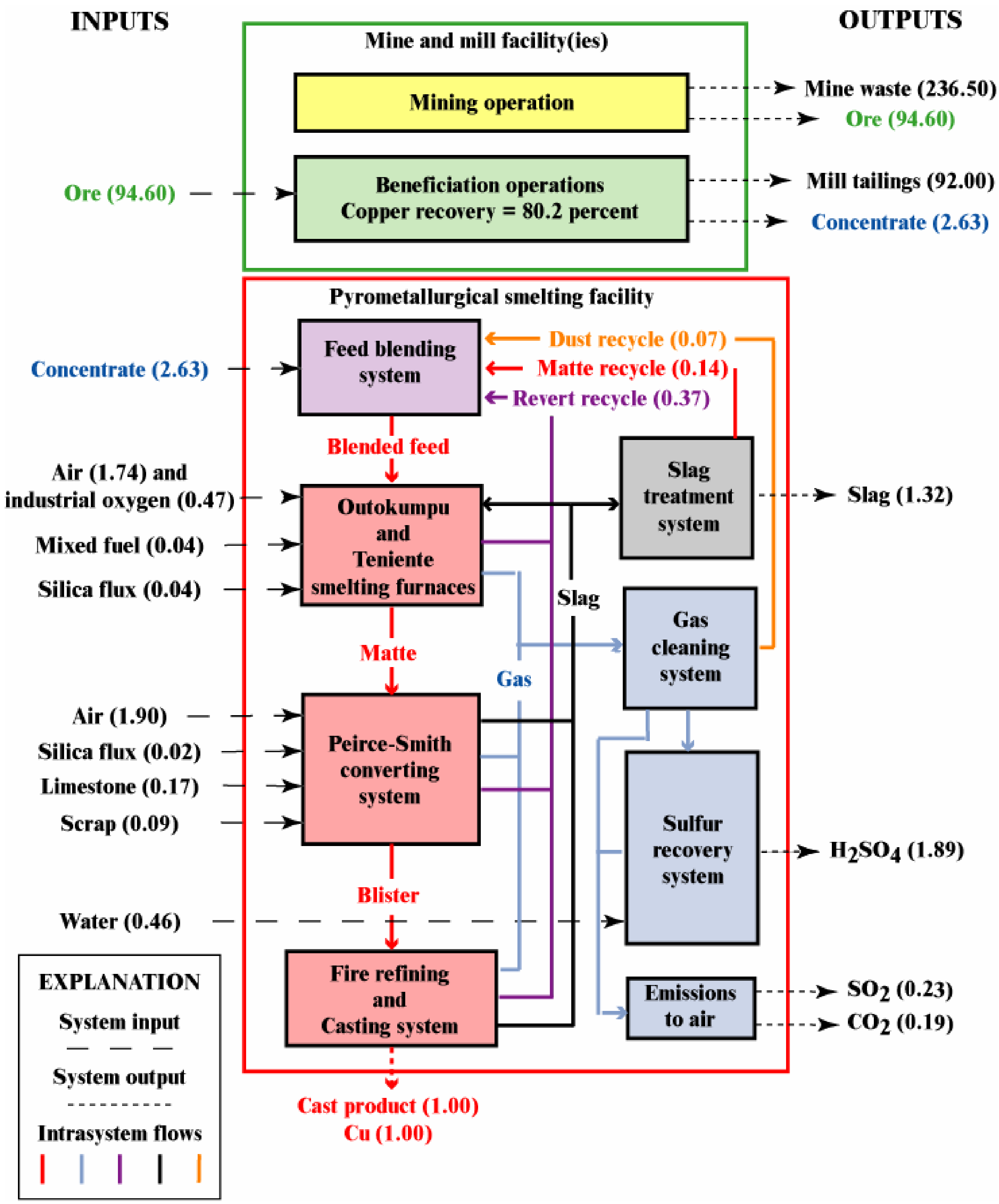

Figure 22. Copper-specific flow diagram of the Chuquicamata smelter.

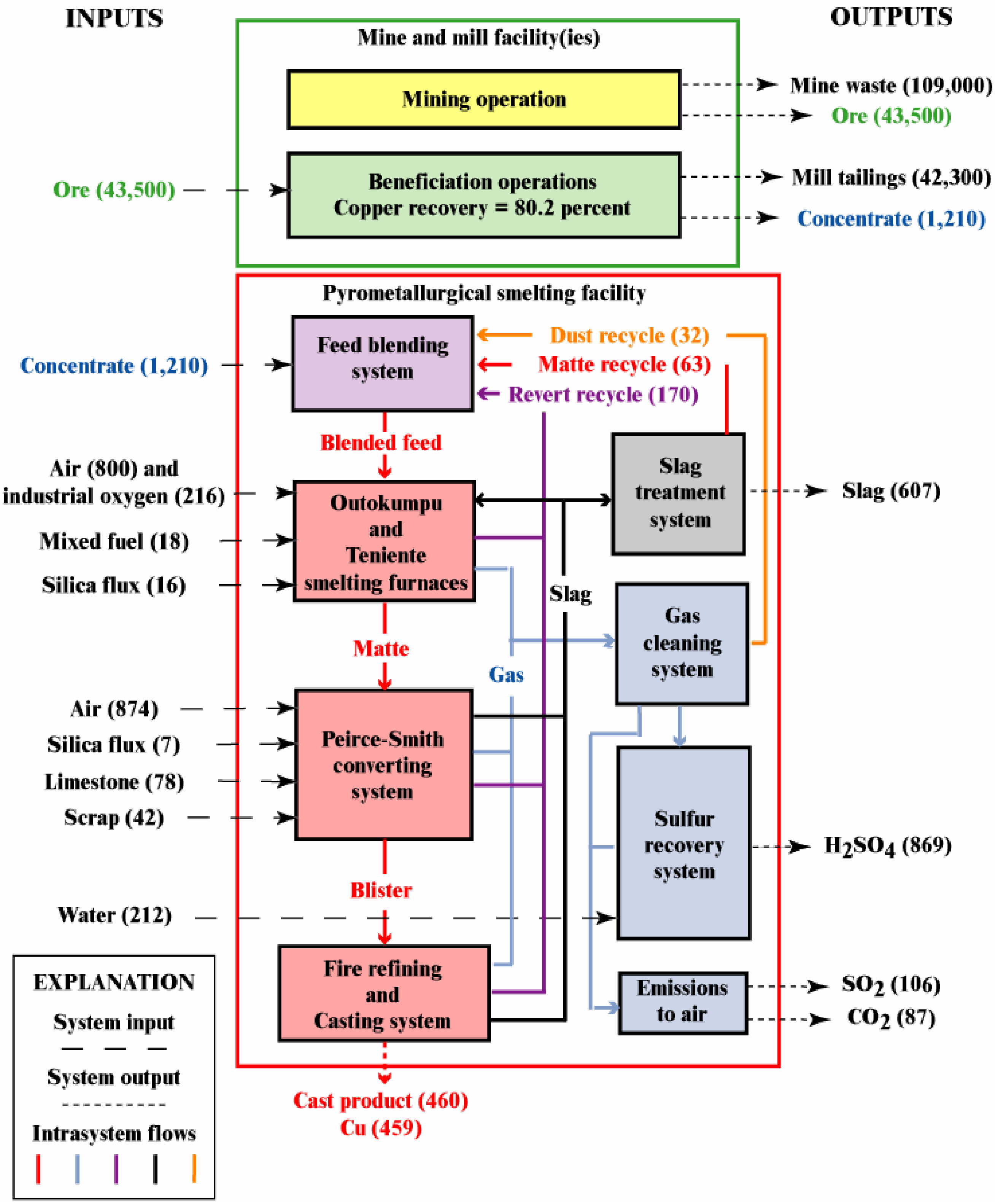

Figure 23. Gross flow diagram of the Chuquicamata smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Dzhezkazgan

Figures 24 and 25 show selected material flows for the Dzhezkazgan smelter in Kazakhstan. The smelter is located in Dzhezkazgan, Kazakhstan (lat 47.78°N., long 67.77°E.). It is owned by the Government of Kazakhstan and Samsung Heavy Industries Co., Ltd. of Seoul, Republic of Korea and is operated by Kazakhmys Corp. of Dzhezkazgan, Kazakhstan with technical assistance from Samsung. It smelts concentrates produced from the ores of regional mines and annual capacity is rated at 300,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Dzhezkazgan smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Cox, Lindsey, and Singer, 2003; Davenport, Jones, King, and Partelpoeg, 2001; Levine, and Wallace, 2001; Mechanical Engineer's Handbook, 5th edition, 1951; MMAJ, 1996; Schloen, 1991; and World Mine Cost Data Exchange, 2004.

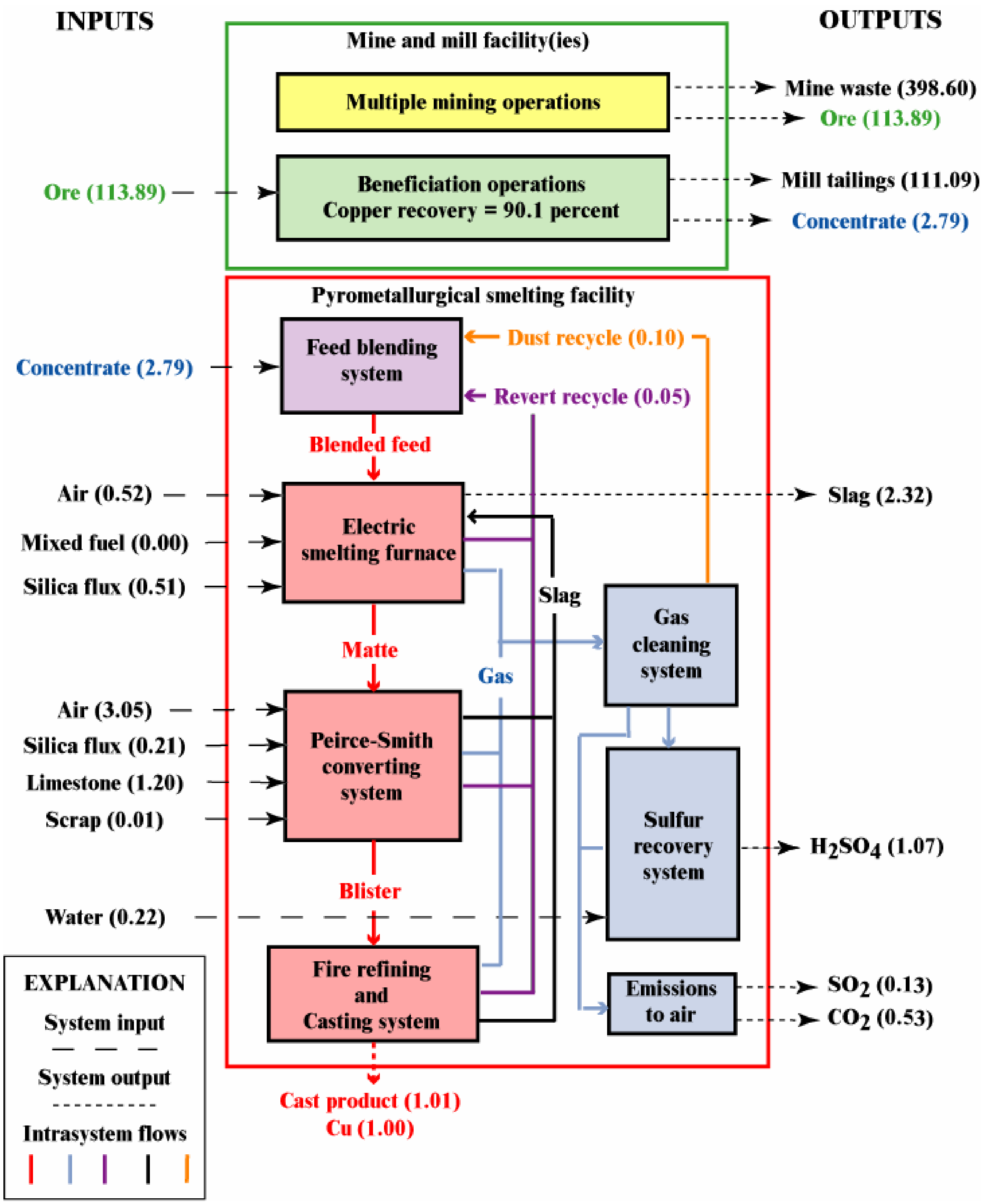

Figure 24. Copper-specific flow diagram of the Dzhezkazgan smelter.

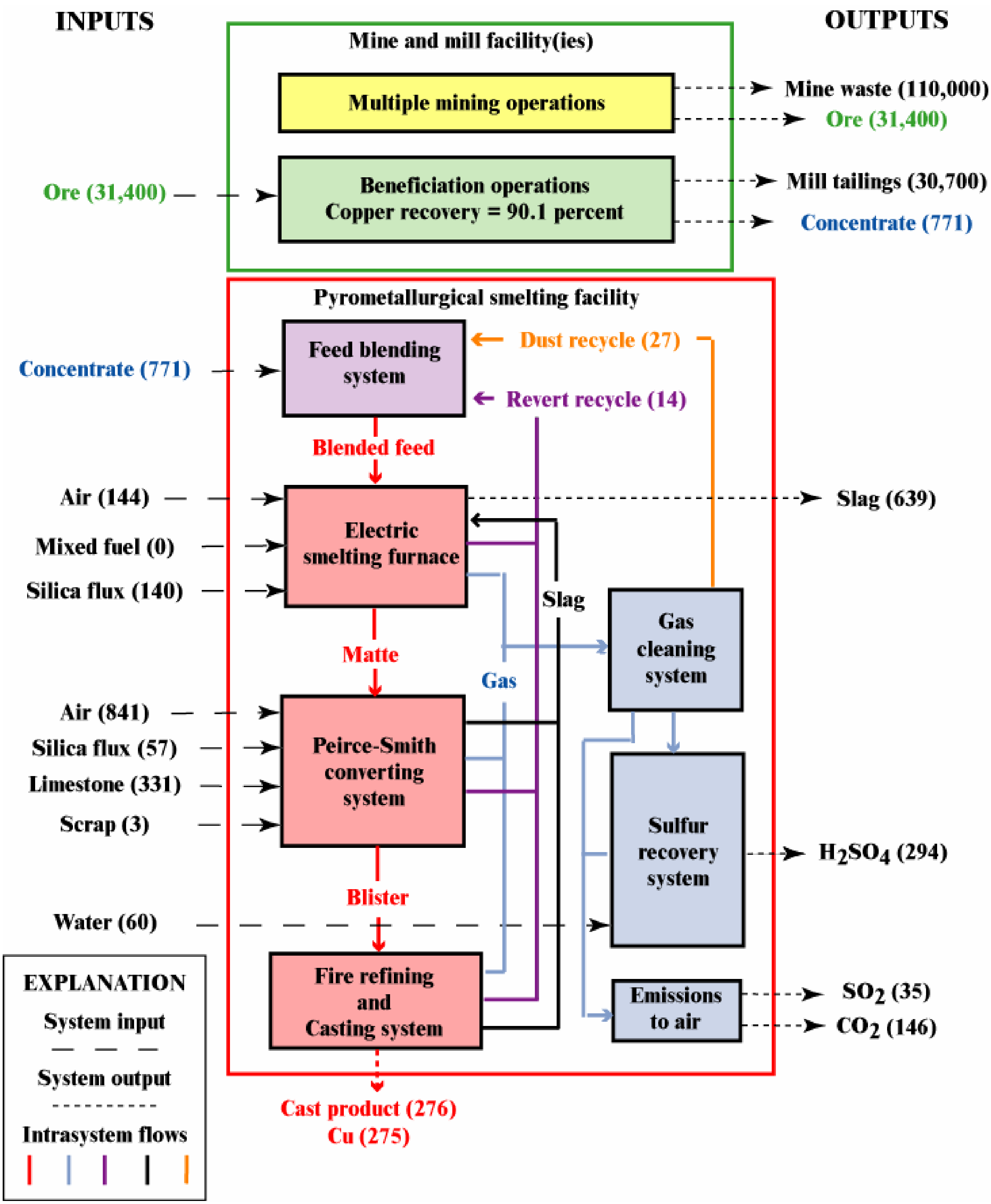

Figure 25. Gross flow diagram of the Dzhezkazgan smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Garfield

Figures 26 and 27 show selected material flows for the Garfield smelter in the United States. The smelter is located in Salt Lake County, Utah (lat 40.70°N., long 112.30°W.). It is owned by Rio Tinto plc of London, United Kingdom, and is operated by Kennecott Utah Copper Corp. of Bingham Canyon, Utah. It smelts concentrate produced from ores from its own Bingham Canyon Mine and annual capacity is rated at 320,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Garfield smelter were extracted from the following sources: Acuna, and Yazawa, 1997; AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Kennecott Utah Copper Corporation, 2002a, b; Mechanical Engineer's Handbook, 5th edition, 1951; Newman, Probert, and Weddick, 1998; Newman, Collins, and Weddick, 1999; Puricelli, Grendel, and Fries, 1998; and World Mine Cost Data Exchange, 2004.

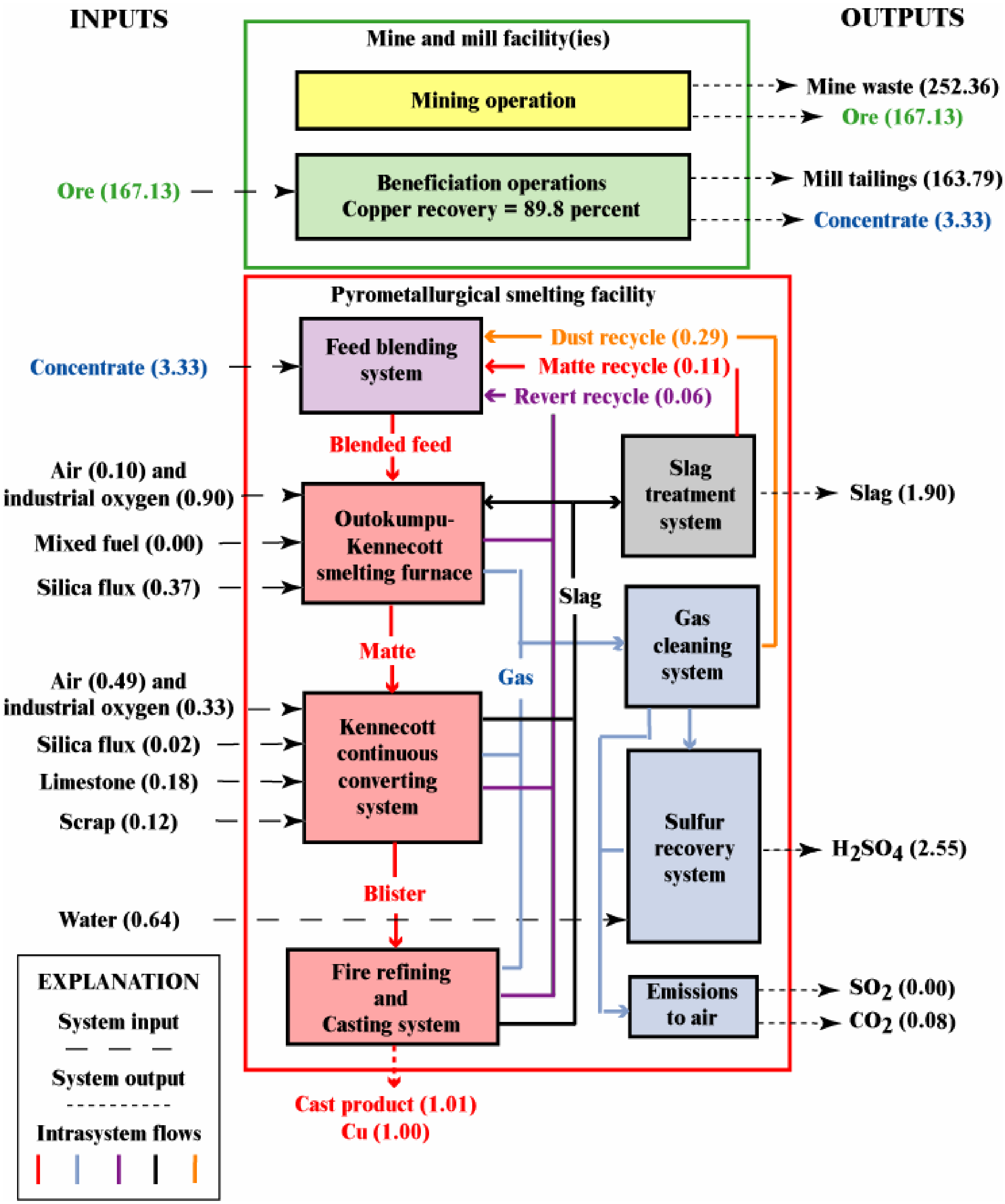

Figure 26. Copper-specific flow diagram of the Garfield smelter.

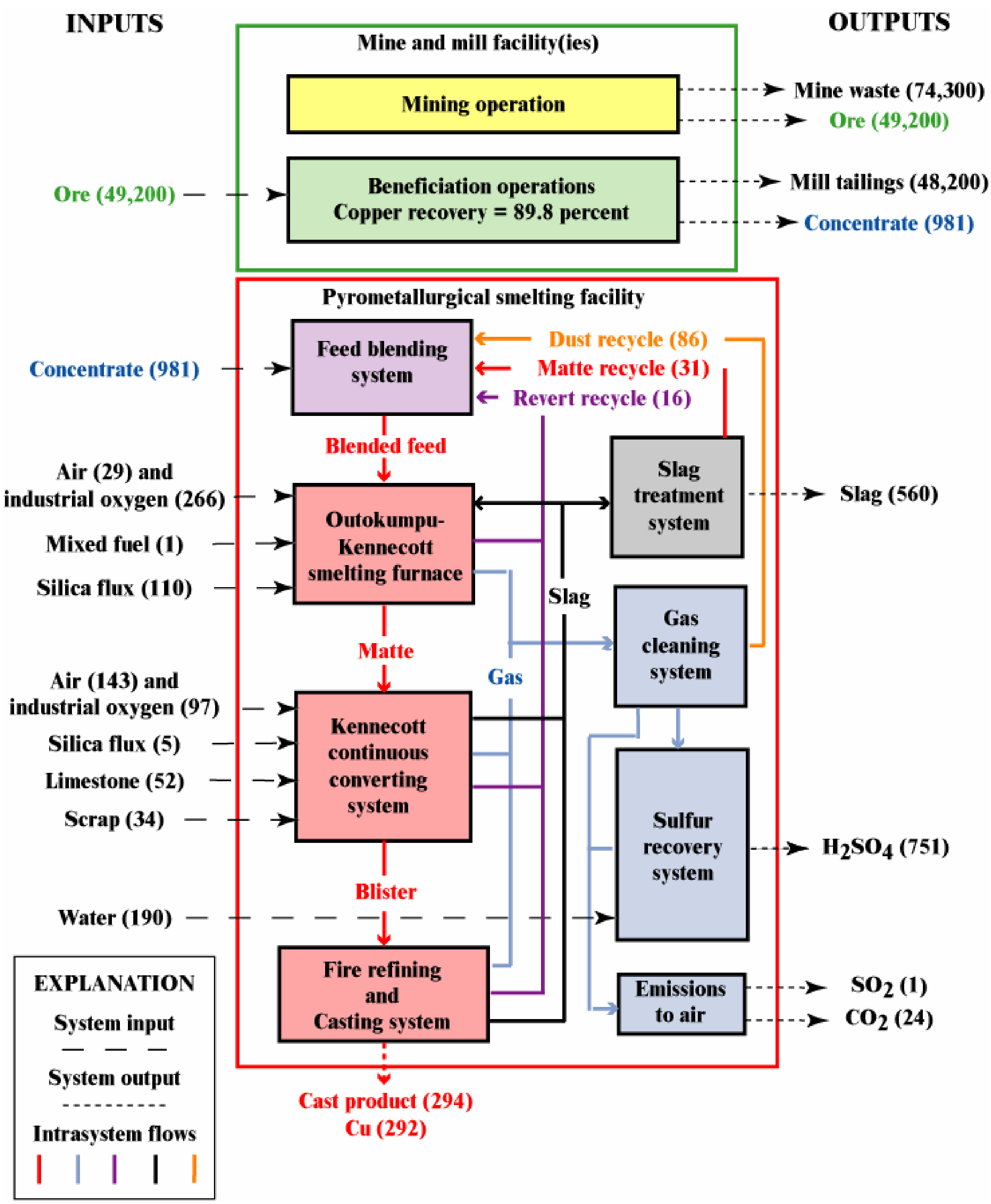

Figure 27. Gross flow diagram of the Garfield smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Glogow I

Figures 28 and 29 show selected material flows for the Glogow I smelter in Poland. The smelter is located in Glogow, Poland (lat 51.56°N., long 16.08°E.). It is owned and operated by KGHM Polska Miedź S.A. of Lubin, Poland. It smelts concentrate produced from ores from its own underground mines and annual capacity is rated at 205,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Glogow I smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Canadian Institute of Mining, Metallurgy and Petroleum, Hydrometallurgy Section, 2001; Czernecki, Smieszek, Gizicki, Dobrzanski, and Warmuz, 1998; Czernecki, Smieszek, Miczkowski, Dobrzanski, and Warmuz, 1999; Davenport, Jones, King, and Partelpoeg, 2001; Dobrzanski, and Kozminski, 2003; Sichen, Bjorkvall, Aune, and Seetharaman, 1999; Gossling, 2001; KGHM Polska Miedz, S.A., Annual Reports, 2000a, b, 2001, 2002, 2003; Kucha, and Cichowska, 2001; Larox, 2000; Mechanical Engineer's Handbook, 5th edition, 1951; Miczkowski, Czernicki, Smieszek, Dobrzanski, and Warmuz, 2003; Mining Technology, 2001; Republic of Poland, 2004; Torres, I. E., Country Specialist, U.S. Geological Survey, private communication, dated March 11, 2003; and Warczok, Utigard, Mroz, Kowalczyk, Warmuz, and Musial, 1991.

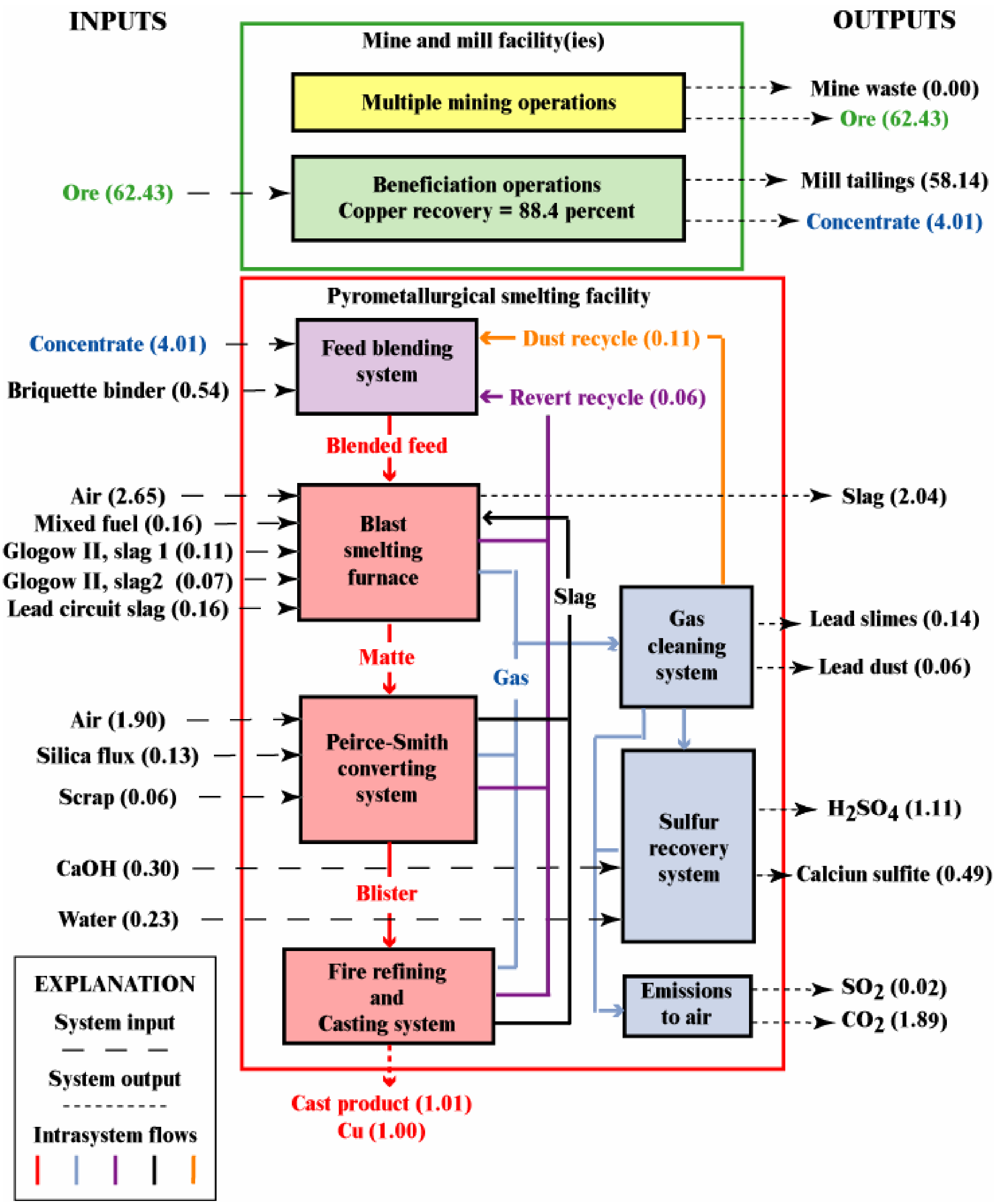

Figure 28. Copper-specific flow diagram of the Glogow I smelter.

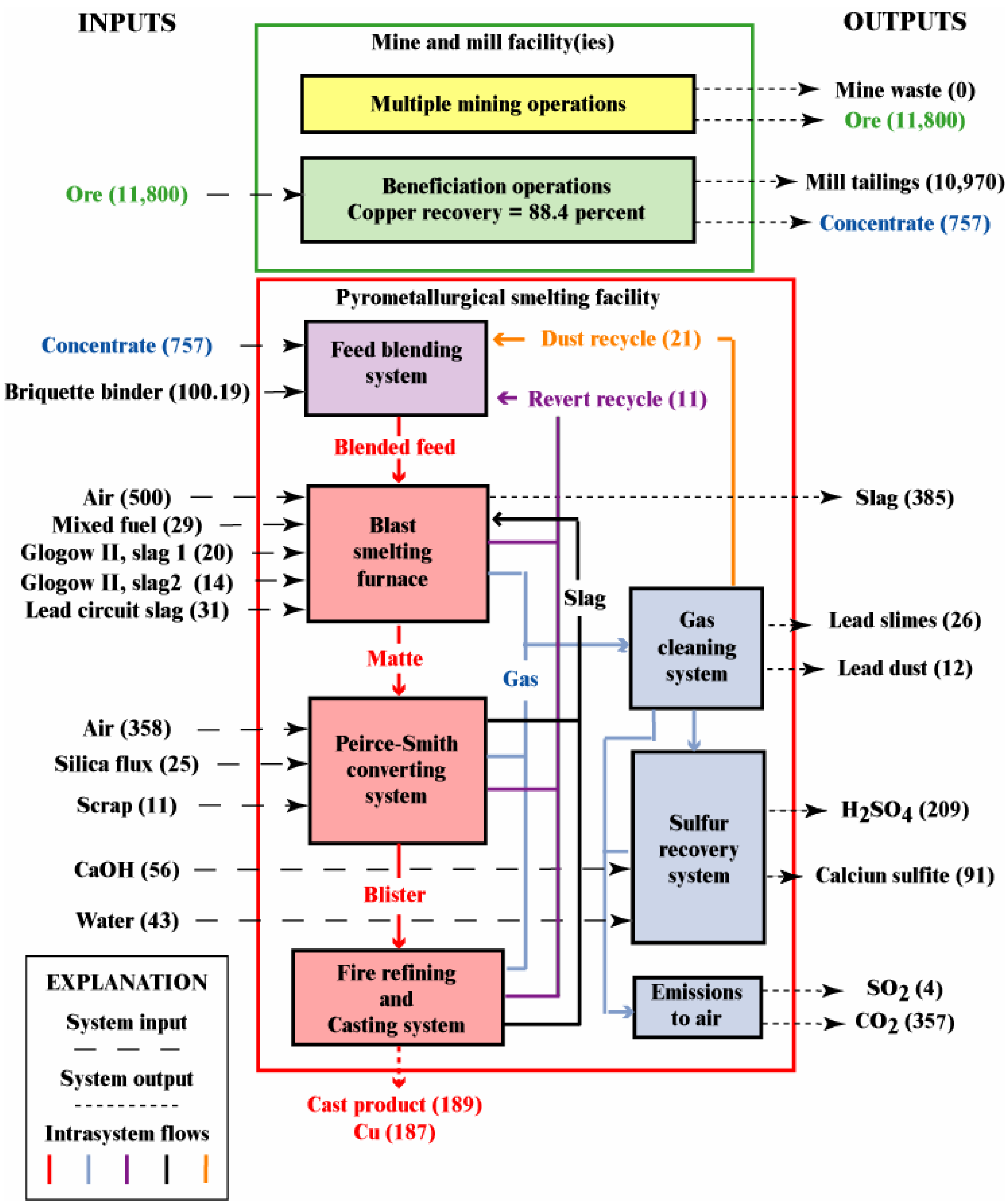

Figure 29. Gross flow diagram of the Glogow I smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Glogow II

Figures 30 and 31 show selected material flows for the Glogow II smelter in Poland. The smelter is located in Glogow, Poland (lat 51.56°N., long 16.08°E.). It is owned and operated by KGHM Polska Miedź S.A. of Lubin, Poland. It smelts concentrate produced from ores from its own underground mines and annual capacity is rated at 220,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Glogow II smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Canadian Institute of Mining, Metallurgy and Petroleum, Hydrometallurgy Section, 2001; Czernecki, Smieszek, Gizicki, Dobrzanski, and Warmuz, 1998; Czernecki, Smieszek, Miczkowski, Dobrzanski, and Warmuz, 1999; Davenport, Jones, King, and Partelpoeg, 2001; Dobrzanski, and Kozminski, 2003; Sichen, Bjorkvall, Aune, and Seetharaman, 1999; Gossling, 2001; KGHM Polska Miedz, S.A., Annual Reports, 2000a, b, 2001, 2002, 2003; Kucha, and Cichowska, 2001; Larox, 2000; Mechanical Engineer's Handbook, 5th edition, 1951; Miczkowski, Czernicki, Smieszek, Dobrzanski, and Warmuz, 2003; Mining Technology, 2001; Republic of Poland, 2004; Torres, I. E., Country Specialist, U.S. Geological Survey, private communication, dated March 11, 2003; and Warczok, Utigard, Mroz, Kowalczyk, Warmuz, and Musial, 1991.

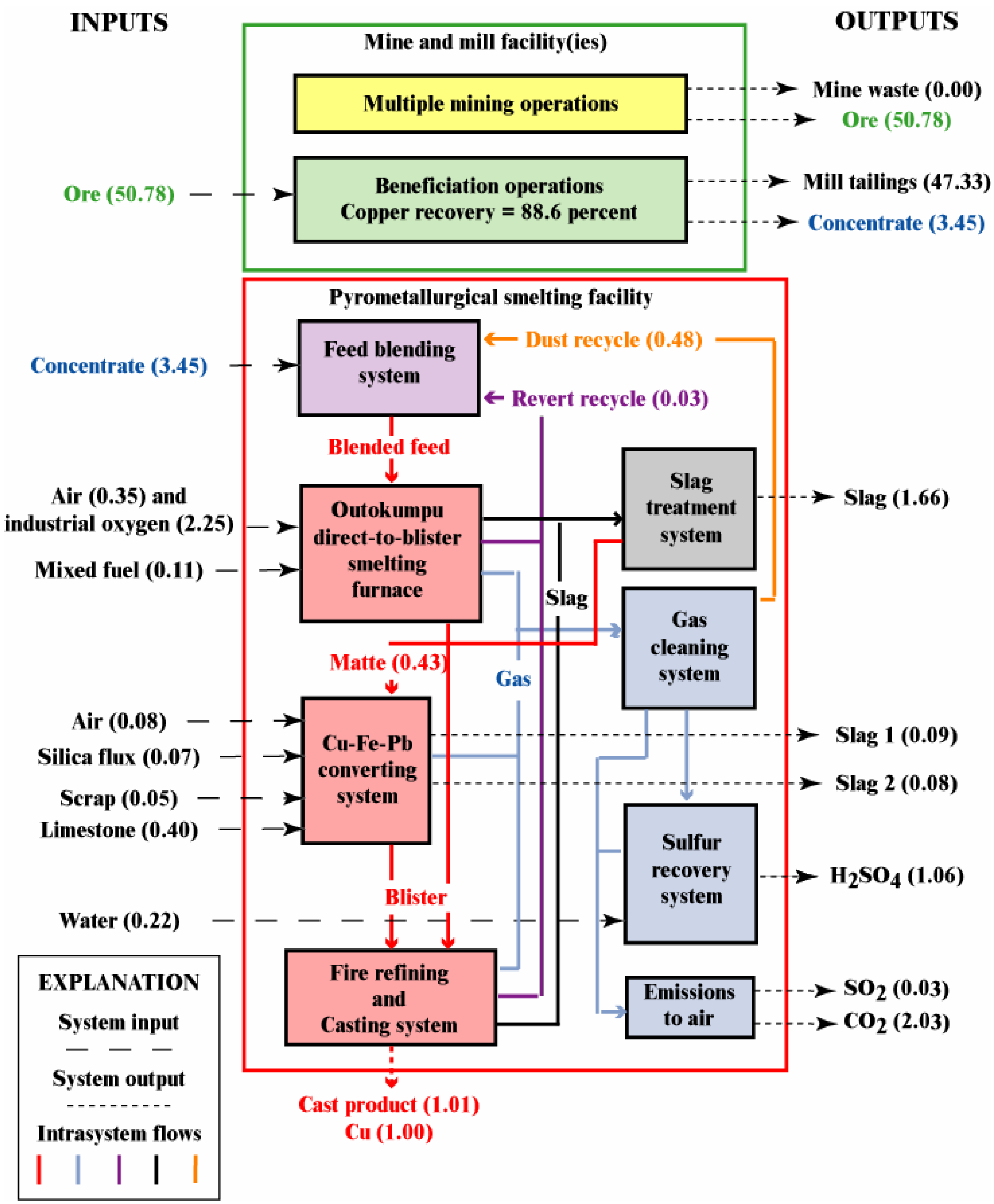

Figure 30. Copper-specific flow diagram of the Glogow II smelter.

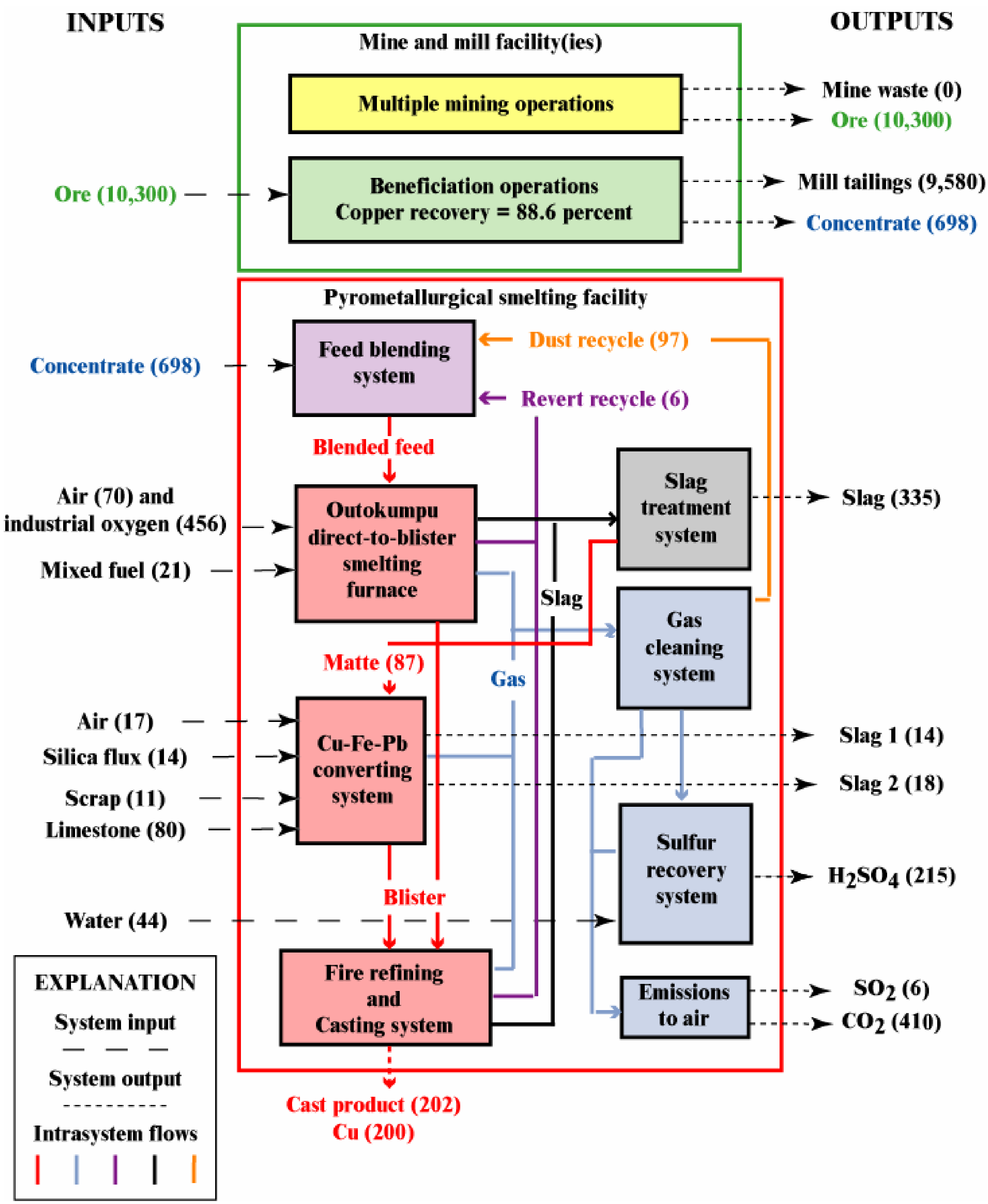

Figure 31. Gross flow diagram of the Glogow II smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Guixi

Figures 32 and 33 show selected material flows for the Guixi smelter in China. The smelter is located in Guixi, China (lat 28.28°N., long 117.18°E.). It is owned by Jiangxi Copper Corporation of Guixi City, China and the Chinese Government and is operated by Jiangxi Copper Company Ltd. Guixi City, China. It smelts concentrate produced from ores from its own, other Chinese, and foreign mines and annual capacity is rated at 250,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Guixi smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Jiangxi Copper Company Limited, 1997; Mechanical Engineer's Handbook, 5th edition, 1951; Tan, and Zhang, 1996; Tse, Pui-Kwan, 2003, Country Specialist, U.S. Geological Survey, personal commun.; and Zeping, 1999.

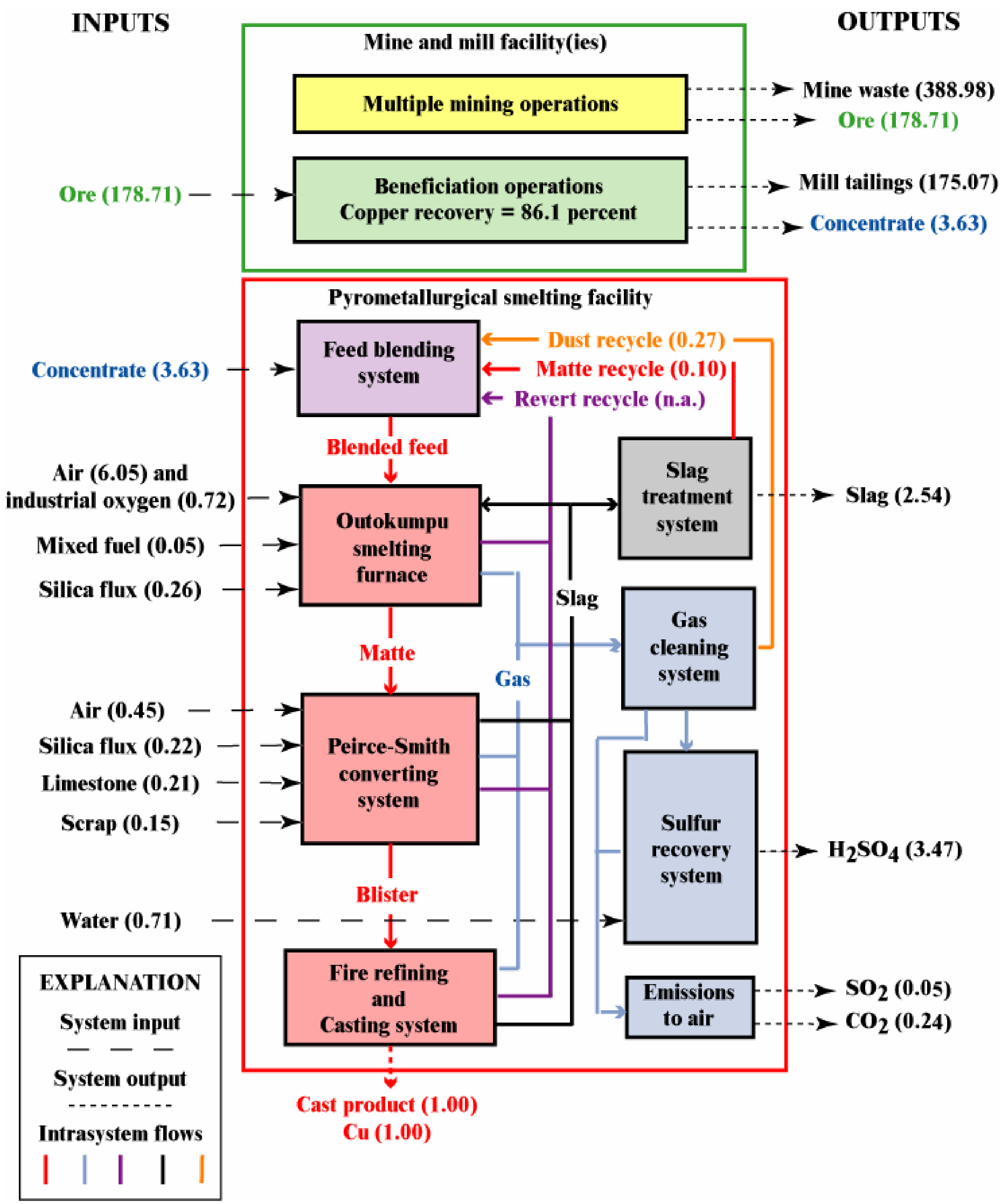

Figure 32. Copper-specific flow diagram of the Guixi smelter.

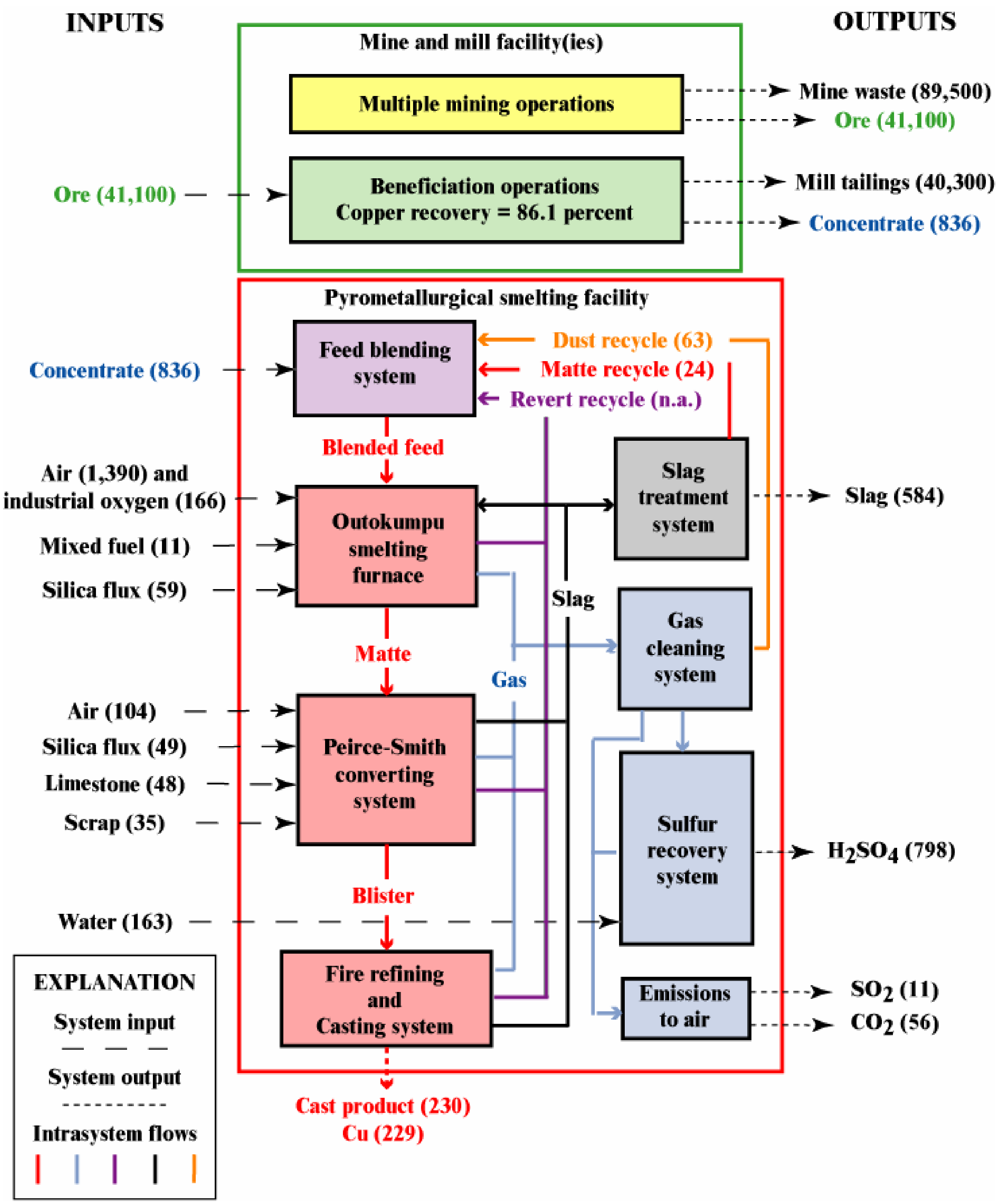

Figure 33. Gross flow diagram of the Guixi smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Hayden

Figures 34 and 35 show selected material flows for the Hayden smelter in the United States. The smelter is located in Hayden, Arizona, (lat 33.00°N., long 110.78°W.). It is owned and operated by Grupo Mexico S.A. de C.V. of Colonia Roma Sur, Mexico. It smelts concentrate produced from local ores, other corporate, and foreign mines and annual capacity is rated at 210,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Hayden smelter were extracted from the following sources: AME Mineral Economics, 2001; Arizona Department of Environmental Quality, 2001, 2002; Asarco, 2000, 2003; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Mechanical Engineer's Handbook, 5th edition, 1951; Rosenkranz, Downey, and De Giacomo 1988; Schloen, 1991; and World Mine Cost Data Exchange, 2004.

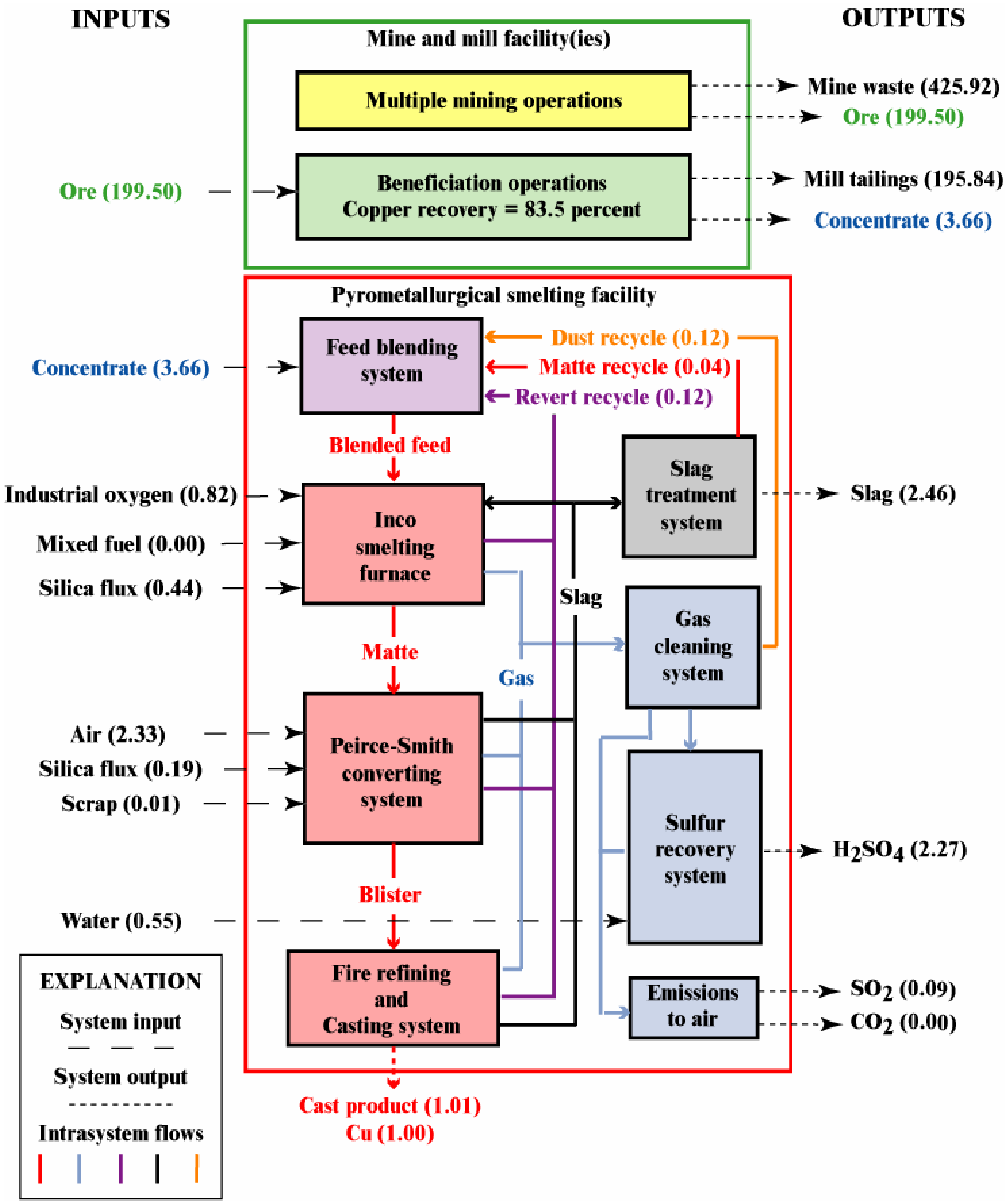

Figure 34. Copper-specific flow diagram of the Hayden smelter.

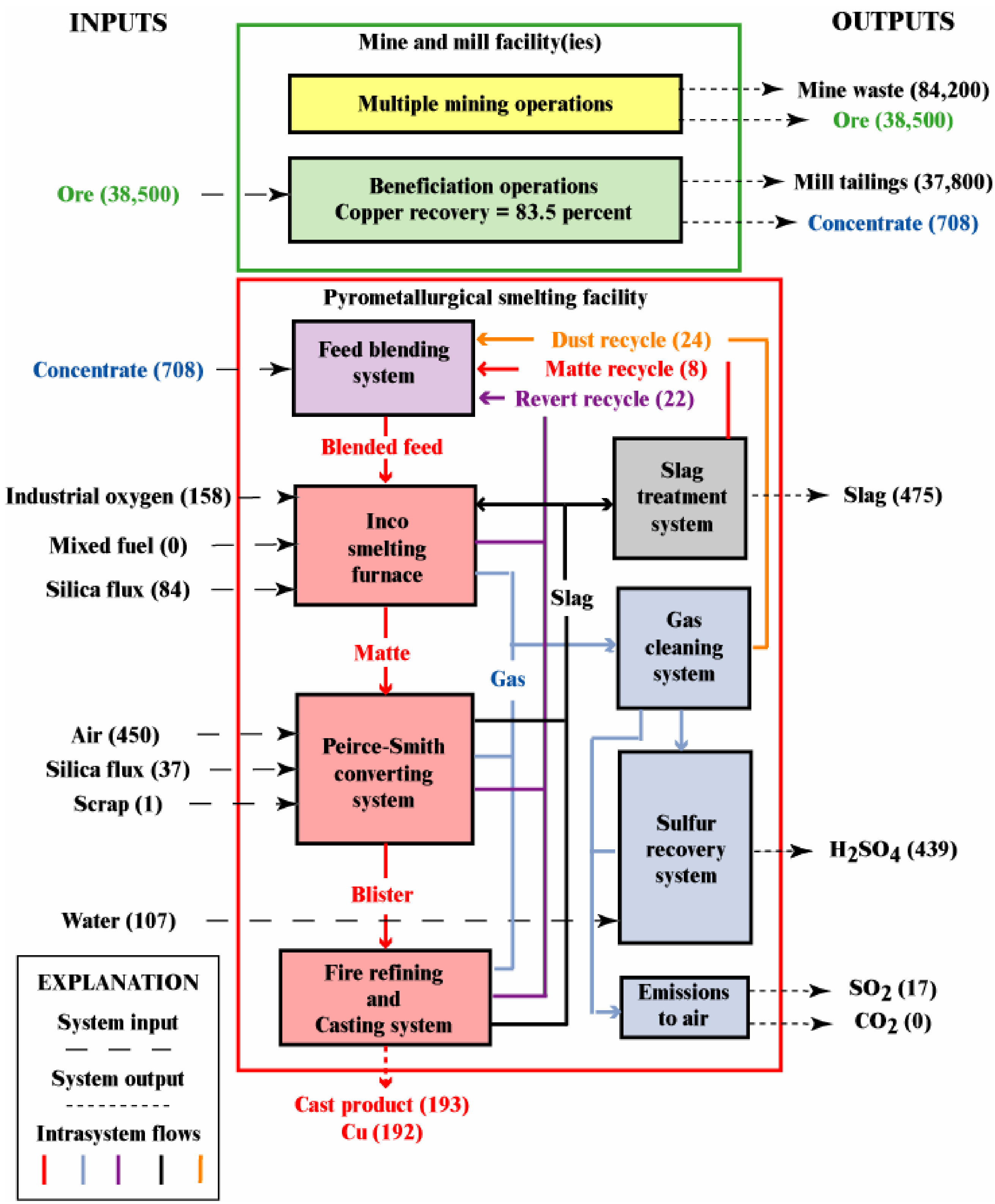

Figure 35. Gross flow diagram of the Hayden smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Huelva

Figures 36 and 37 show selected material flows for the Huelva smelter in Spain. The smelter is located in Huelva, Spain (lat 37.26°N., long 6.95°W.). It is owned by Freeport-McMoRan Copper & Gold Inc. of New Orleans, Louisiana and is operated by Atlantic Copper S.A. of Madrid, Spain. It imports and smelts concentrate produced from Freeport's Indonesian Grasberg Mine and annual capacity is rated at 330,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Huelva smelter were extracted from the following sources: AME Mineral Economics, 2001; Atlantic Copper, Inc., 2002; Barios, Contreras, and Palacios, 1998; Biswas, and Davenport, 1980; Contreras, Alonso, Hidalgo, and Palacios, 2003; Davenport, Jones, King, and Partelpoeg, 2001; Mechanical Engineer's Handbook, 5th edition, 1951; Schloen, 1991; World Mine Cost Data Exchange, 2003; and Yahoo Business, 2003.

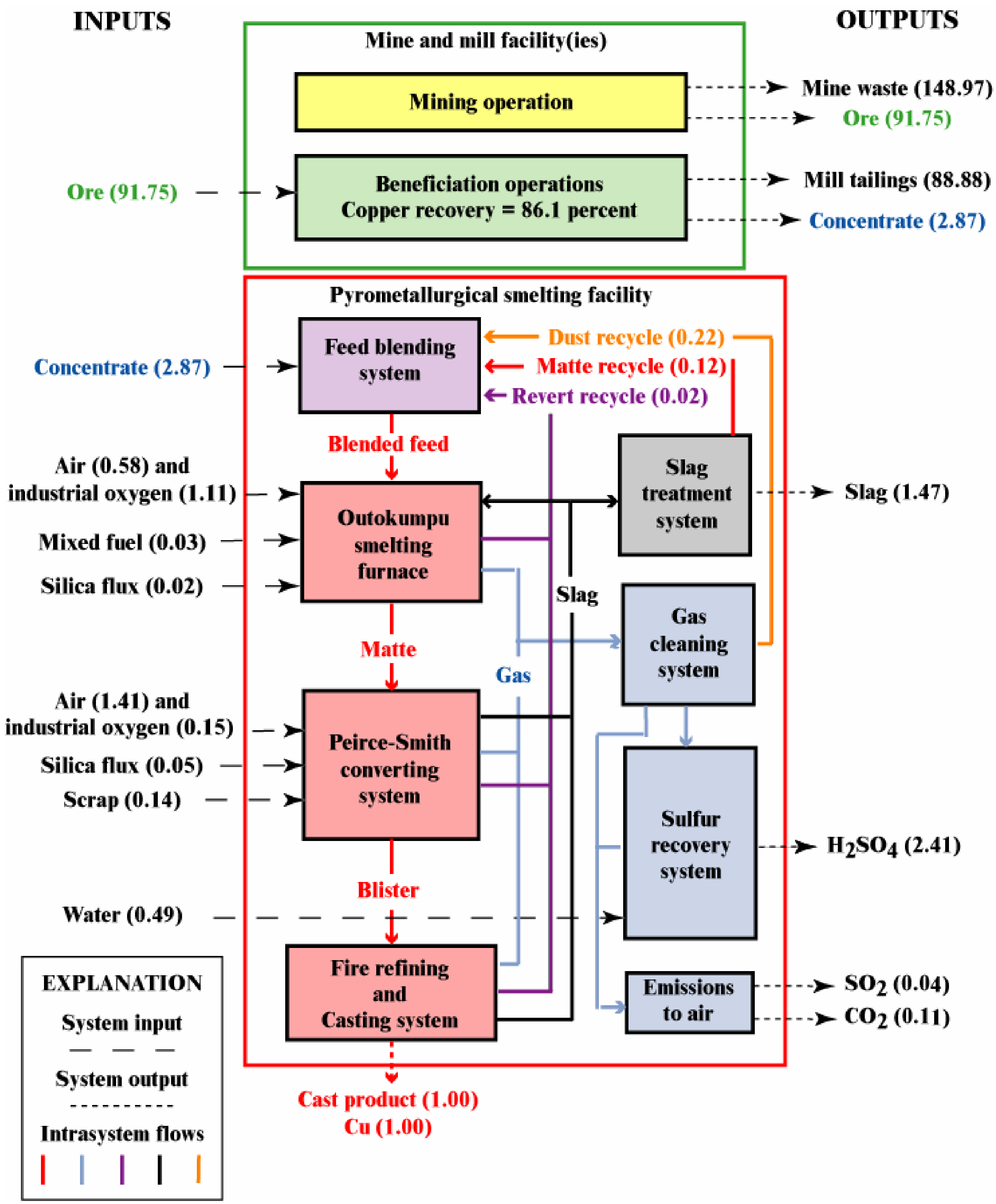

Figure 36. Copper-specific flow diagram of the Huelva smelter.

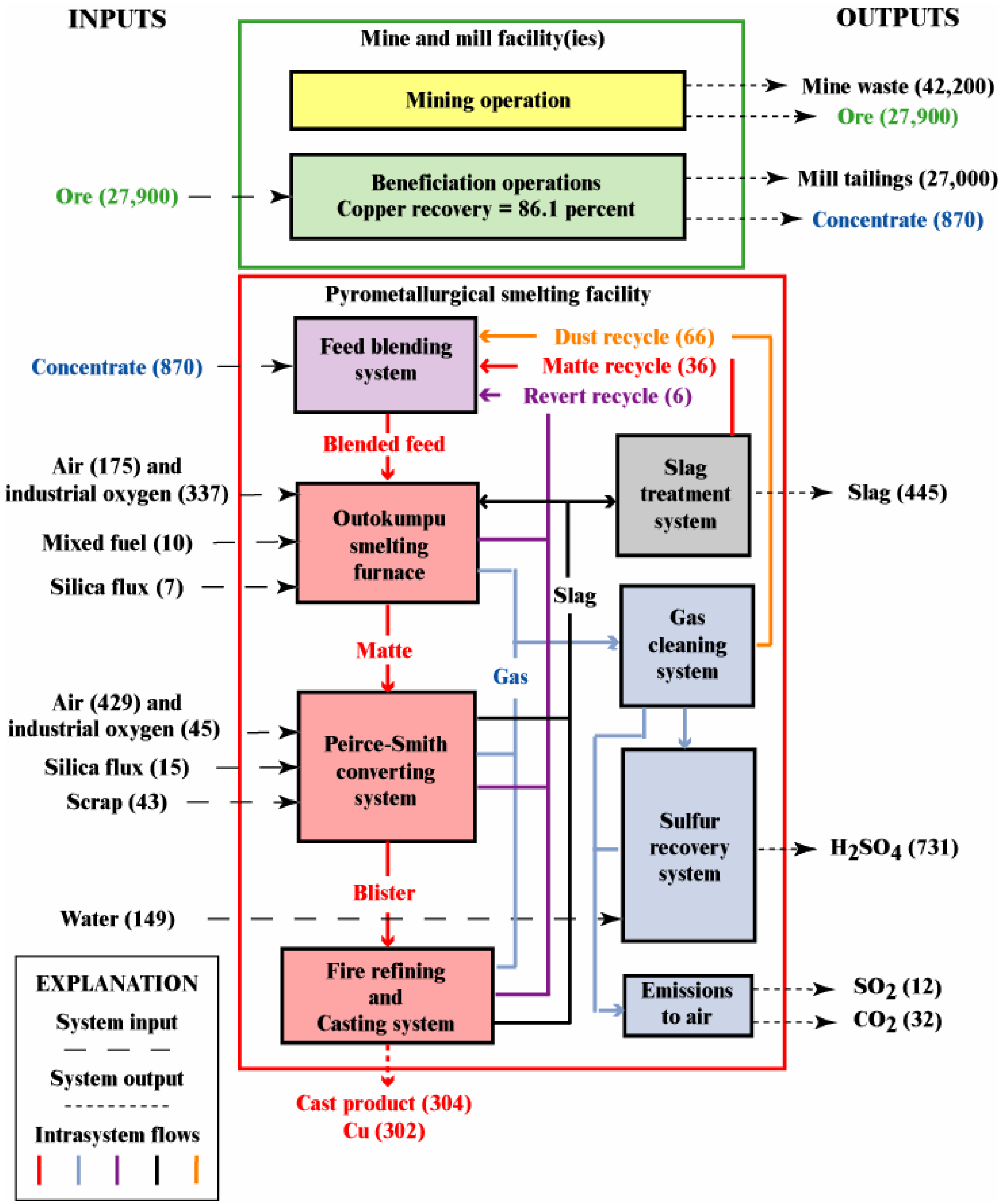

Figure 37. Gross flow diagram of the Huelva smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Ilo

Figures 38 and 39 show selected material flows for the Ilo smelter in Peru. The smelter is located in Ilo, Peru (lat 17.63°S., long 71.33°W.). It is owned by Cerro Trading Company Inc. [a subsidiary of the Marmon Group of Chicago, Illinois] (14.2 percent), Grupo Mexico S.A. de C.V. of Colonia Roma Sur CP, DF, Mexico (54.2 percent), and Phelps Dodge Corporation of Phoenix, Arizona, (14 percent) and operated by Southern Peru Copper Corp. of Lima, Peru. It smelts concentrate produced from Peruvian ores and annual capacity is rated at 330,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Ilo smelter were extracted from the following sources: AME Mineral Economics, 2001; Asarco, 1999; Bengoa, Palacios, and Sanchez, 2003; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Grupo Mexico, 2003; Mechanical Engineer's Handbook, 5th edition, 1951; Mining Journal, 1998; Schloen, 1991; Southern Peru Copper Corp., 2002; Torres, 1998; and World Mine Cost Data Exchange, 2004.

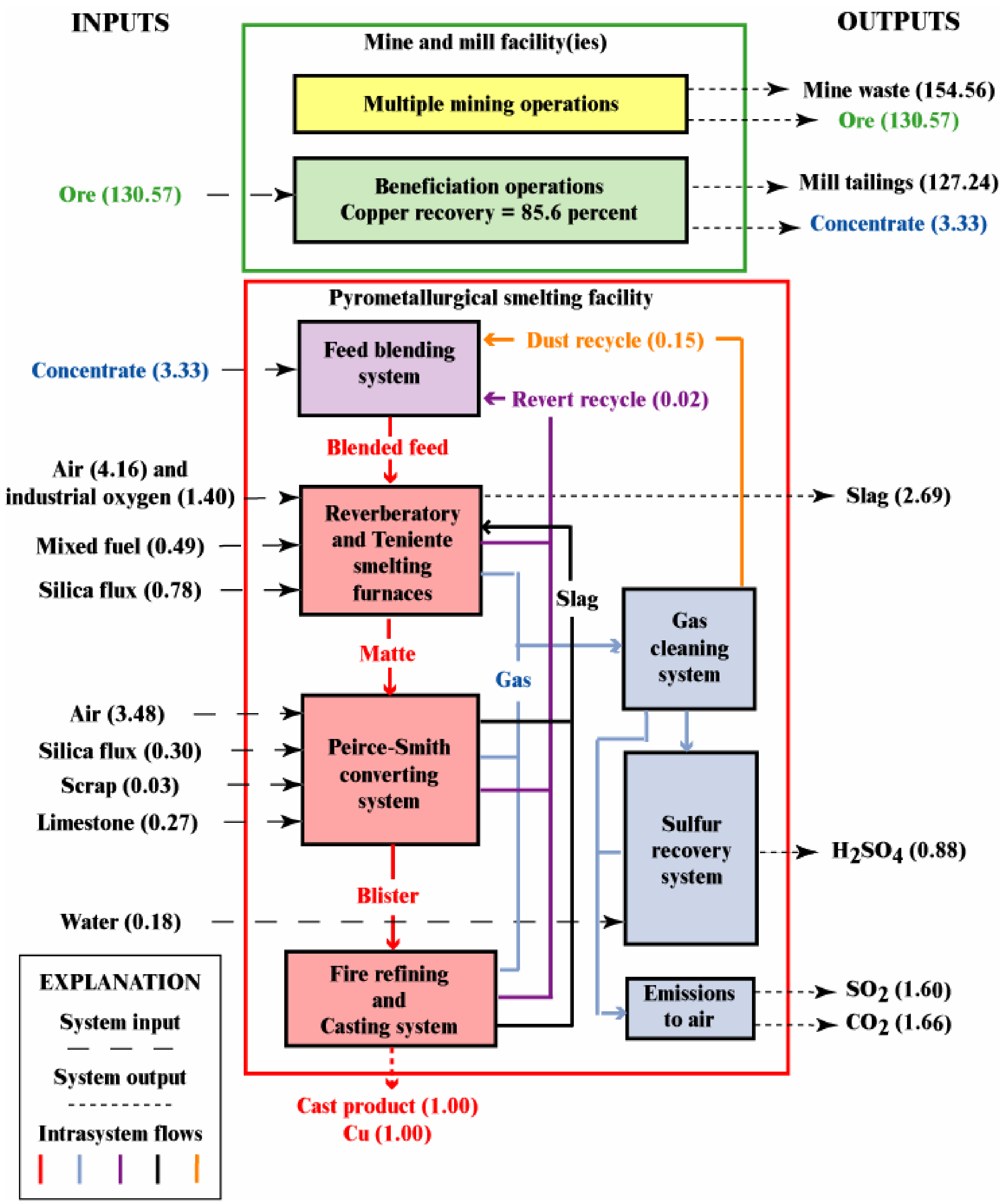

Figure 38. Copper-specific flow diagram of the Ilo smelter.

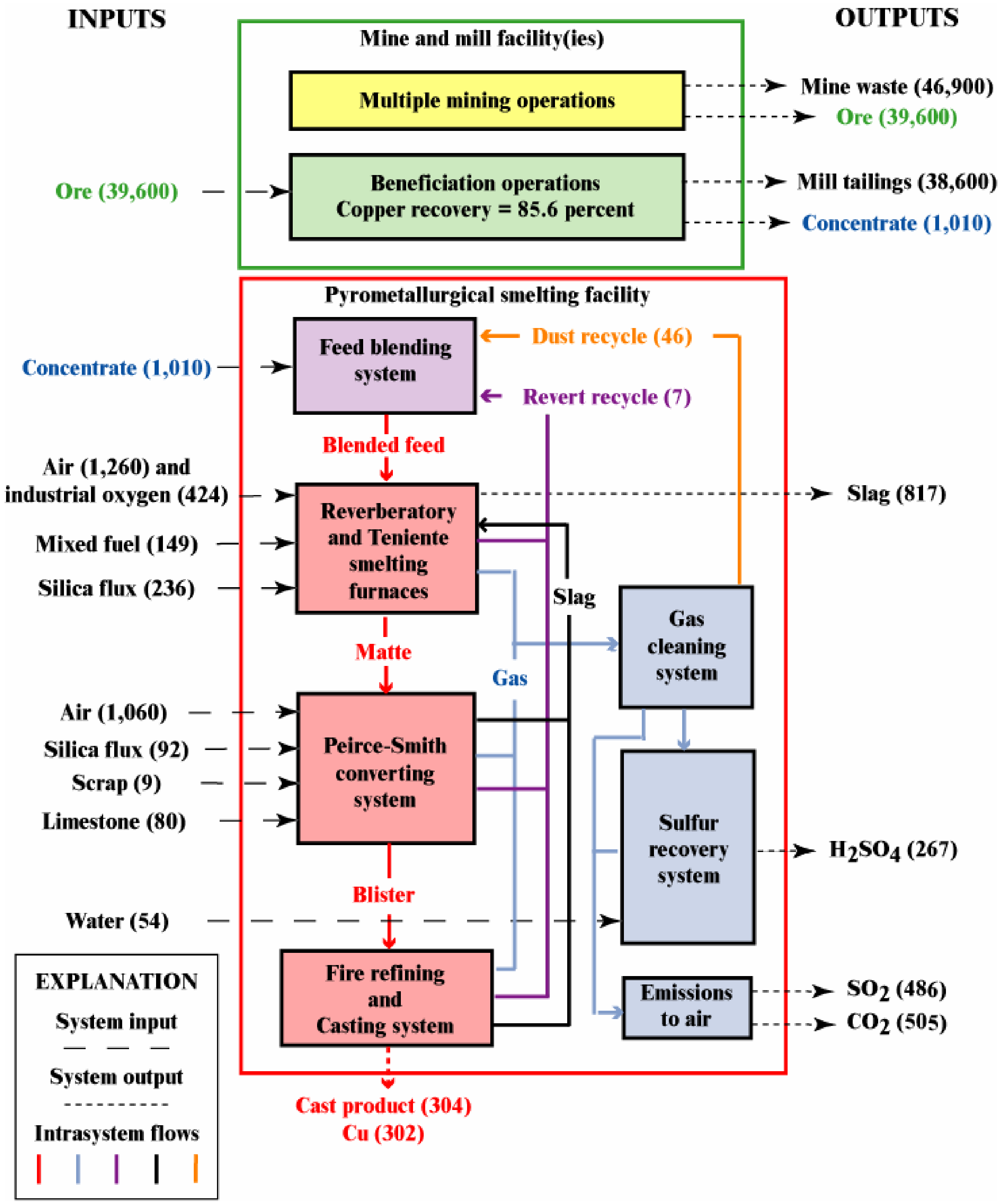

Figure 39. Gross flow diagram of the Ilo smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Kunming

Figures 40 and 41 show selected material flows for the Kunming smelter in China. The smelter is located in Kunming, China (lat 25.04°N., long 102.72°E.). It is owned by Yunnan Copper Industrial (Group) Company of Kunming, China and the Chinese Government and is operated by Yunnan Copper Industrial Corp. Ltd. of Kunming, China. It smelts concentrate produced from Chinese and foreign ores and annual capacity is rated at 160,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Kunming smelter were extracted from the following sources: AME Mineral Economics, 2001; Arthur, and Li, 2003; Arthur, Partington, Fan, and Li, 2003; Biswas, and Davenport, 1980; China Scrap, 2003; Davenport, Jones, King, and Partelpoeg, 2001; Erdnet Mining Corporation, 2002; Mechanical Engineer's Handbook, 5th edition, 1951; Ramachamdran, Diaz, Eltringham, Jiang, Lehner, Mackey, Newman, and Tarasov, 2003; Tse, 2001; World Mine Cost Data Exchange, 2004; Wei, 2003; Xstrata, 2000; and Yunnan Copper Industrial Corp., Ltd., 2001.

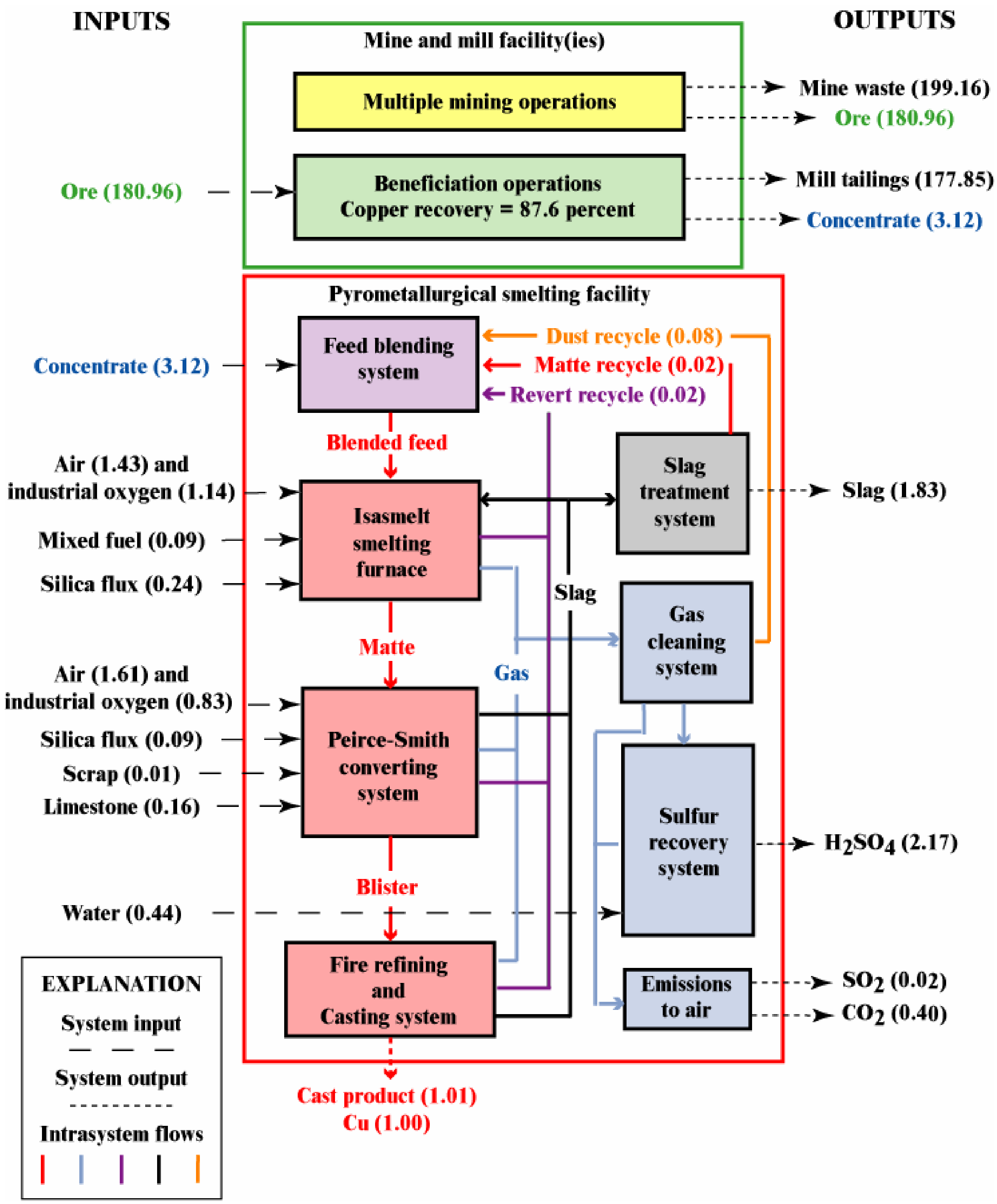

Figure 40. Copper-specific flow diagram of the Kunming smelter.

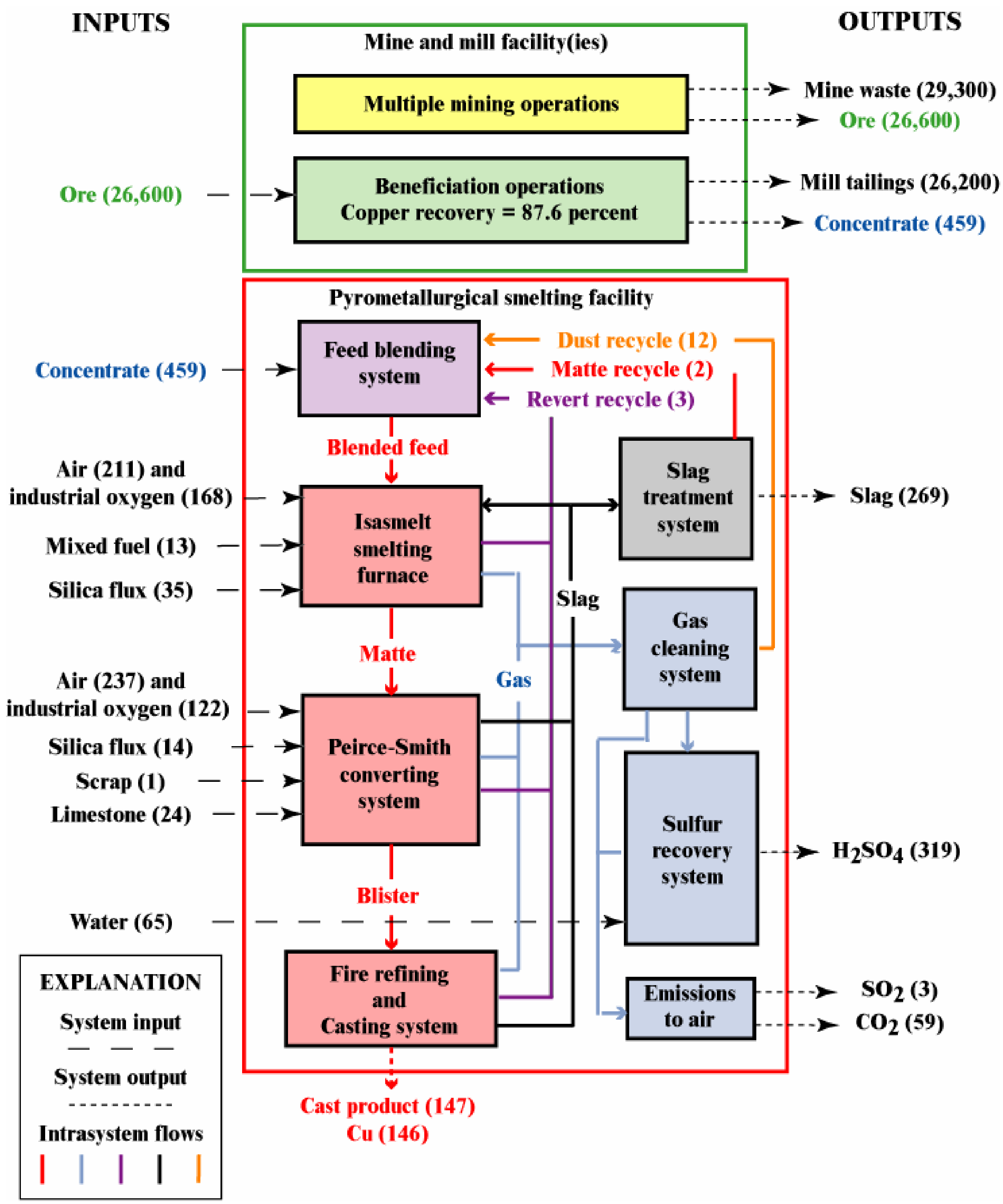

Figure 41. Gross flow diagram of the Kunming smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Las Ventanas

Figures 42 and 43 show selected material flows for the Las Ventanas smelter in Chile. The smelter is located in Quinteros, Chile (lat 30.28°S., long 71.22°W.). It is owned and operated by Empresa Naćional de Minería of Santiago, Chile. It smelts concentrates produced from multiple small mines in Chile and annual capacity is rated at 150,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Las Ventanas smelter were extracted from the following sources: Achurra, Chacana, Buchi, and Condore, 2003; Acuna, and Yazawa, 1997; Acuna, Zuniga, Guibout, and Ruz, 1999; Alvaredo, Archurra; and Mac Kay, 1998; AME Mineral Economics, 2001; Biswas, and Davenport, 1980; CIPMA, 2002; Chilean Copper Comission, 2000; Davenport, Jones, King, and Partelpoeg, 2001; ENAMI, Annual Report, 2001; Gossling, 2001; Imris, Rebollodo, Sanchez, Castro, Achurra, and Hernandez, 1999; Lagos, Lehuede, and Andia, 2000; Mechanical Engineer's Handbook, 5th edition, 1951; Montenegro, Fujisawa, Warczuk, and Rivero, 2003; Morales, and Mac-Kay, 1999; O'Ryan, and Diaz, 1998; Ponce, and Sanchez, 1999; Rojas, and Sanhueza, 1999; Sanchez, and Castro, 2002; Schloen, 1991; Sociedad Nacional de Mineria de Chile, 2002; Valenzuela–Jara, Palacios, Cordero, and Sanchez, 2002; Valenzuela–Jara, Palacios, Cordero, and Sanchez, 2003; Velasco, 2000; and World Mine Cost Data Exchange, 2004.

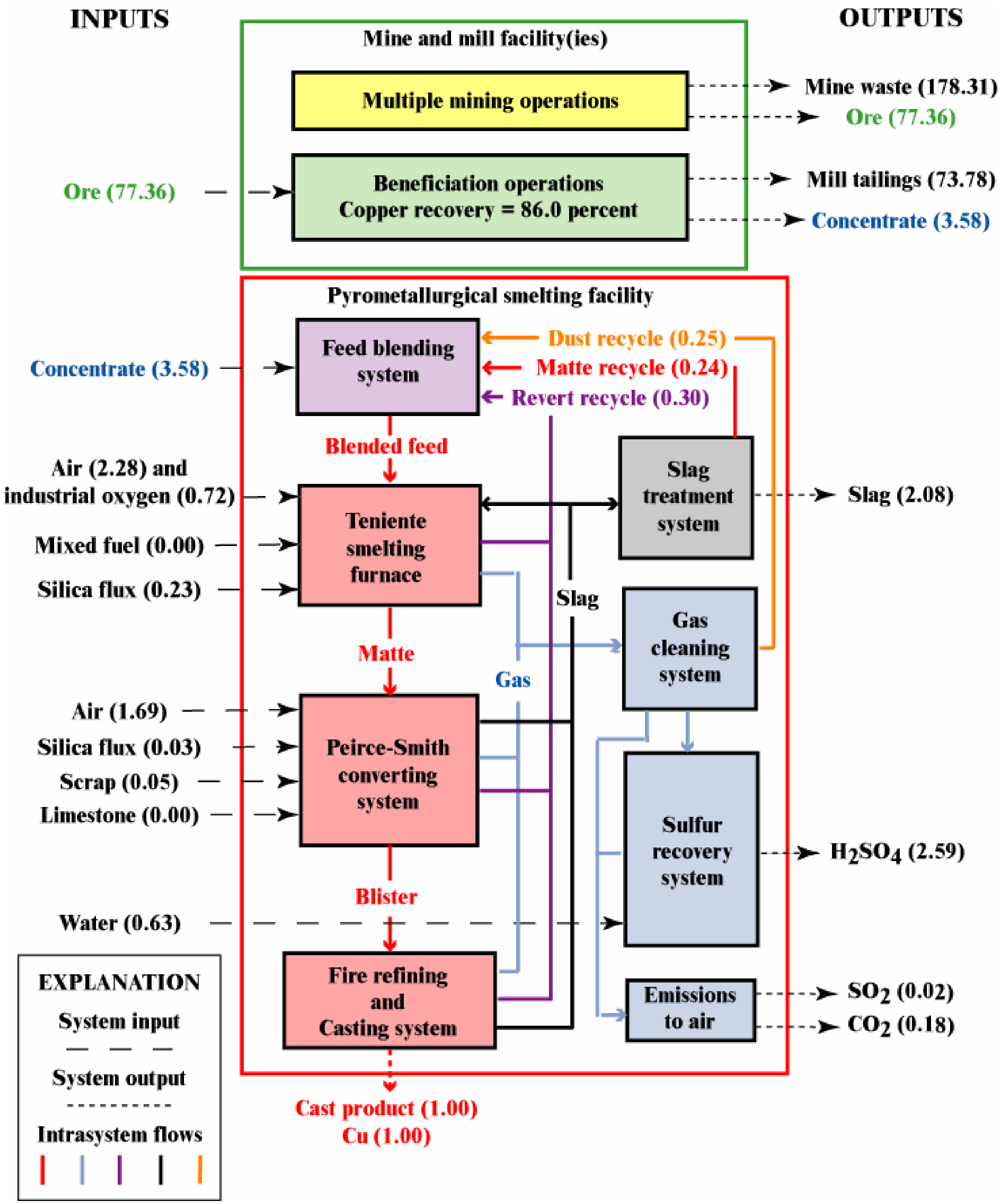

Figure 42. Copper-specific flow diagram of the Las Ventanas smelter.

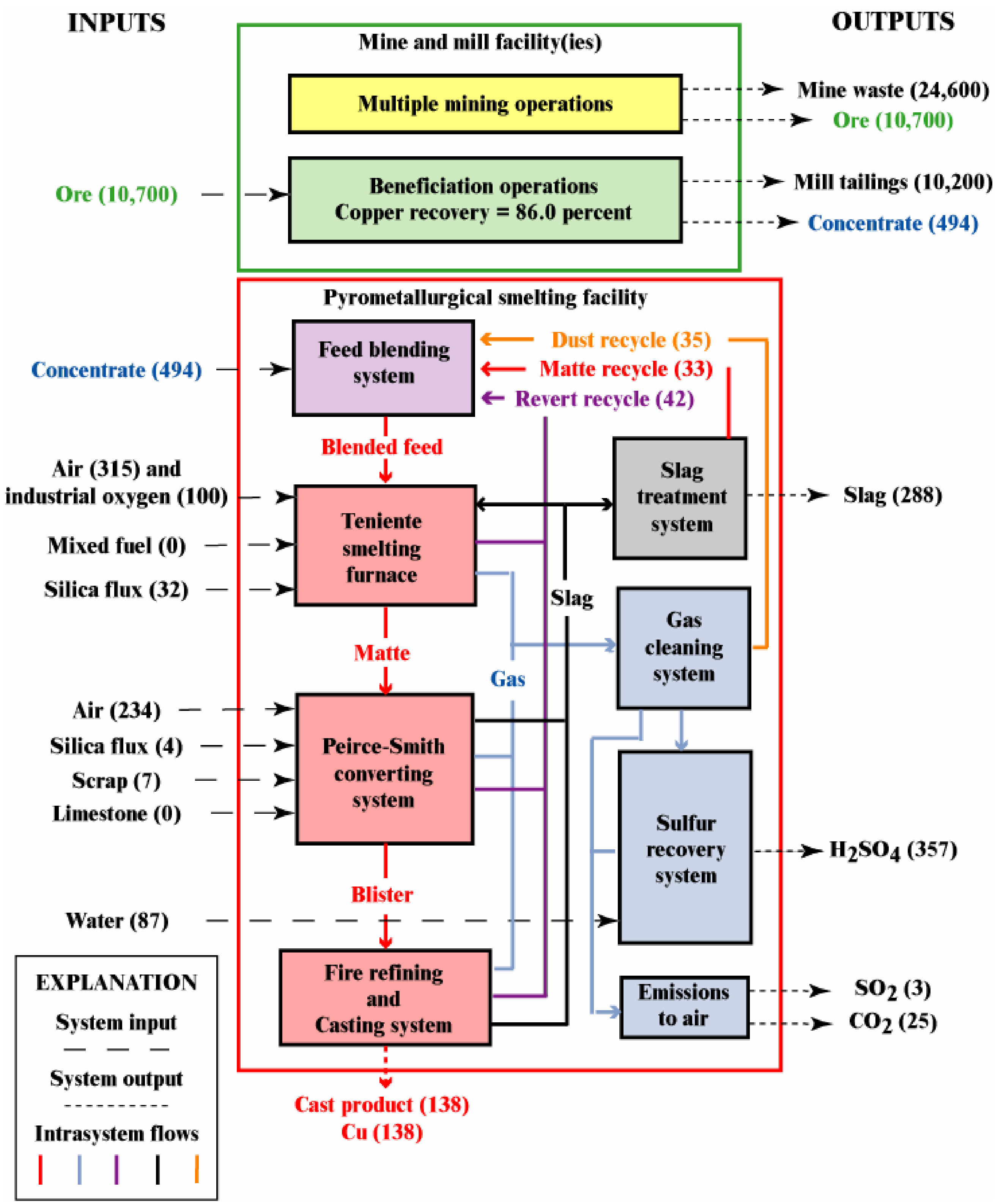

Figure 43. Gross flow diagram of the Las Ventanas smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Miami

Figures 44 and 45 show selected material flows for the Miami smelter in the United States. The smelter is located in Globe, Arizona (lat 33.38°N., long 110.87°W.). It is owned and operated by Phelps Dodge Corp. of Phoenix, Arizona. It smelts concentrate produced from mines in Arizona and some foreign ores and annual capacity is rated at 180,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Miami smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Mechanical Engineer's Handbook, 5th edition, 1951; Sallee, and Ushakov, 1999; Ushikov, Vladimir, Metallurgical Engineer, Phelps Dodge, Miami, Arizona, private correspondence; and World Mine Cost Data Exchange, 2004; Zeping, 1999.

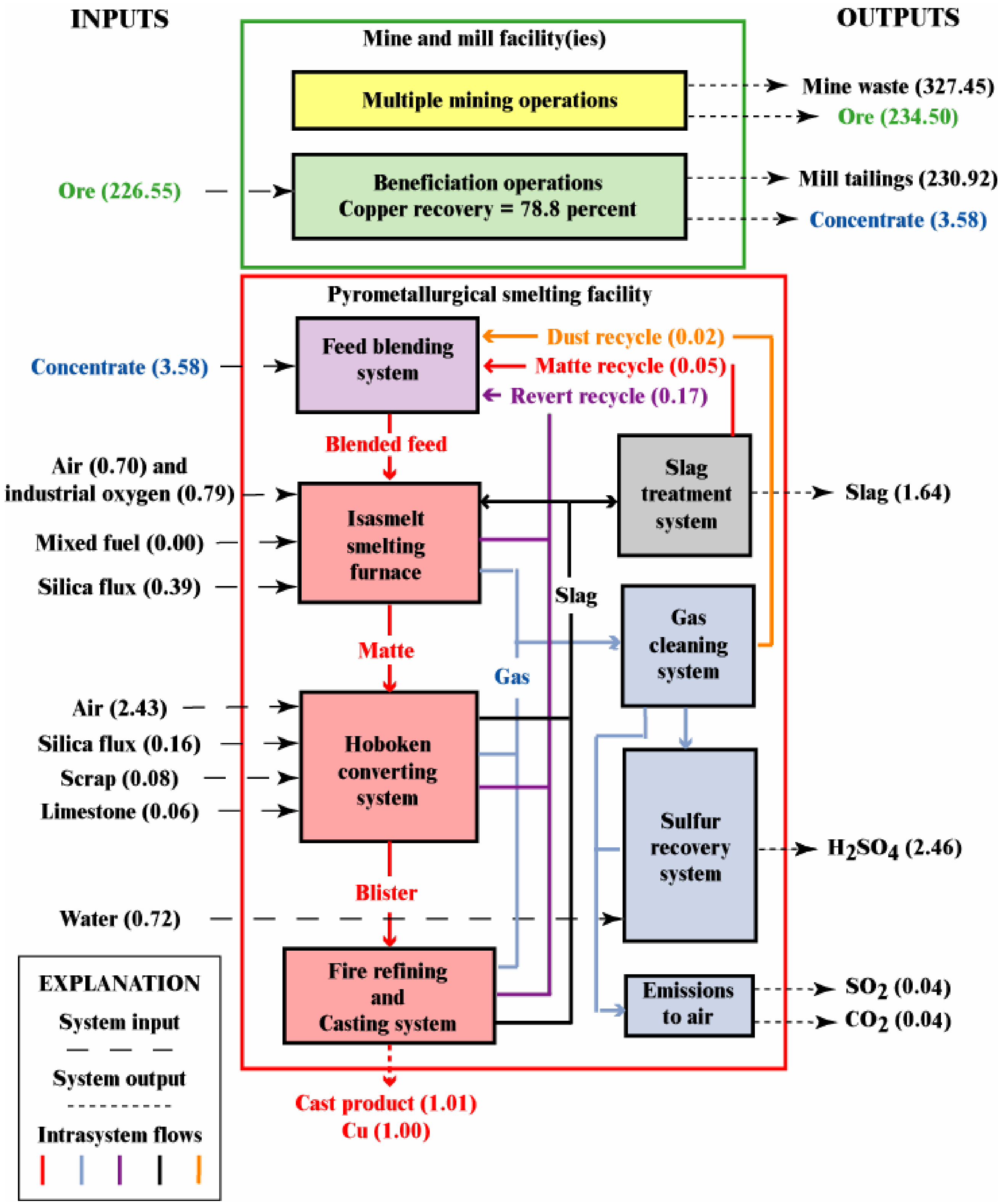

Figure 44. Copper-specific flow diagram of the Miami smelter.

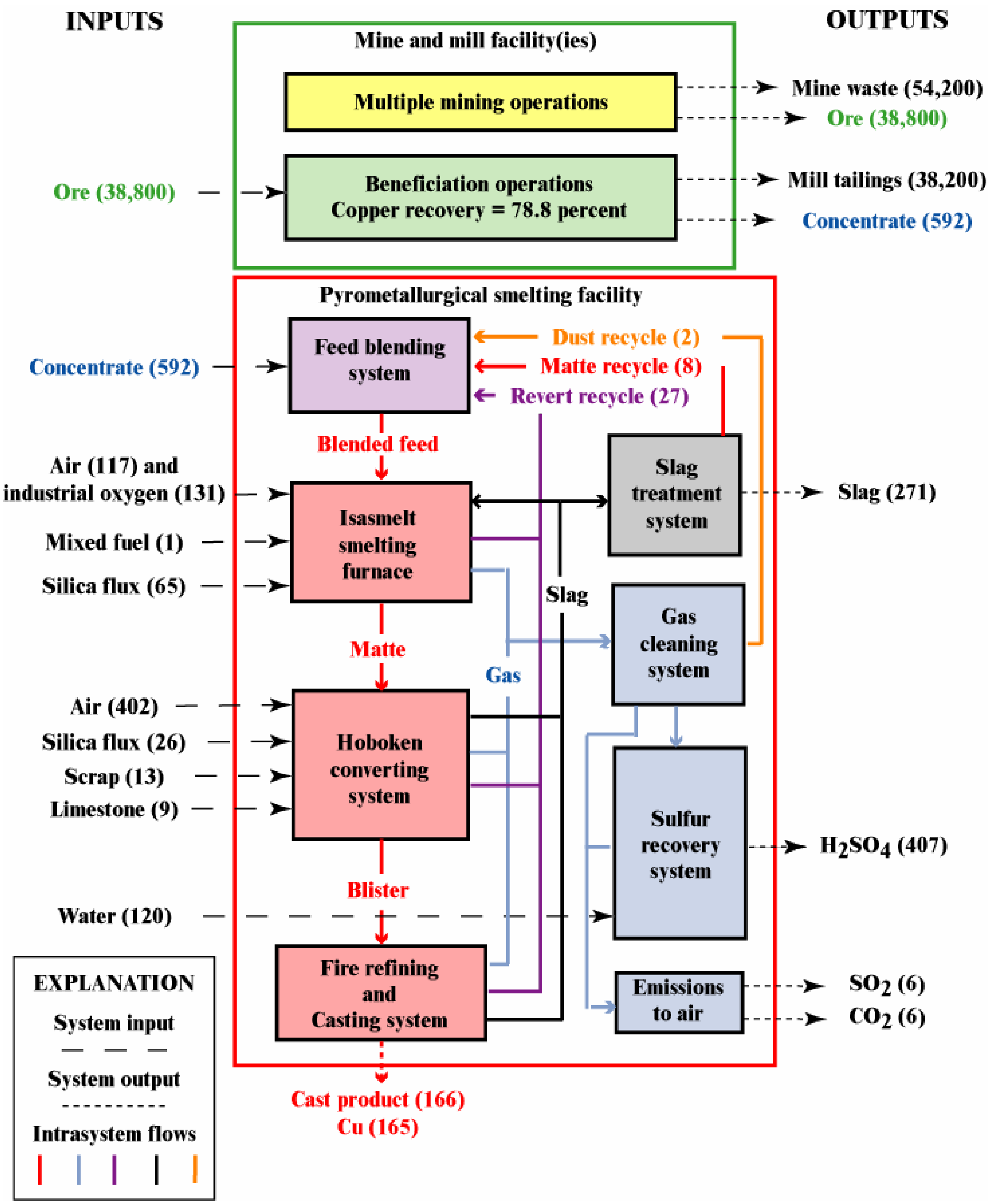

Figure 45. Gross flow diagram of the Miami smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Mount Isa

Figures 46 and 47 show selected material flows for the Mount Isa smelter in Australia. The smelter is located in Mount Isa, Australia (lat 20.73°S., long 139.50°E.). It is owned by Xstrata plc of Zug, Switzerland, and is operated by Mount Isa Mines, Ltd. of Brisbane, Australia. It smelts concentrate produced from close proximity ores and annual capacity is rated at 265,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Mount Isa smelter were extracted from the following sources: AME Mineral Economics, 2001; Arthur, Butler, Edwards, Fountain, Hunt, and Tuppurainen, 2003; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Edwards, 1998; Hollis, Werny, and Yeowart, 1999; Mechanical Engineer's Handbook, 5th edition, 1951; MIM, 2003; Player, 1995; and World Mine Cost Data Exchange, 2004.

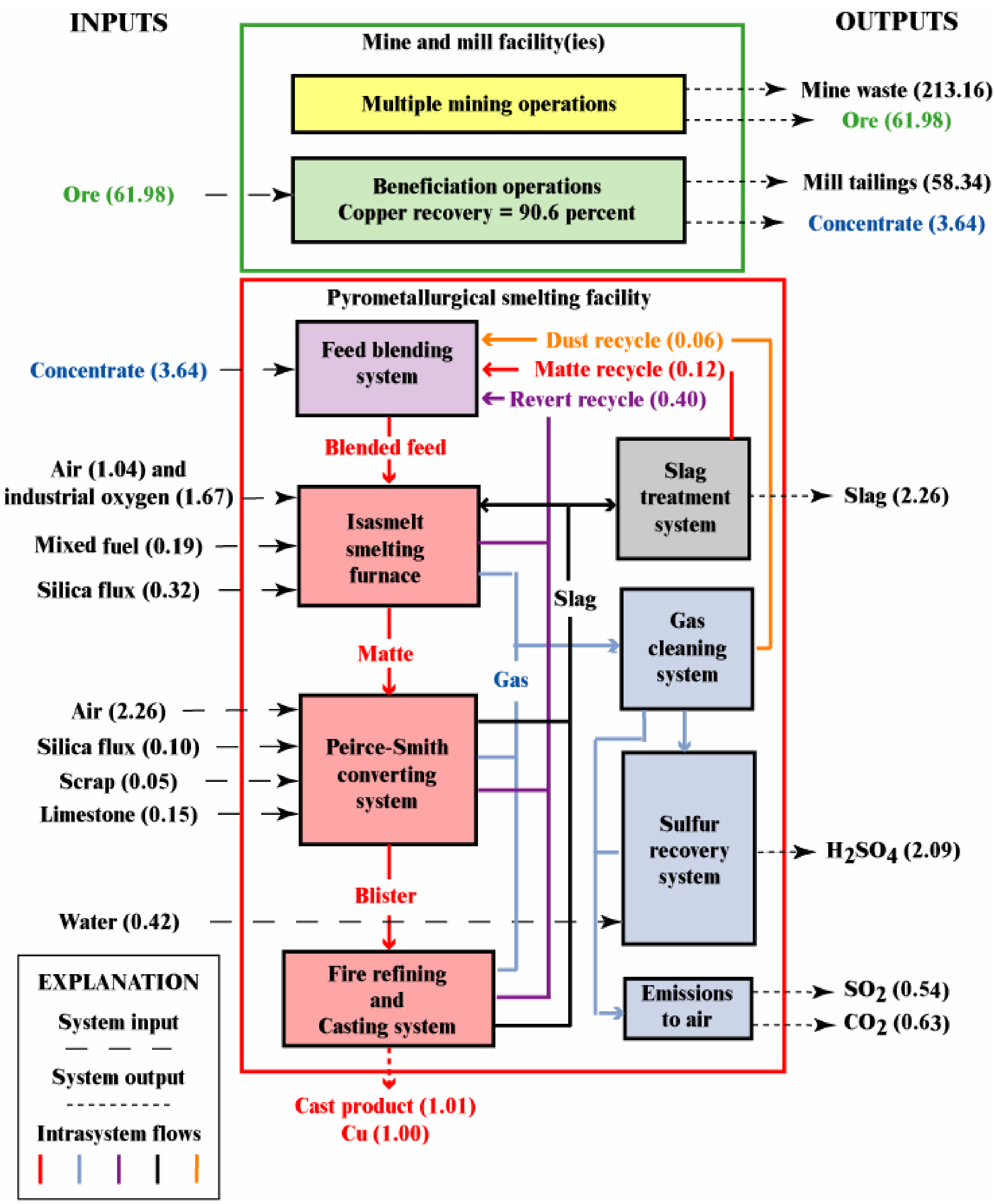

Figure 46. Copper-specific flow diagram of the Mount Isa smelter.

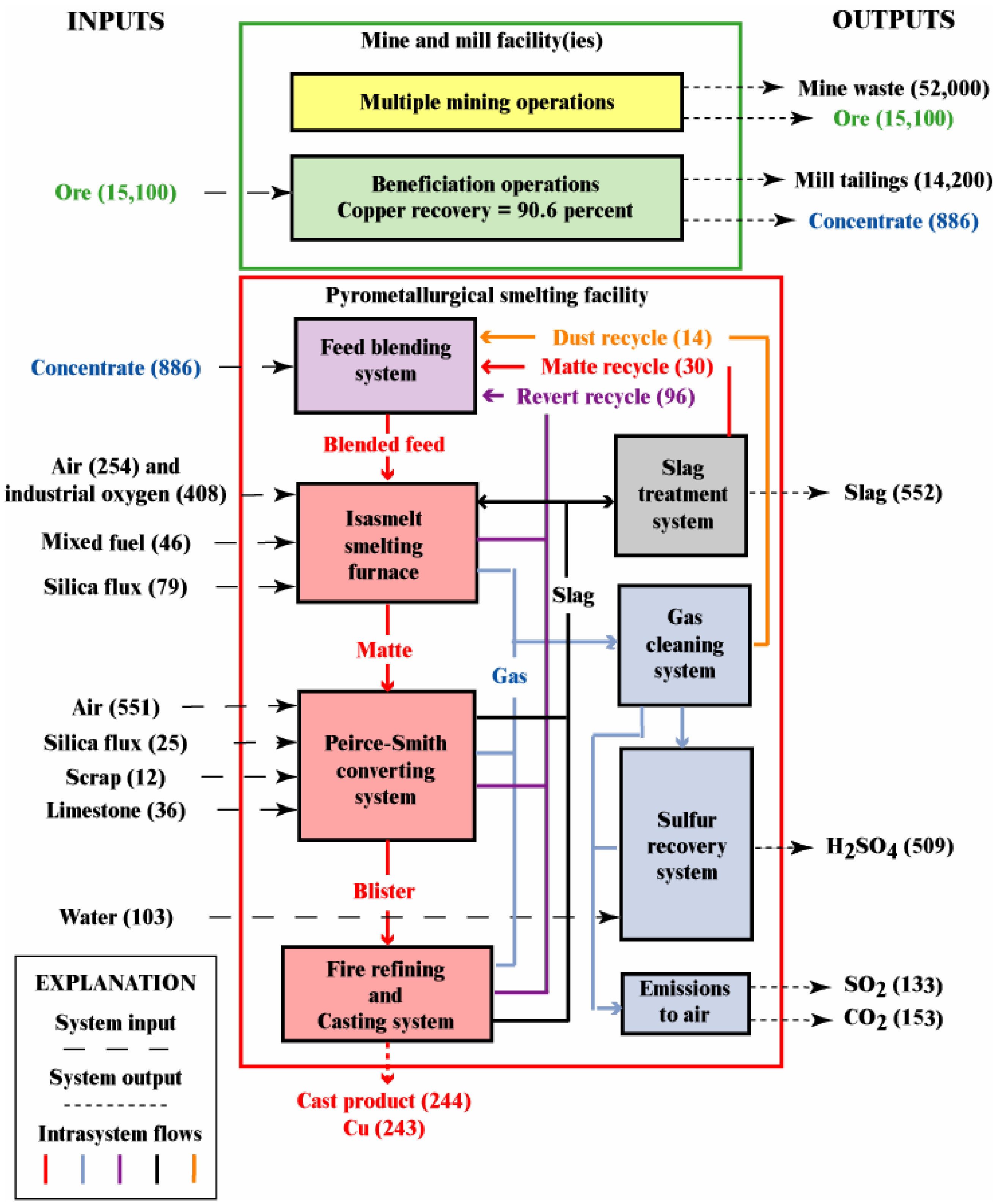

Figure 47. Gross flow diagram of the Mount Isa smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Nacozari (La Caridad)

Figures 48 and 49 show selected material flows for the Nacozari (La Caridad) smelter in Mexico. The smelter is located in Nacozari, Mexico (lat 30.37°N., long 109.53°W.). It is owned and operated by Grupo Mexico S.A. de C.V. of Colonia Roma Sur CP, DF, Mexico. It smelts concentrate produced from Mexican and foreign ores and annual capacity is rated at 330,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Nacozari (La Caridad) smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Chavoya, and Alvaredo, 1991; Davenport, Jones, King, and Partelpoeg, 2001; Grupo mexico, 2002, 2003; Imris, Rebollodo, Sanchez, Castro, Achurra, and Hernandez, 1999; Mechanical Engineer's Handbook, 5th edition, 1951; Meza, J.V., Manager, Metallurgical Operations, Mexicana de Cobre, Grupo Mexico, personal correspondence through Torres, I.E., U.S. Geological Survey, Mexico Country Specialist, dated February 24, 2003, re Sulfuric acid production for 2000 - 02, at Mexicana de Cobre, 4p; Morales, and Mac-Kay, 1999; Rentz, Krippner, Hahre, and Schultmann, 1999; Schloen, 1991; and World Mine Cost Data Exchange, 2004.

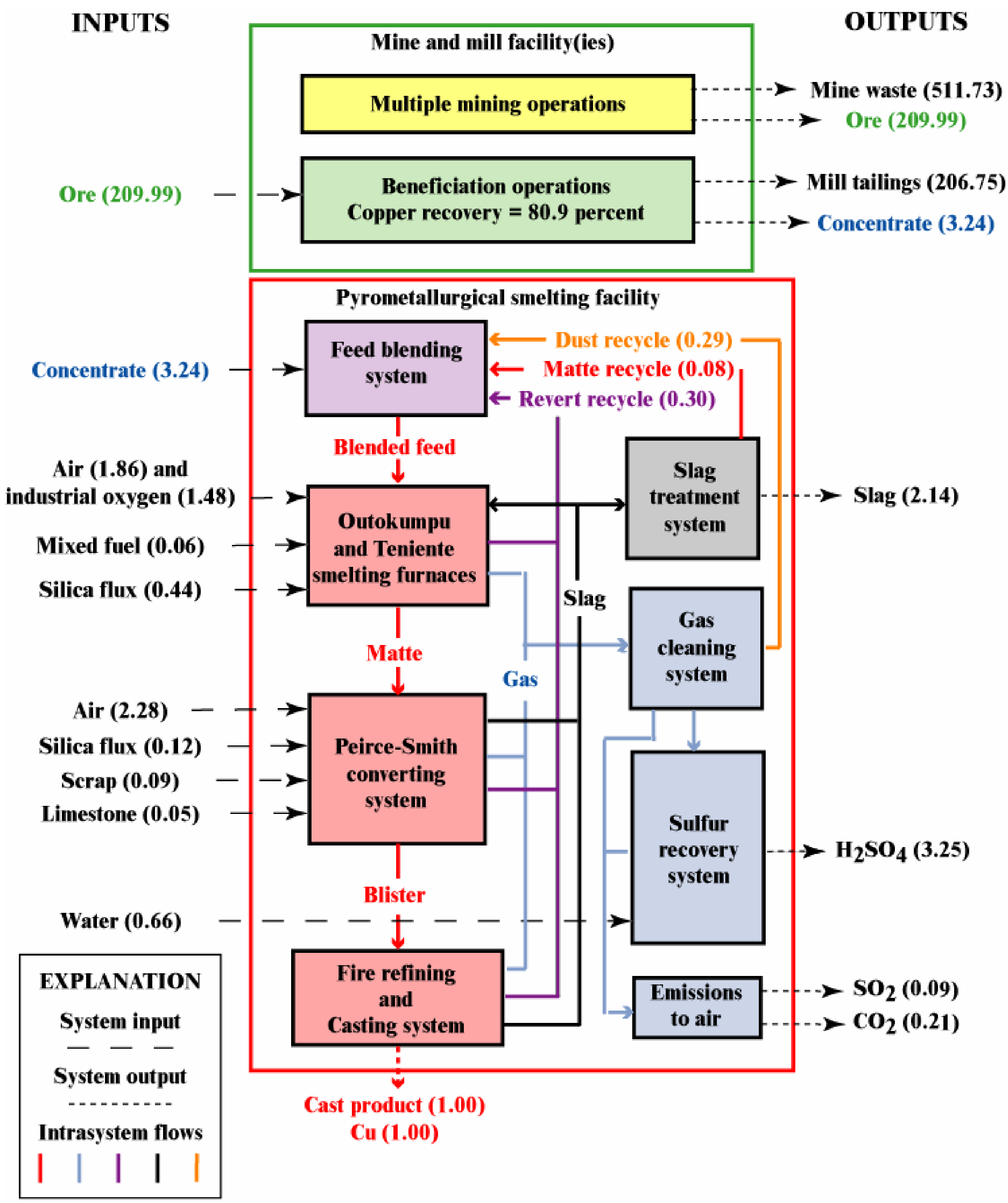

Figure 48. Copper-specific flow diagram of the Nacozari (La Caridad) smelter.

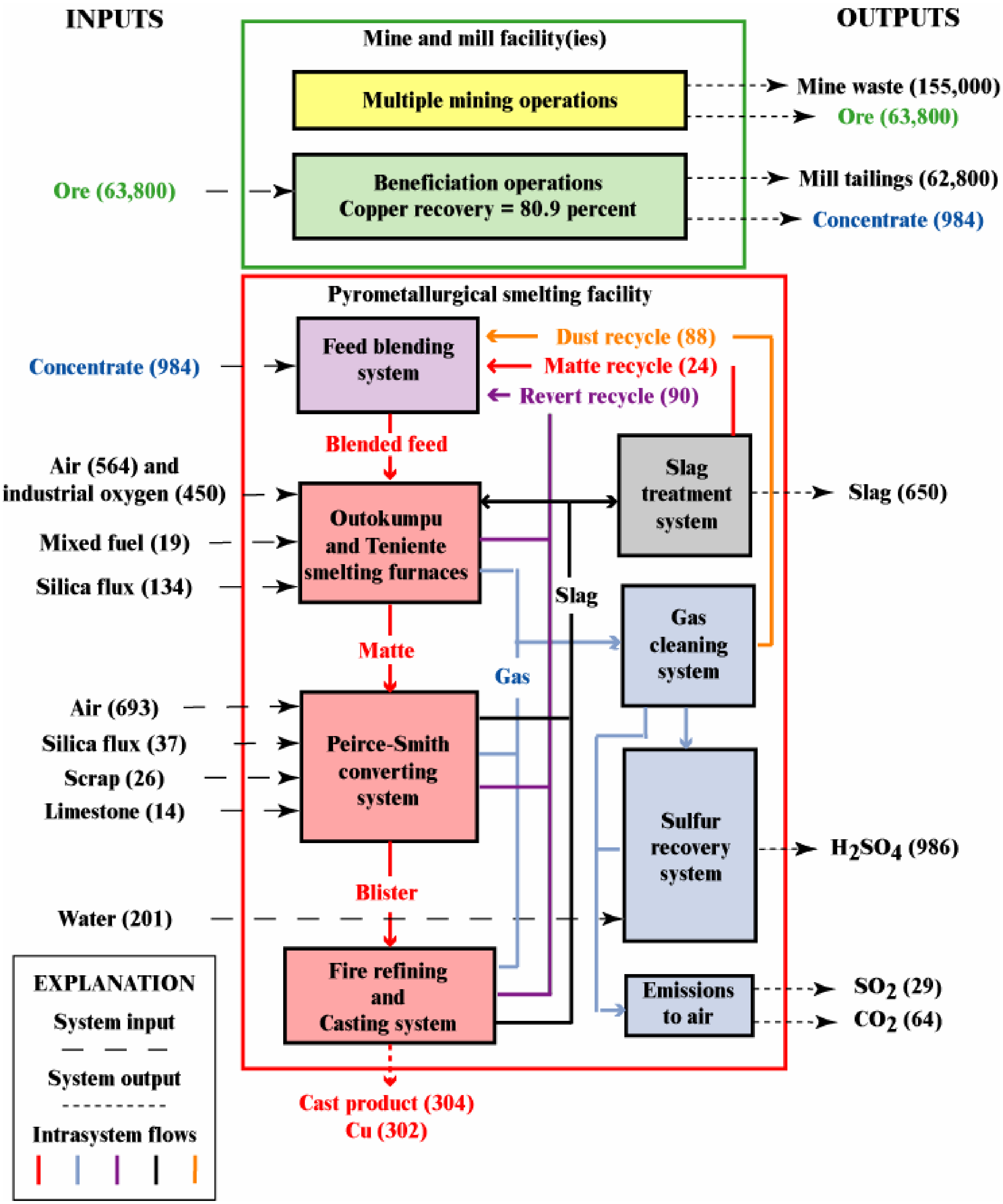

Figure 49. Gross flow diagram of the Nacozari (La Caridad) smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Naoshima

Figures 50 and 51 show selected material flows for the Naoshima smelter in Japan. The smelter is located in Naoshima, Japan (lat 34.45°N., long 134.00°E.). It is owned and operated by Mitsubishi Materials Corporation of Tokyo, Japan. It imports and smelts concentrate produced from foreign ores and annual capacity is rated at 270,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Naoshima smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Hirai, Yasuda, and Hoshi, 1999; Mitsubishi Materials Company, 2003; Nippon Mining and Metals, Ltd, 2001; Rentz, Krippner, Hahre, and Schultmann, 1999; and World Mine Cost Data Exchange 2004.

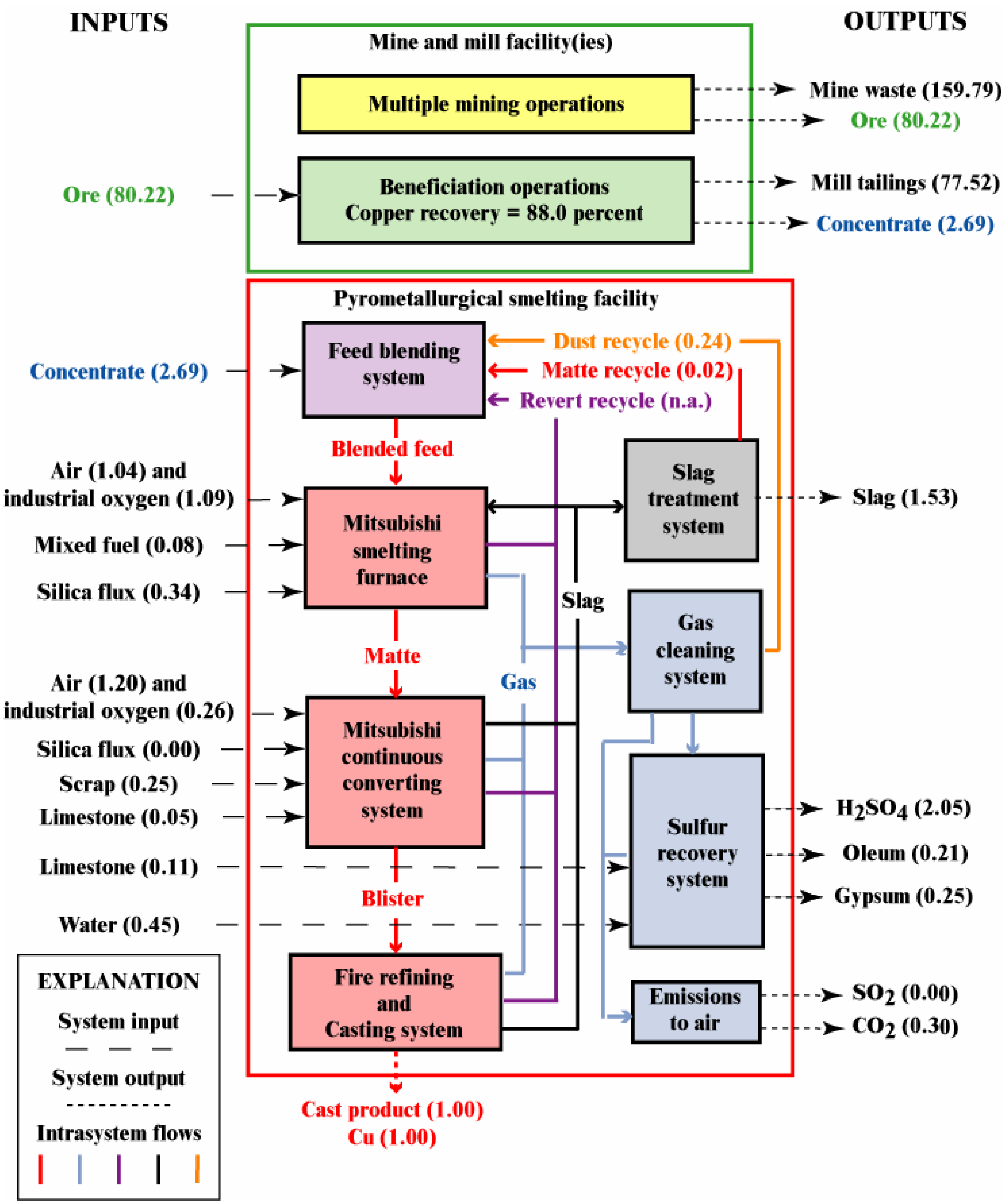

Figure 50. Copper-specific flow diagram of the Naoshima smelter.

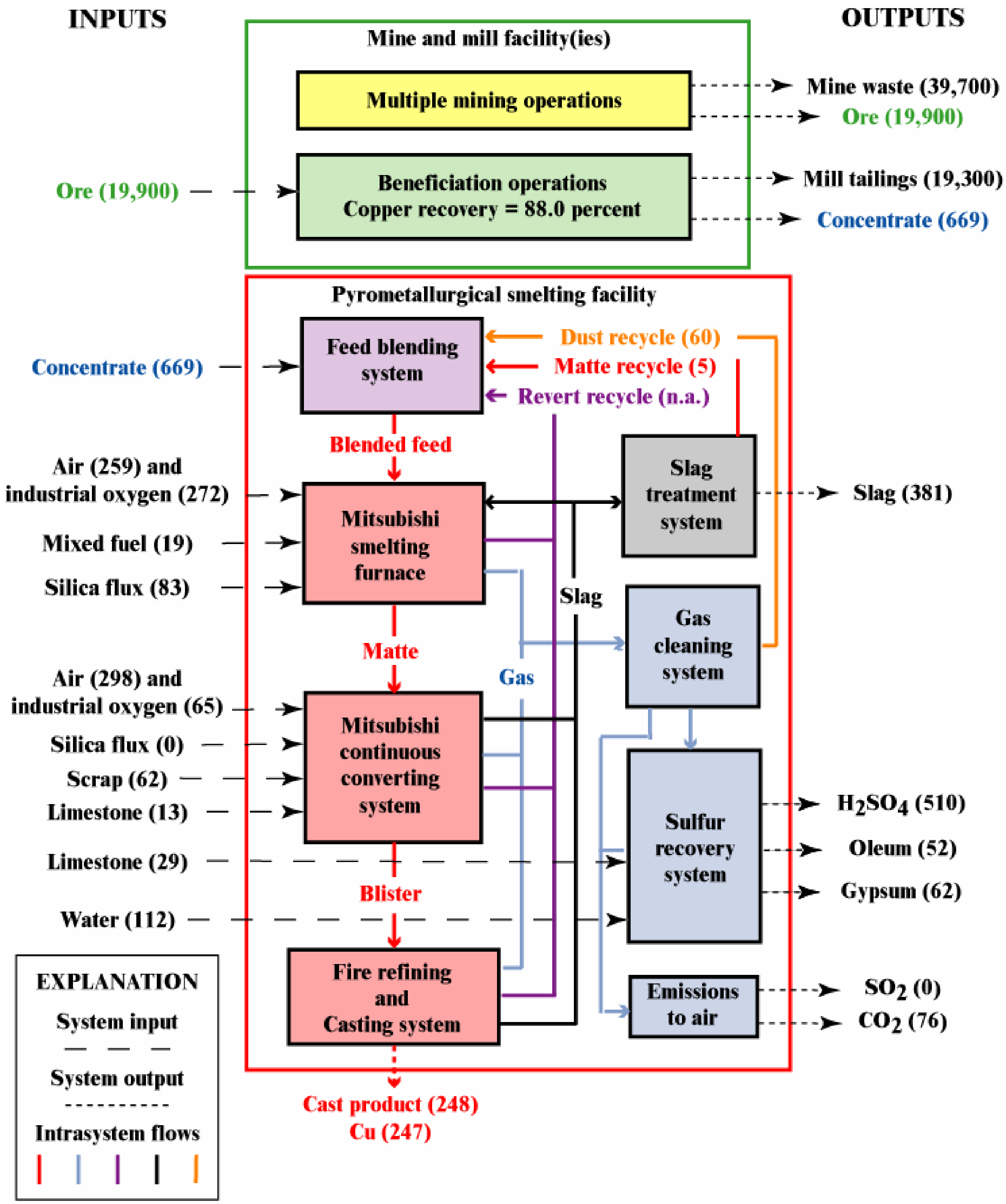

Figure 51. Gross flow diagram of the Naoshima smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Norddeutsche Affinerie

Figures 52 and 53 show selected material flows for the Norddeutsche Affinerie smelter in Germany. The smelter is located in Hamburg, Germany (lat 53.55°N., long 10.00°E.). It is owned and operated by a consortium of Degussa AG of Düsseldorf, Germany; Inmet Mining Corp. of Toronto, Canada; and Xstrata plc of Zug, Switzerland. It imports and smelts concentrate produced from foreign ores and annual capacity is rated at 420,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Norddeutsche Affinerie smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Edelstein, D.L., U.S. Geological Survey Copper Commodity Specialist, 2003, Private communication, dated December 8, 2003, re Norddeutsche primary smelter capacity; Environmental Atlas Hamburg, 1999; Gossling, 2001; Mechanical Engineer's Handbook, 5th edition, 1951; Newman, 2001; Norddeutsche Affiniere, 2000a, b; Rentz, Krippner, Hahre, and Schultmann, 1999; Schloen, 1991; and World Mine Cost Data Exchange, 2004.

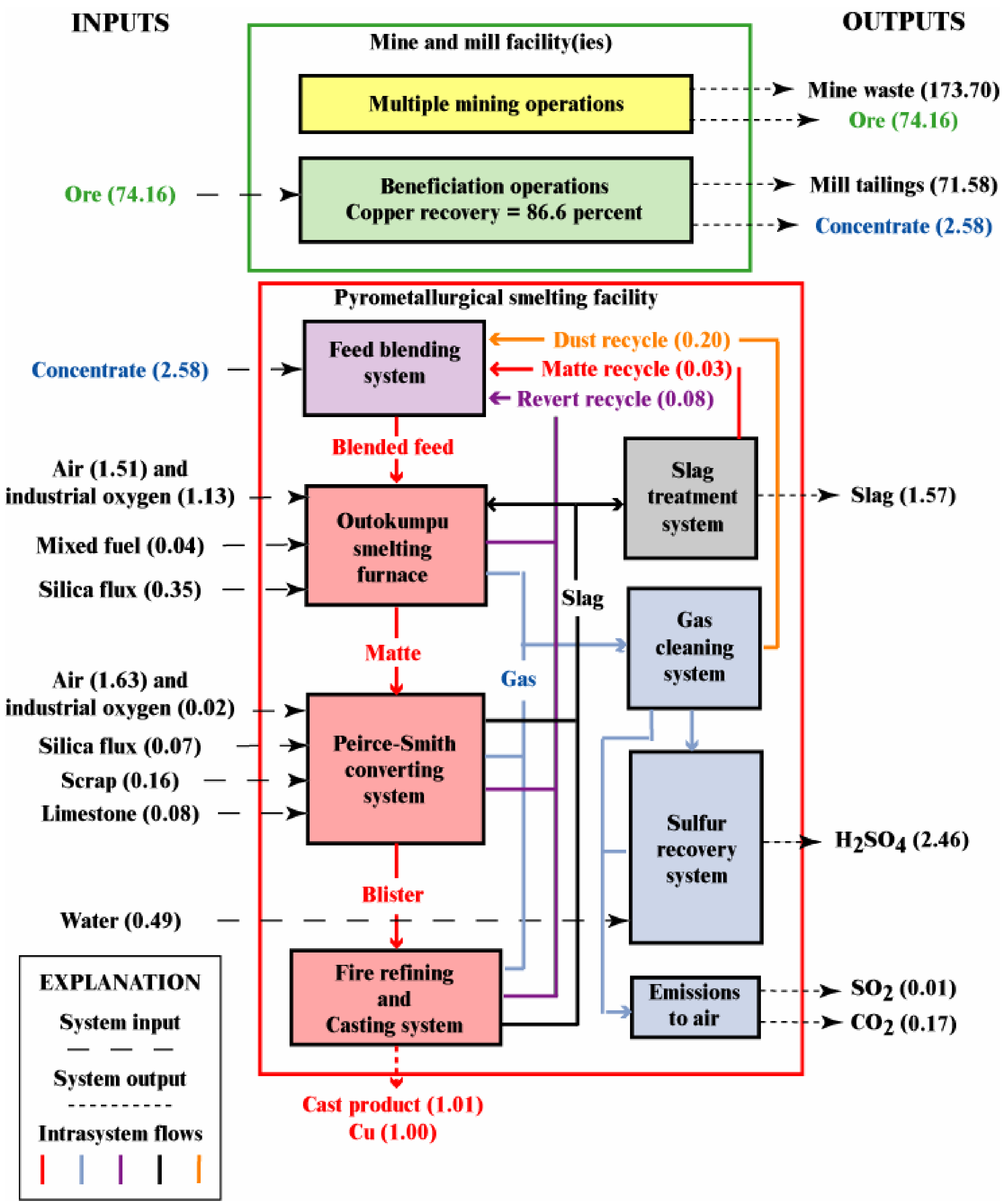

Figure 52. Copper-specific flow diagram of the Norddeutsche Affinerie smelter.

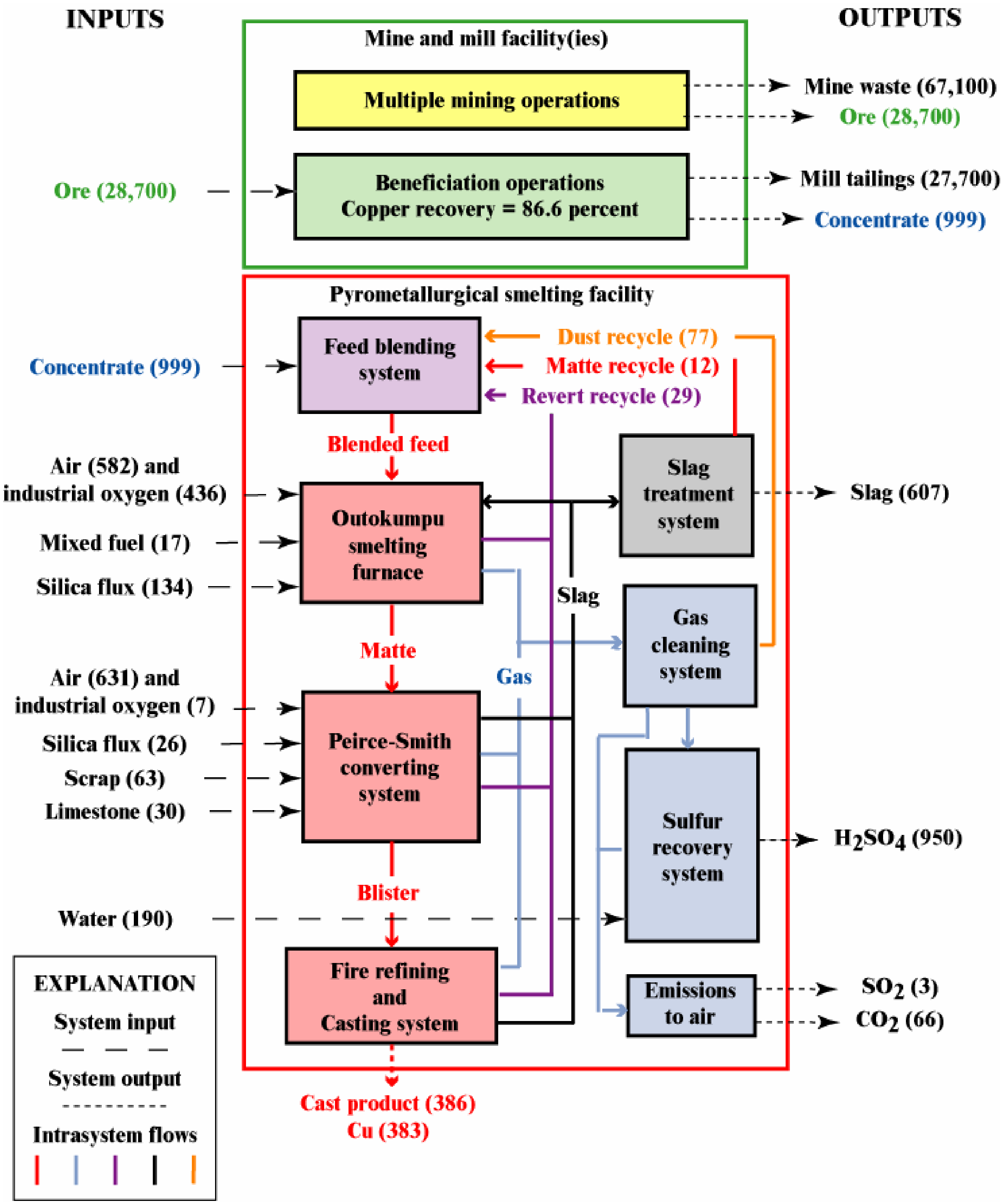

Figure 53. Gross flow diagram of the Norddeutsche Affinerie smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Norilsk

Figures 54 and 55 show selected material flows for the Norilsk smelter in Russia. The smelter is located in Norilsk, Russia (lat 69.34°N., long 88.22°E.). It is owned and operated by Mining Metallurgical Company Norilsk Nickel of Moscow, Russia. It smelts concentrate produced from Norilsk's polymetallic copper-nickel ores obtained from underground mining and annual capacity is rated at 400,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Norilsk smelter were extracted from the following sources: Bond, and Levine, 2001; Mining industry of Kazakhstan, 2001; Levine, Wallace, 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Mechanical Engineer's Handbook, 5th Edition, 1951; Riekkola–Vanhanen, 1999; and Zeping, 1999.

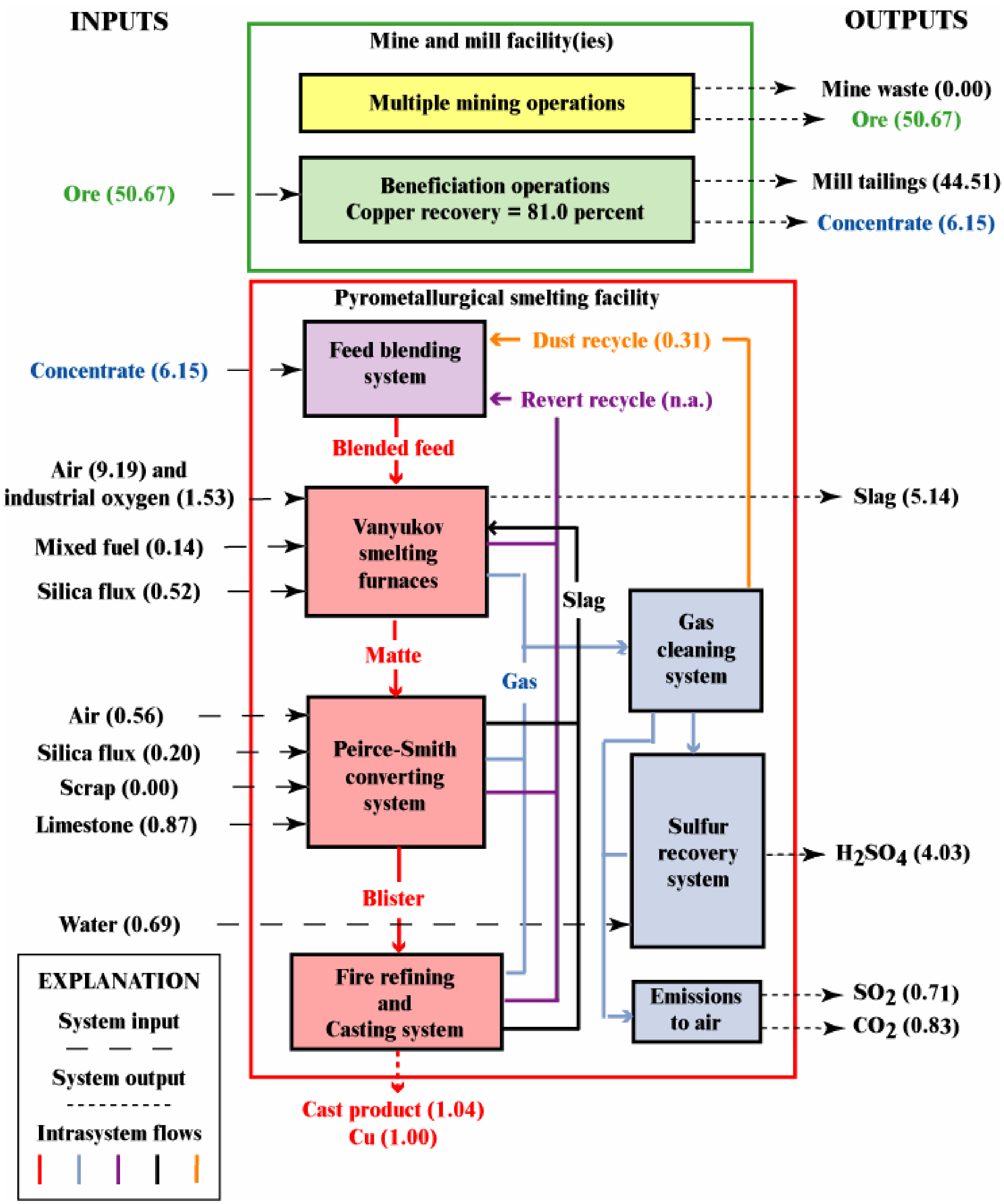

Figure 54. Copper-specific flow diagram of the Norilsk smelter.

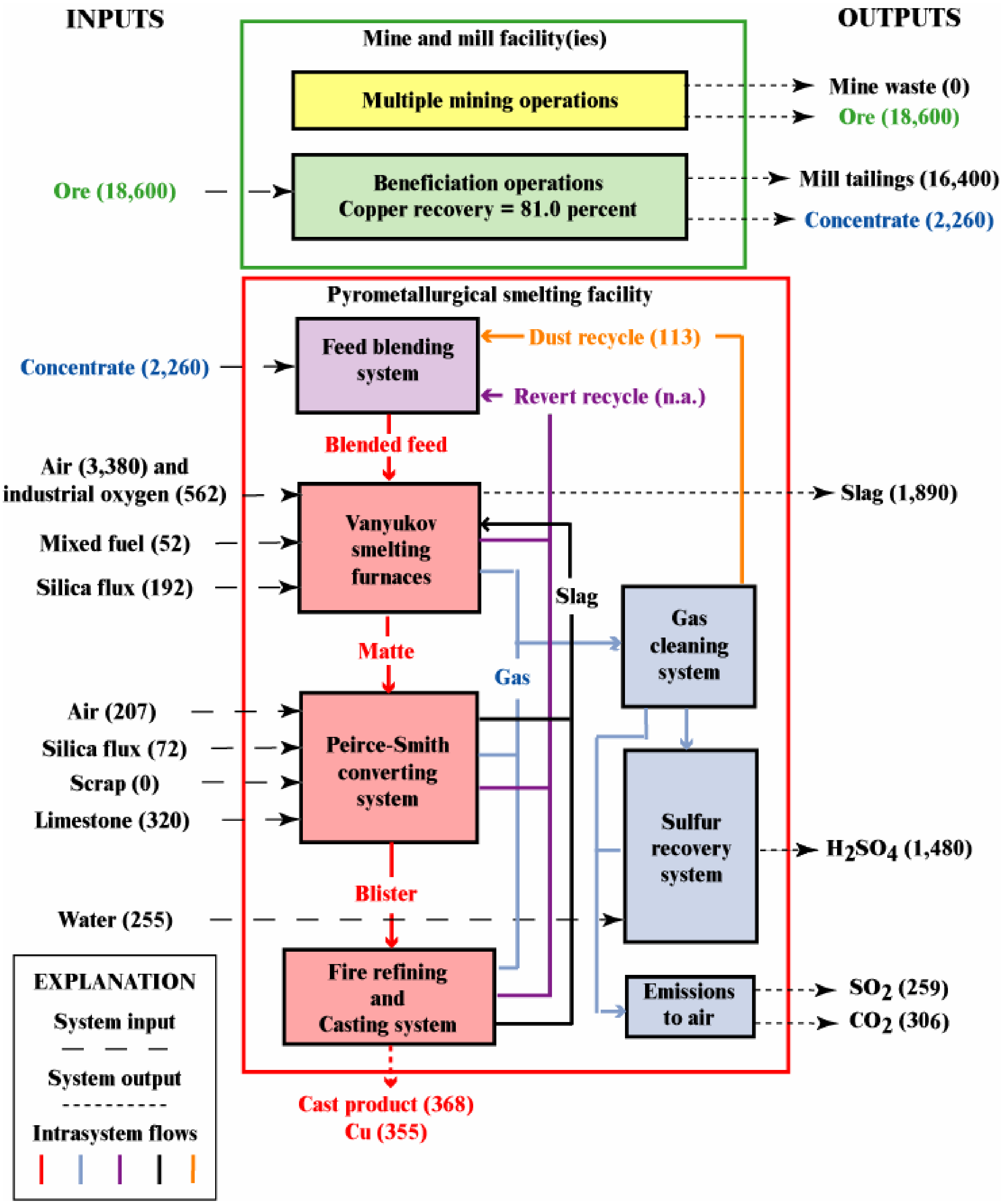

Figure 55. Gross flow diagram of the Norilsk smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Olympic Dam

Figures 56 and 57 show selected material flows for the Olympic Dam smelter in Australia. The smelter is located in Olympic Dam, Australia (lat 30.50°S., long 136.90°E.). It is owned and operated by WMC Resources, Ltd. of Southbank, Australia. It smelts concentrate produced from local high-grade ores, which allows it to bypass the converting step. The annual capacity of the Olympic Dam smelter is rated at 200,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Olympic Dam smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Canadian Institute of Mining, Metallurgy and Petroleum, Hydrometallurgy Section, 2001; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Hunt, Day, Shaw, and West, 1999; Mechanical Engineer's Handbook, 5th edition, 1951; Ramachamdran, Diaz, Eltringham, Jiang, Lehner, Mackey, Newman, and Tarasov, 2003; and World Mine Cost Data Exchange, 2004.

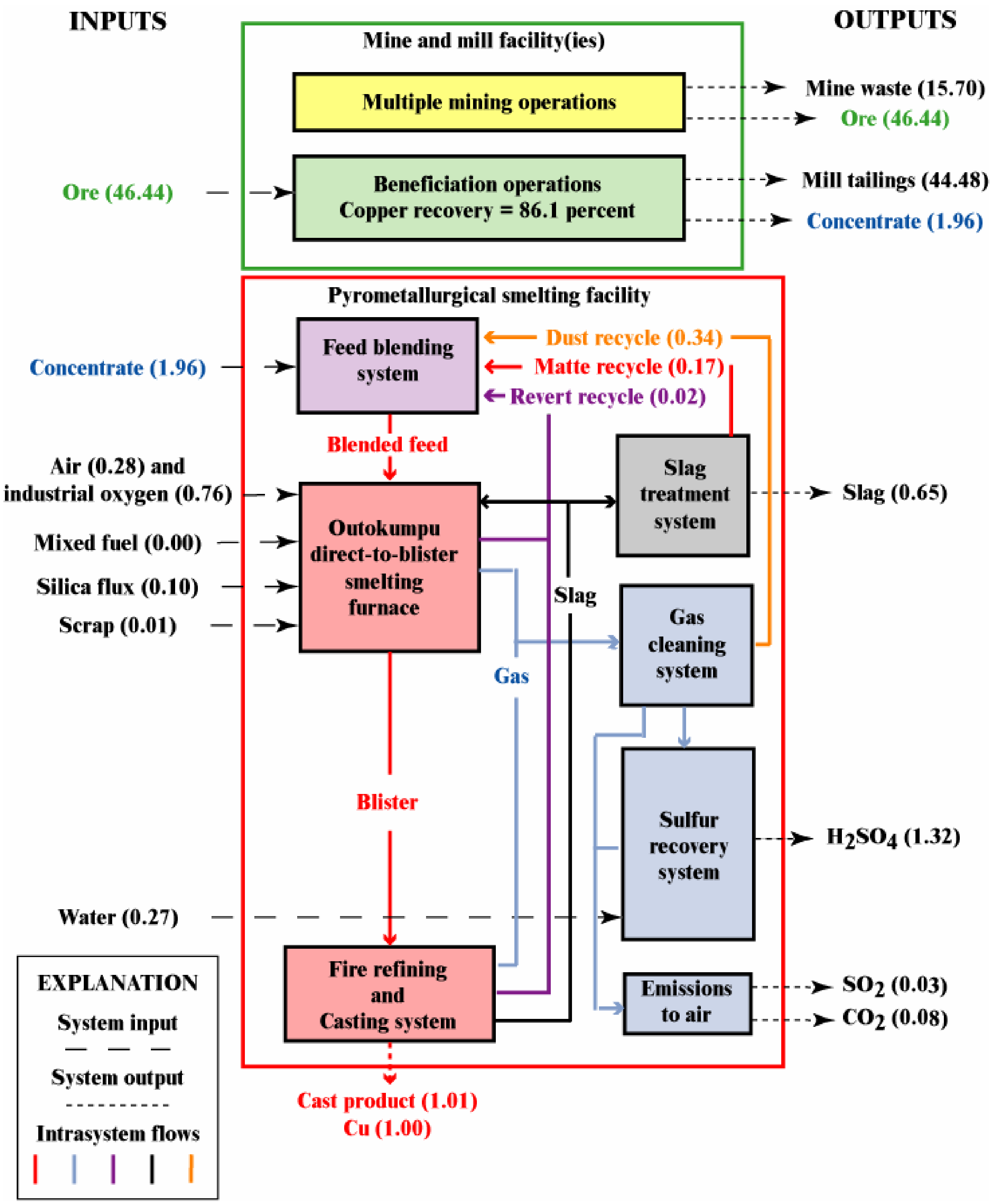

Figure 56. Copper-specific flow diagram of the Olympic Dam smelter.

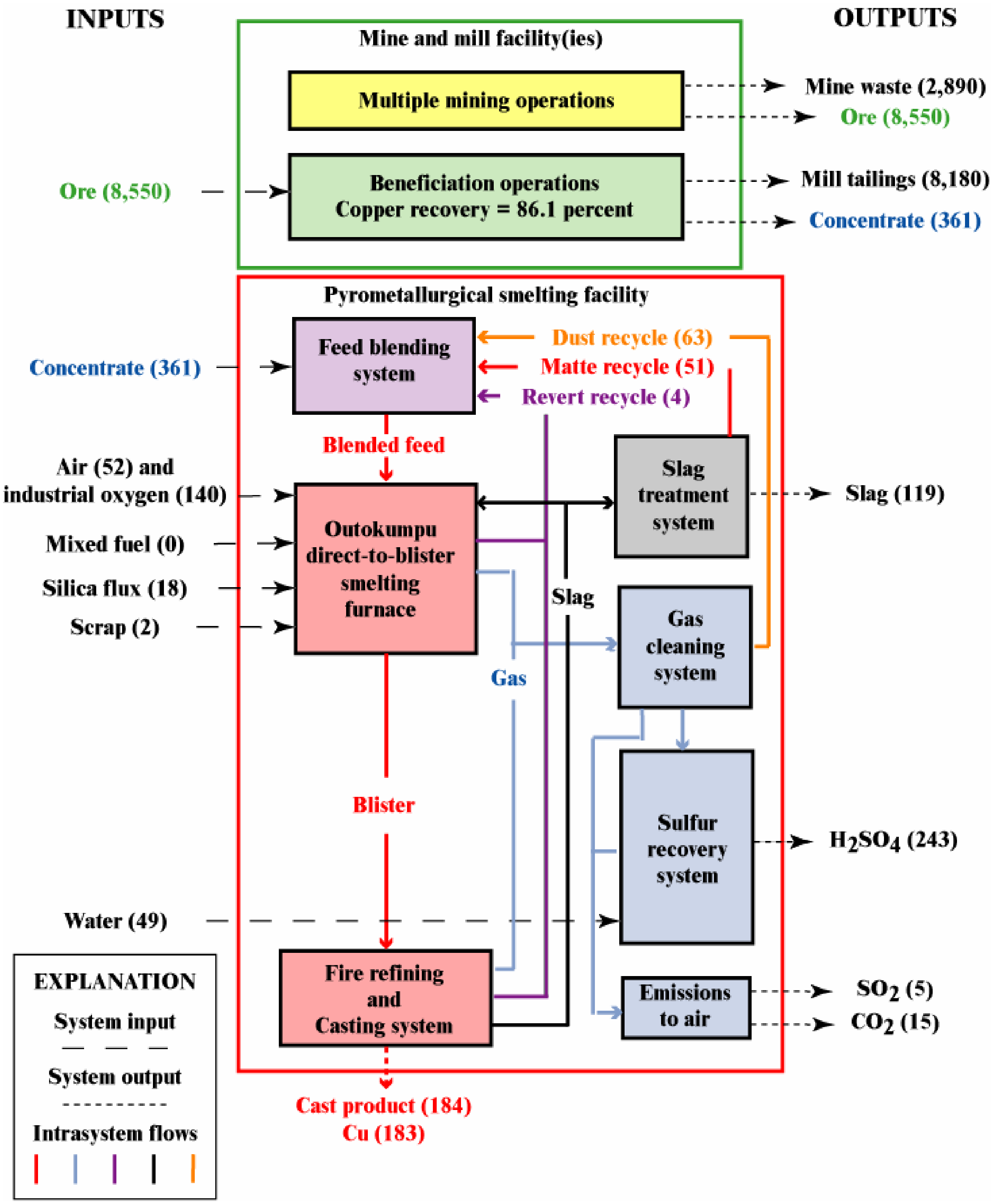

Figure 57. Gross flow diagram of the Olympic Dam smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Onahama

Figures 58 and 59 show selected material flows for the Onahama smelter in Japan. The smelter is located in Fukushima, Japan (lat 36.95°N., long 140.90°E.). It is owned and operated by a consortium that includes: Dowa Mining Co. Ltd., The Furukawa Electric Company Limited, Mitsubishi Materials Corporation, and Mitsui Mining & Smelting Co. Ltd., all of Tokyo, Japan. It imports and smelts concentrate produced from foreign ores and annual capacity is rated at 258,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Onahama smelter were extracted from the following sources: AME Mineral Economics, 2001; Ando, Steiner, Selinger, and Shin, 2002; Biswas, and Davenport, 1980; Cresttec, 2002; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Japan Automobile Manufacturers Association, Inc., 2003; Mechanical Engineer's Handbook, 5th edition, 1951; NTIS, 1989; Onahama Smelting and Refining Co., Ltd., 2003; Tan, and Zhang, 1996; World Mine Cost Data Exchange, 2004; and Wu, 2002.

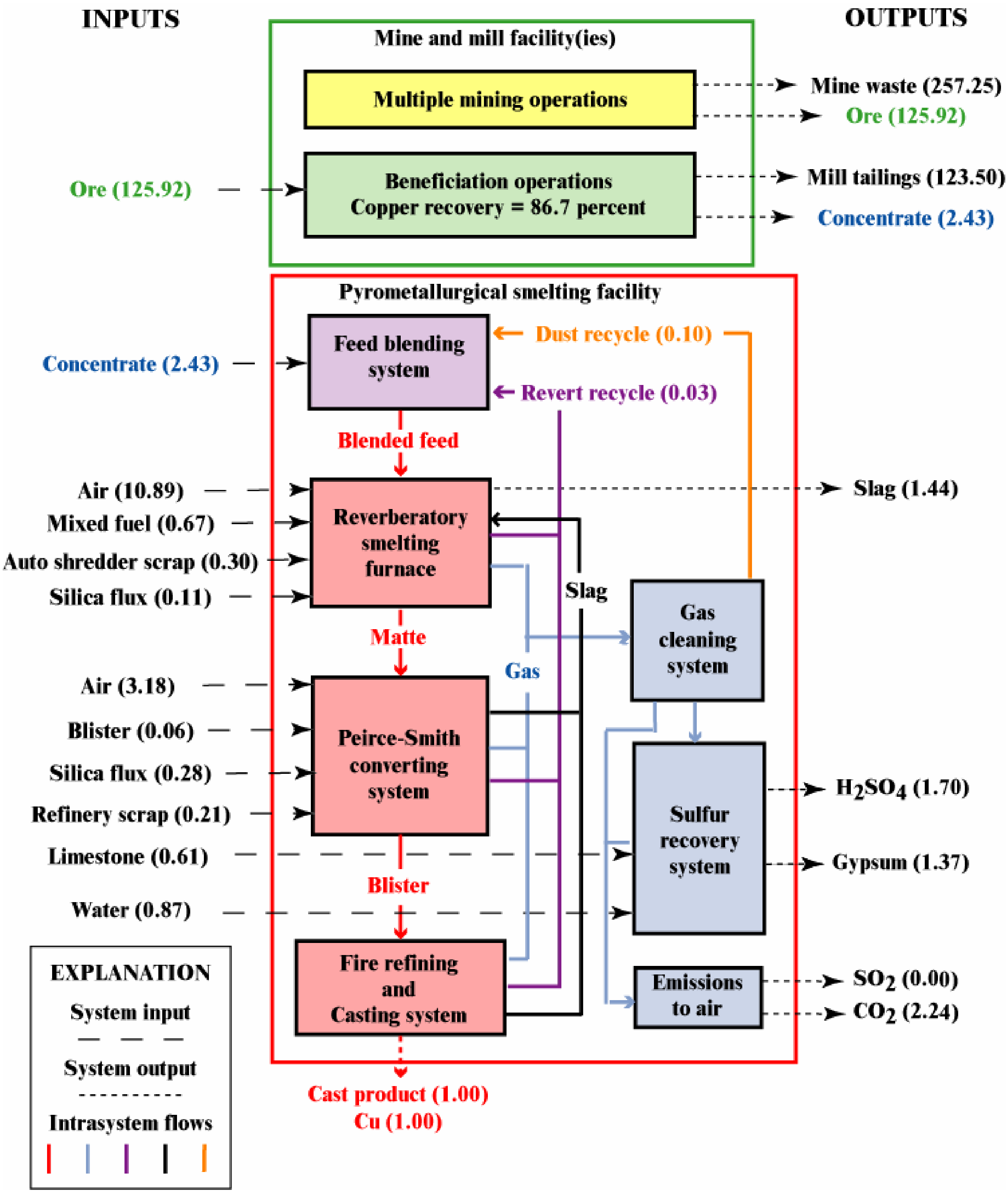

Figure 58. Copper-specific flow diagram of the Onahama smelter.

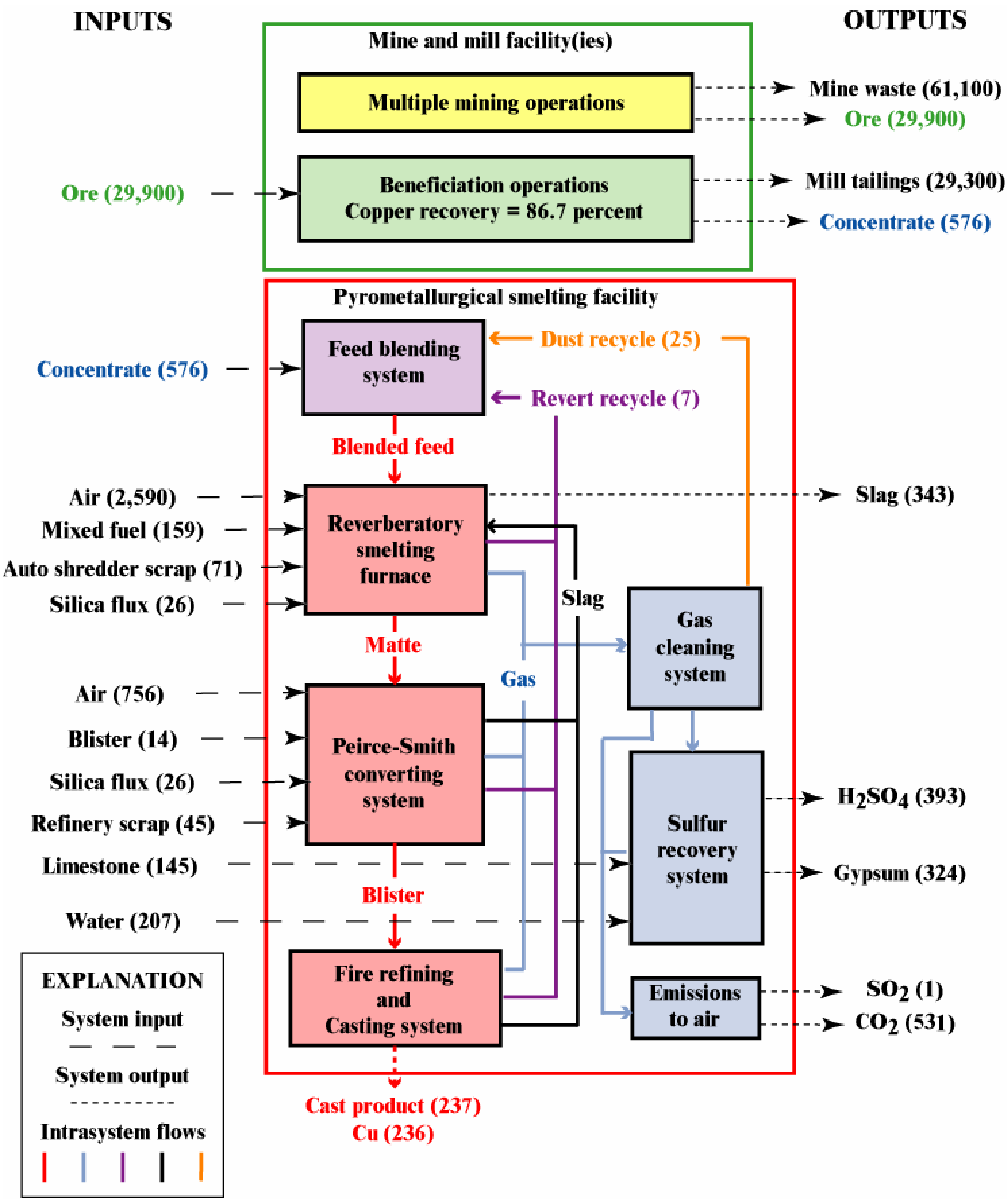

Figure 59. Gross flow diagram of the Onahama smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Onsan I

Figures 60 and 61 show selected material flows for the Onsan I smelter in the Republic of Korea. The smelter is located in Ulsan, Republic of Korea (lat 35.42°N., long 129.33°E.). It is owned by Japan Korea Joint Smelting Co., Ltd., which is a consortium that includes: Marubeni Corporation, Mitsui Mining and Smelting Co. Ltd., and Nippon Mining & Metals Company Ltd., all of Tokyo Prefecture, Japan, and LG Group of Seoul, Republic of Korea. It is operated by LG Nikko Copper Inc. of Seoul, Republic of Korea. It imports and smelts concentrates produced from foreign ores and annual capacity is rated at 210,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Onsan I smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Kang, and Song, 1999; Kyungpook National University, 2003; Lee, Kang, Cho, and Lee, 1999; LG-Nikko Copper Co., Inc., 2003; Mechanical Engineer's Handbook, 5th edition, 1951; Reuters, 2002, 2003; Schloen, 1991; Torres, I. E., Country Specialist, U.S. Geological Survey, private communication, dated February 24, 2003, re Onsan Smelter Capacity; Tse, 2002; World Mine Cost Data Exchange, 2004; and Wu, 2002.

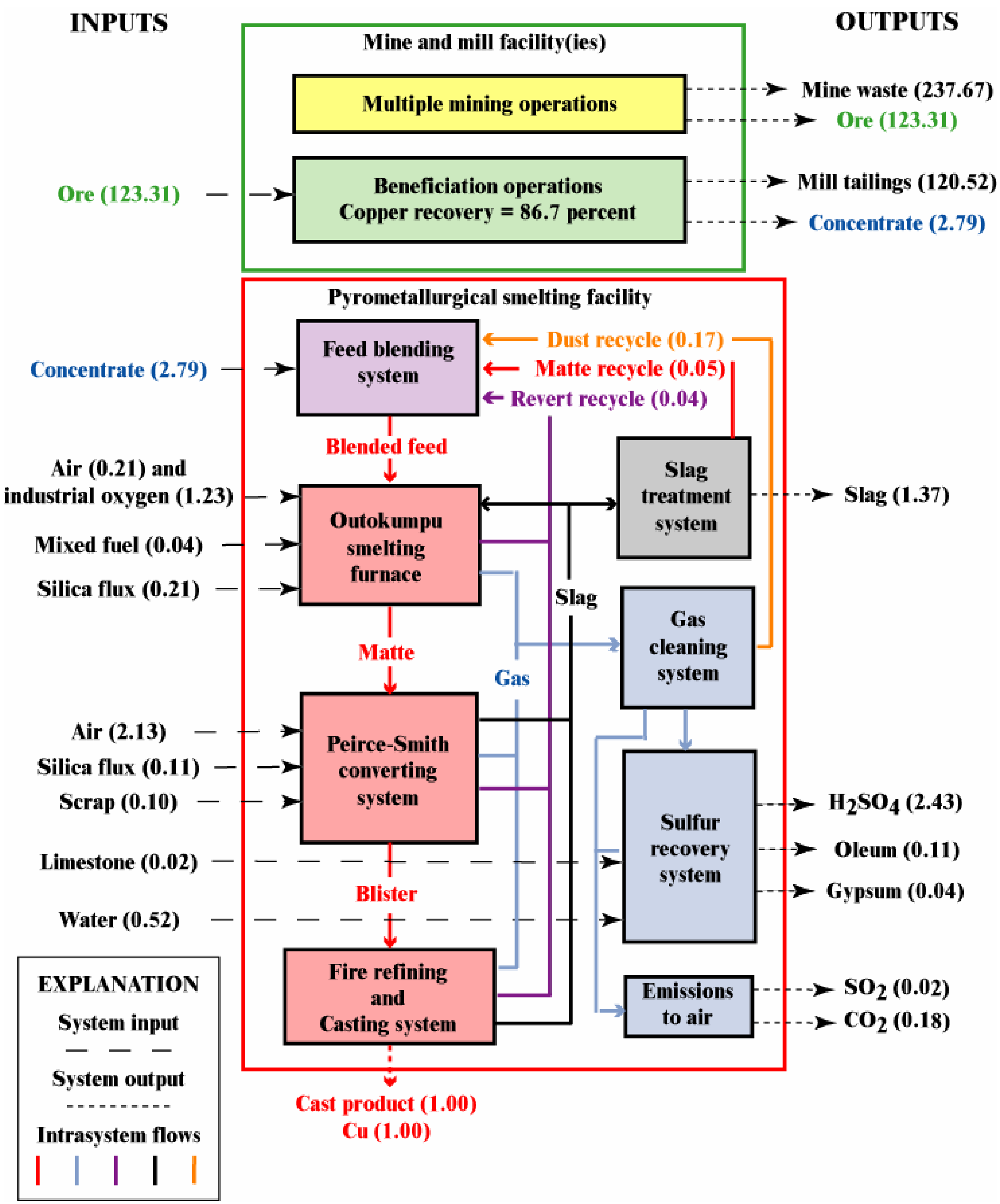

Figure 60. Copper-specific flow diagram of the Onsan I smelter.

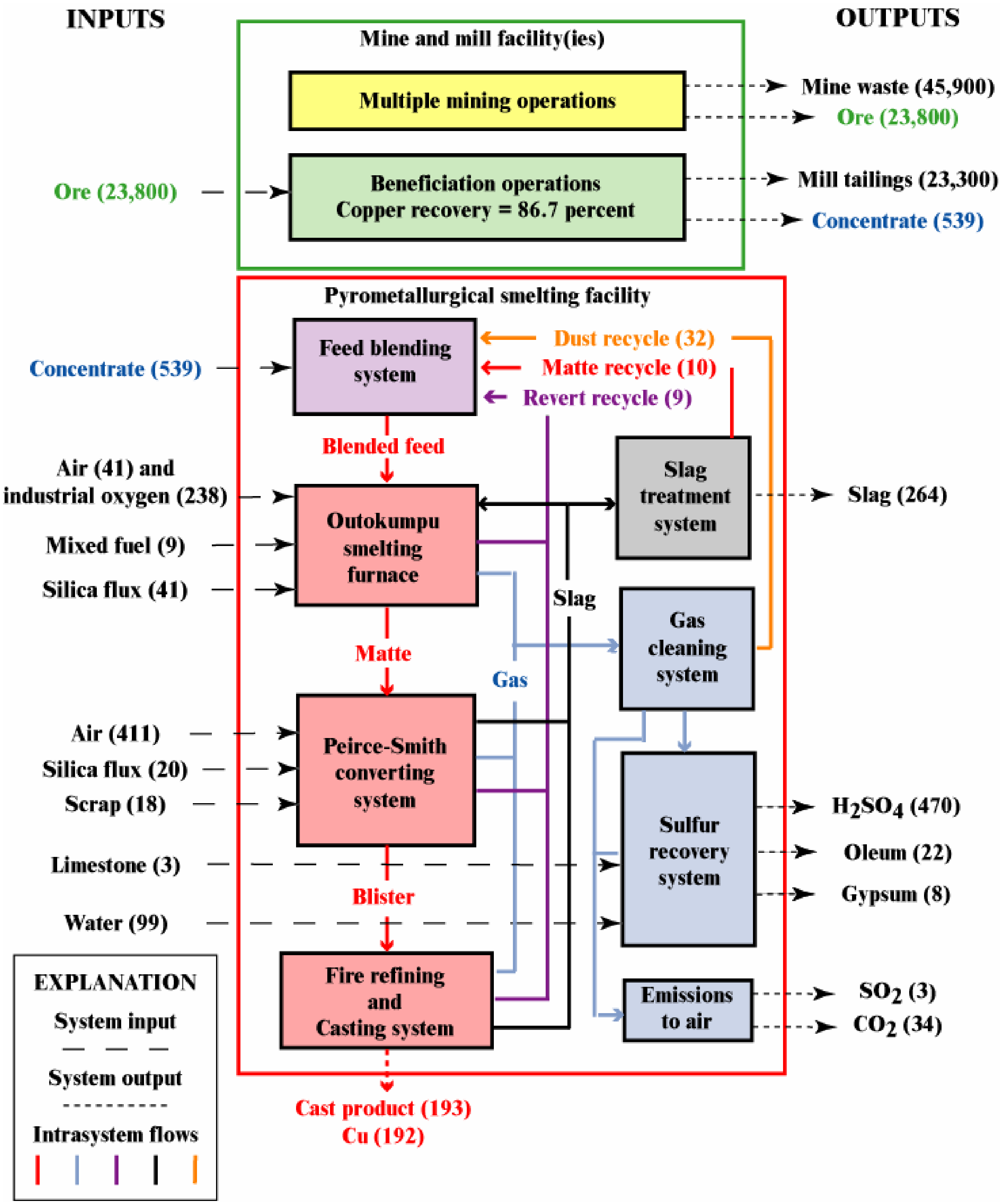

Figure 61. Gross flow diagram of the Onsan I smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Onsan II

Figures 62 and 63 show selected material flows for the Onsan II smelter in the Republic of Korea. The smelter is located in Ulsan, Republic of Korea (lat 35.42°N., long 129.33°E.). It is owned by Japan Korea Joint Smelting Co., Ltd., which is a consortium that includes: Marubeni Corporation, Mitsui Mining and Smelting Co. Ltd., and Nippon Mining & Metals Company Ltd., all of Tokyo Prefecture, Japan, and LG Group of Seoul, Republic of Korea. It is operated by LG Nikko Copper Inc. of Seoul, Republic of Korea. It imports and smelts concentrates produced from foreign ores and annual capacity is rated at 210,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Onsan II smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Kang, and Song, 1999; Kyungpook National University, 2003; Lee, Kang, Cho, and Lee, 1999; LG-Nikko Copper Co., Inc., 2003; Mechanical Engineer's Handbook, 5th edition, 1951; Reuters, 2002, 2003; Schloen, 1991; Torres, I. E., Country Specialist, U.S. Geological Survey, private communication, dated February 24, 2003, re Onsan Smelter Capacity; Tse, 2002; World Mine Cost Data Exchange, 2004; and Wu, 2002.

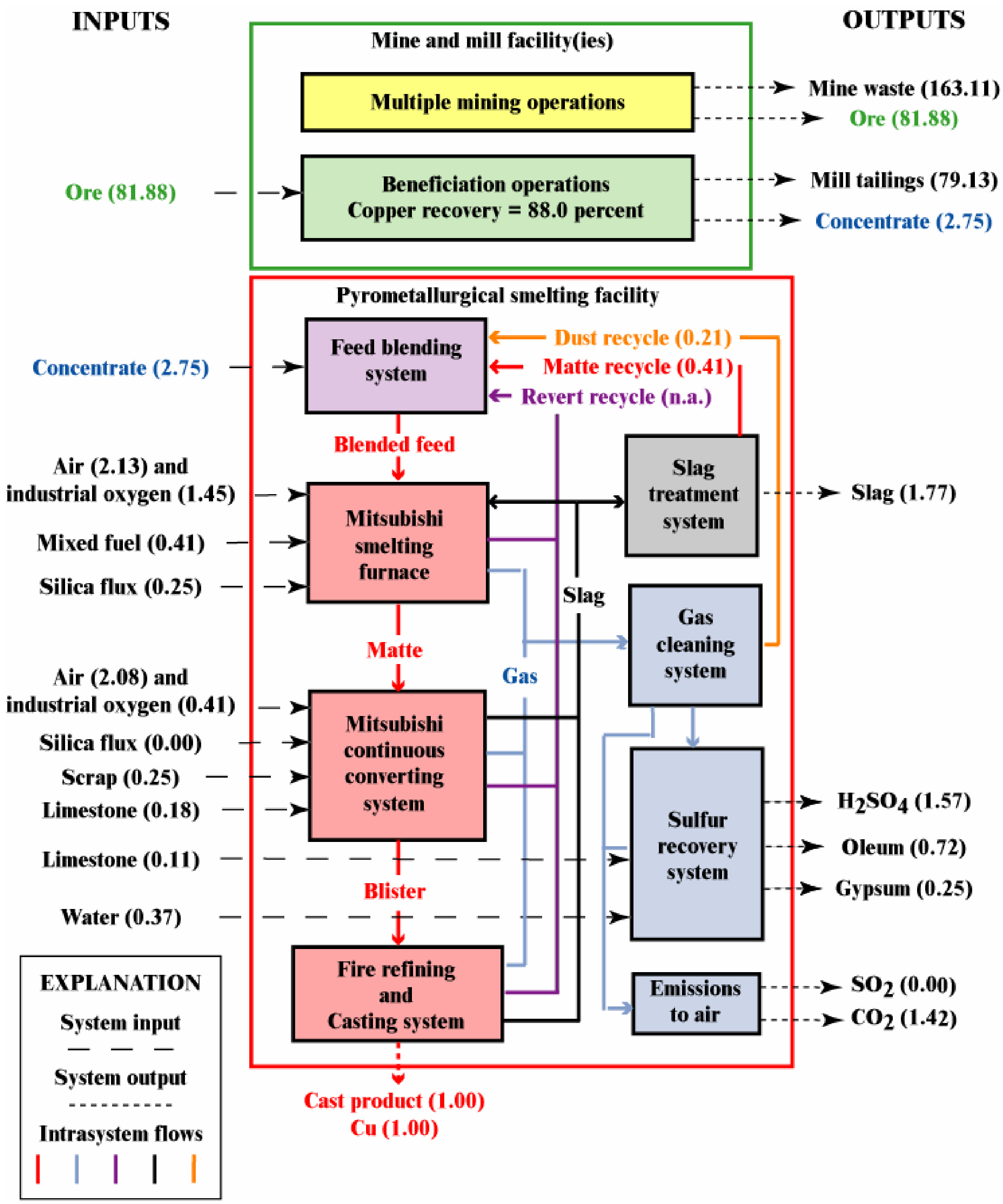

Figure 62. Copper-specific flow diagram of the Onsan II smelter.

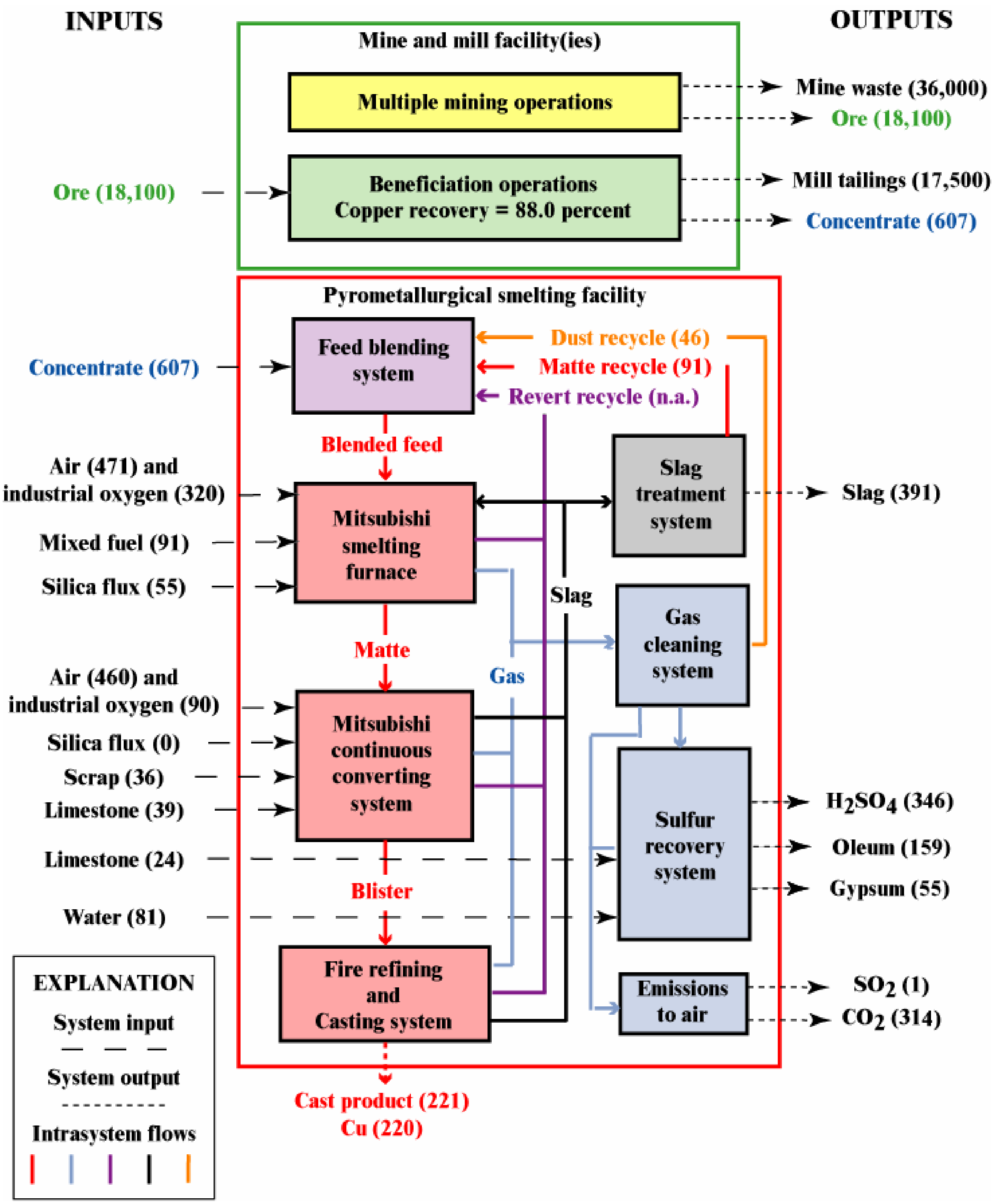

Figure 63. Gross flow diagram of the Onsan II smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Potrerillos

Figures 64 and 65 show selected material flows for the Potrerillos smelter in Chile. The smelter is located in Antofagasta, Chile (lat 26.30°S., long 69.50°W.). It is owned and operated by Corporación Nacional del Cobre de Chile (CODELCO) of Santiago, Chile. As part of the Salvador Division of CODELCO, it smelts concentrate from the El Salvador Mine and annual capacity is rated at 220,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Potrerillos smelter were extracted from the following sources: Achurra, Chacana, Buchi, and Condore, 2003; Acuna, and Yazawa, 1997; Acuna, Zuniga, Guibout, and Ruz, 1999; Alvaredo, Archurra, and Mac Kay, 1998; Alvaredo, and Godoy, 1999; AME Mineral Economics, 2001; Biswas, and Davenport, 1980; CIPMA, 2002; CODELCO, 1999, 2000a, b; CODELCO, undated, a, b; Chilean Copper Comission, 2000; Davenport, Jones, King, and Partelpoeg, 2001; E&MJ, 2003; Gossling, 2001; Imris, Rebollodo, Sanchez, Castro, Achurra, and Hernandez, 1999; Mechanical Engineer's Handbook, 5th edition, 1951; Morales, and Mac-Kay, 1999; Northern Miner, 2002; O'Ryan, and Diaz, 1998; Sanchez, and Castro, 2002; Valenzuela–Jara, Palacios, Cordero, and Sanchez, 2002; Sociedad Nacional de Mineria de Chile, 2002; Velasco, 2000; and World Mine Cost Data Exchange 2004.

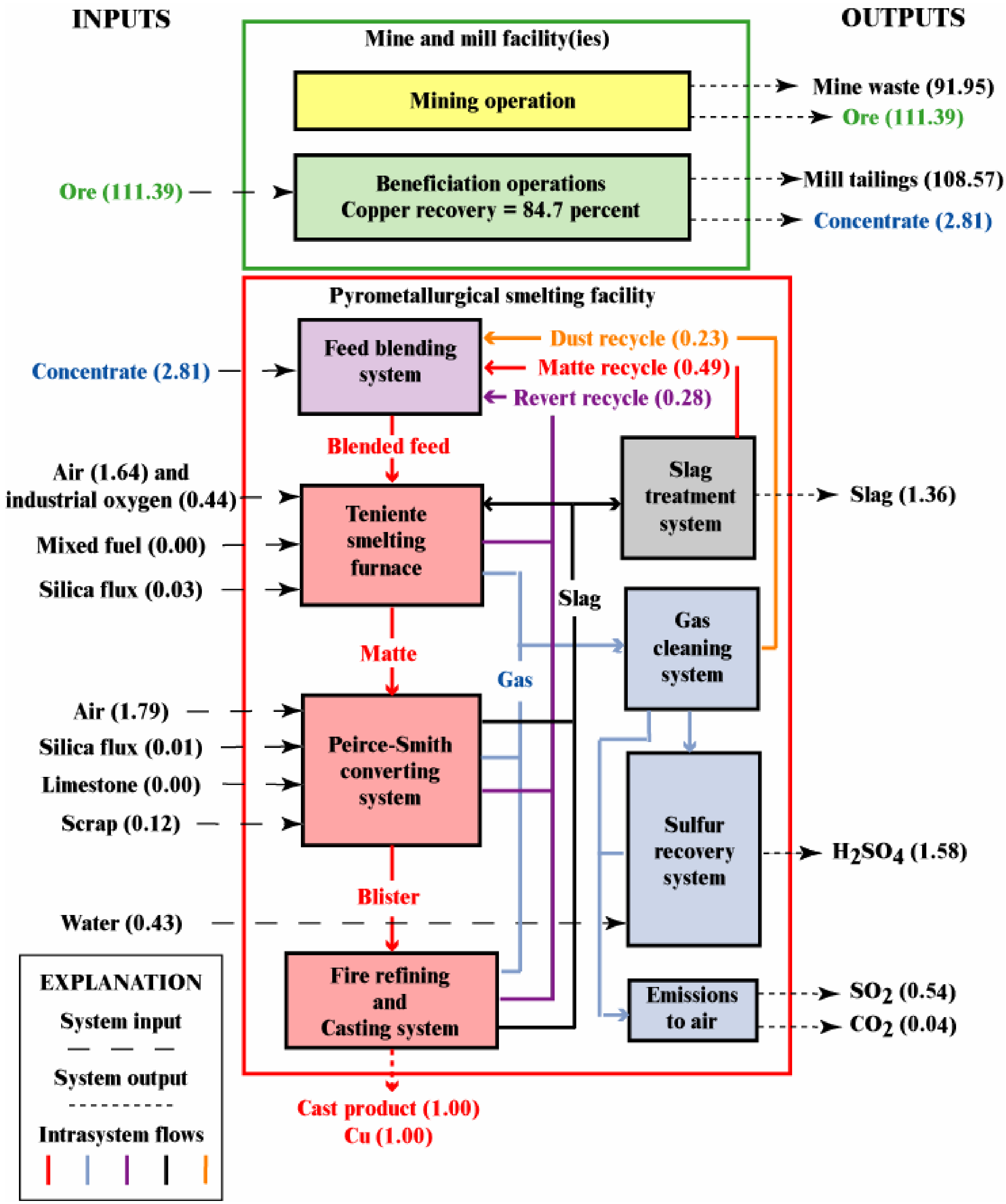

Figure 64. Copper-specific flow diagram of the Potrerillos smelter.

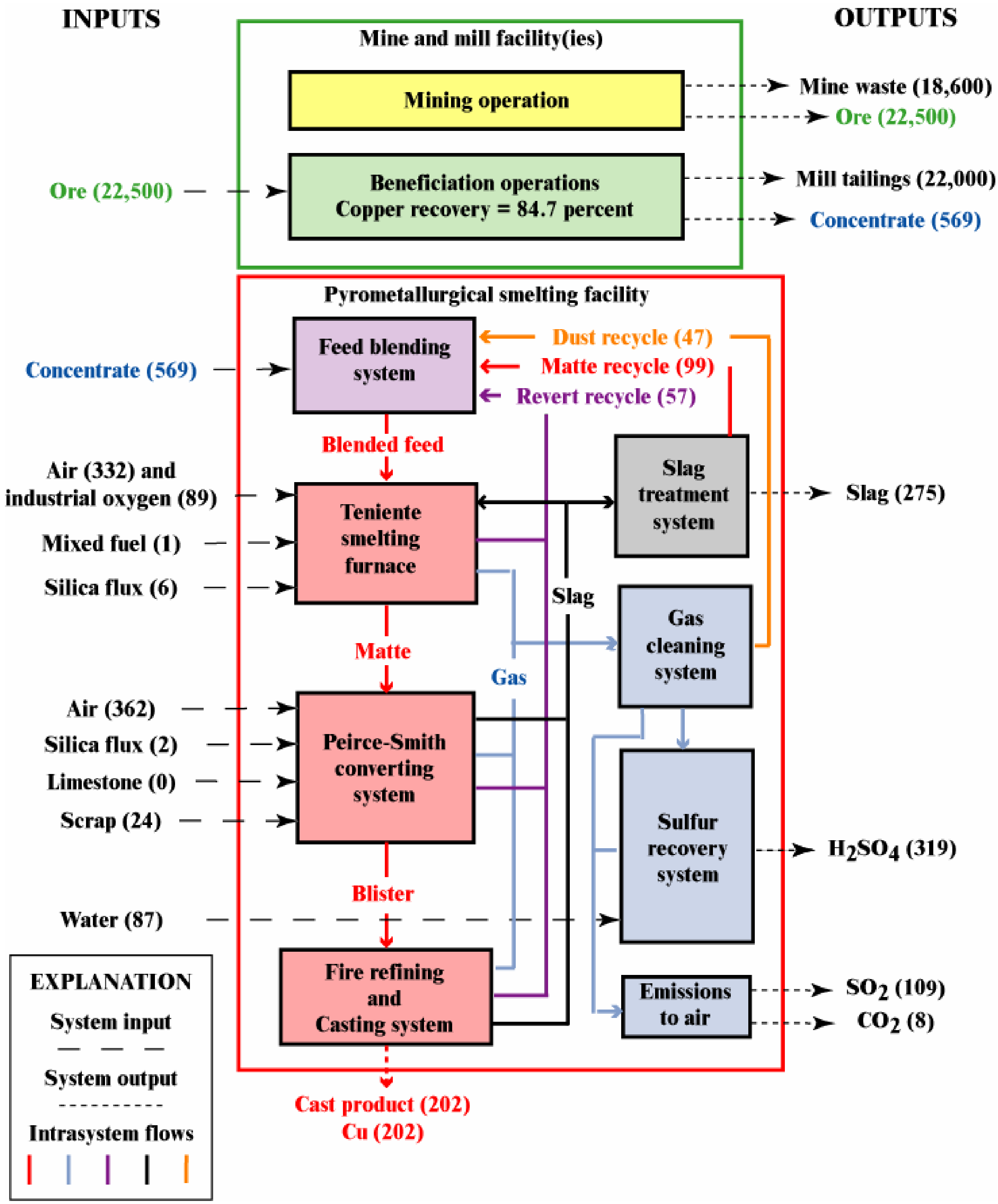

Figure 65. Gross flow diagram of the Potrerillos smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Ronnskar

Figures 66 and 67 show selected material flows for the Ronnskar smelter in Sweden. The smelter is located in Skelleftehamn, Sweden (lat 65.00°N., long 21.60°E.). It is owned by Boliden A.B. of Väsby, Sweden, and is operated by Boliden Mineral A.B. of Skelleftehamn, Sweden. It smelts Swedish concentrate and annual capacity is rated at 240,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Ronnskar smelter were extracted from the following sources: AME Mineral Economics, 2001; Biswas, and Davenport, 1980; Boliden A.B., 2002; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Mechanical Engineer's Handbook, 5th edition, 1951; and World Mine Cost Data Exchange 2004.

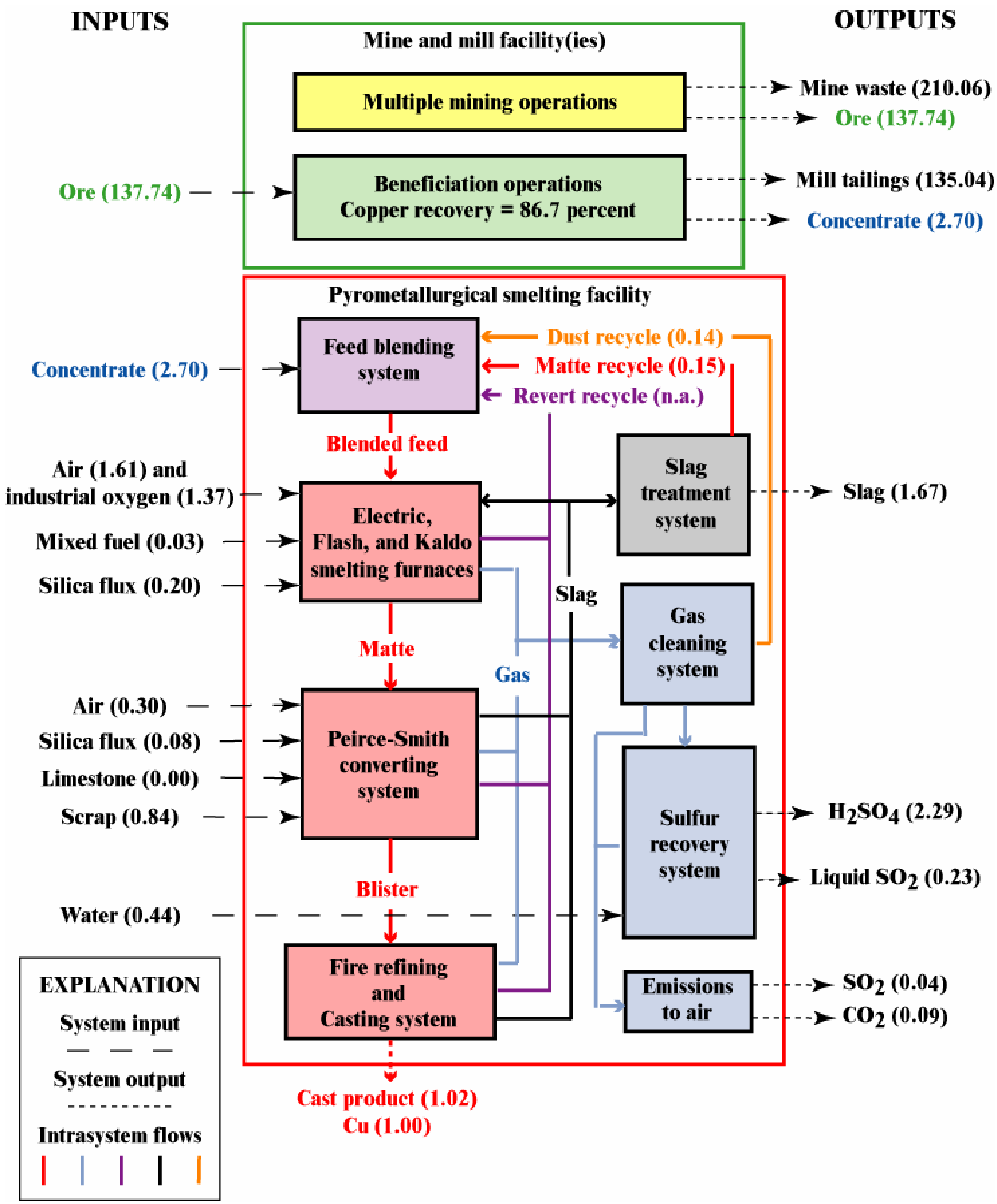

Figure 66. Copper-specific flow diagram of the Ronnskar smelter.

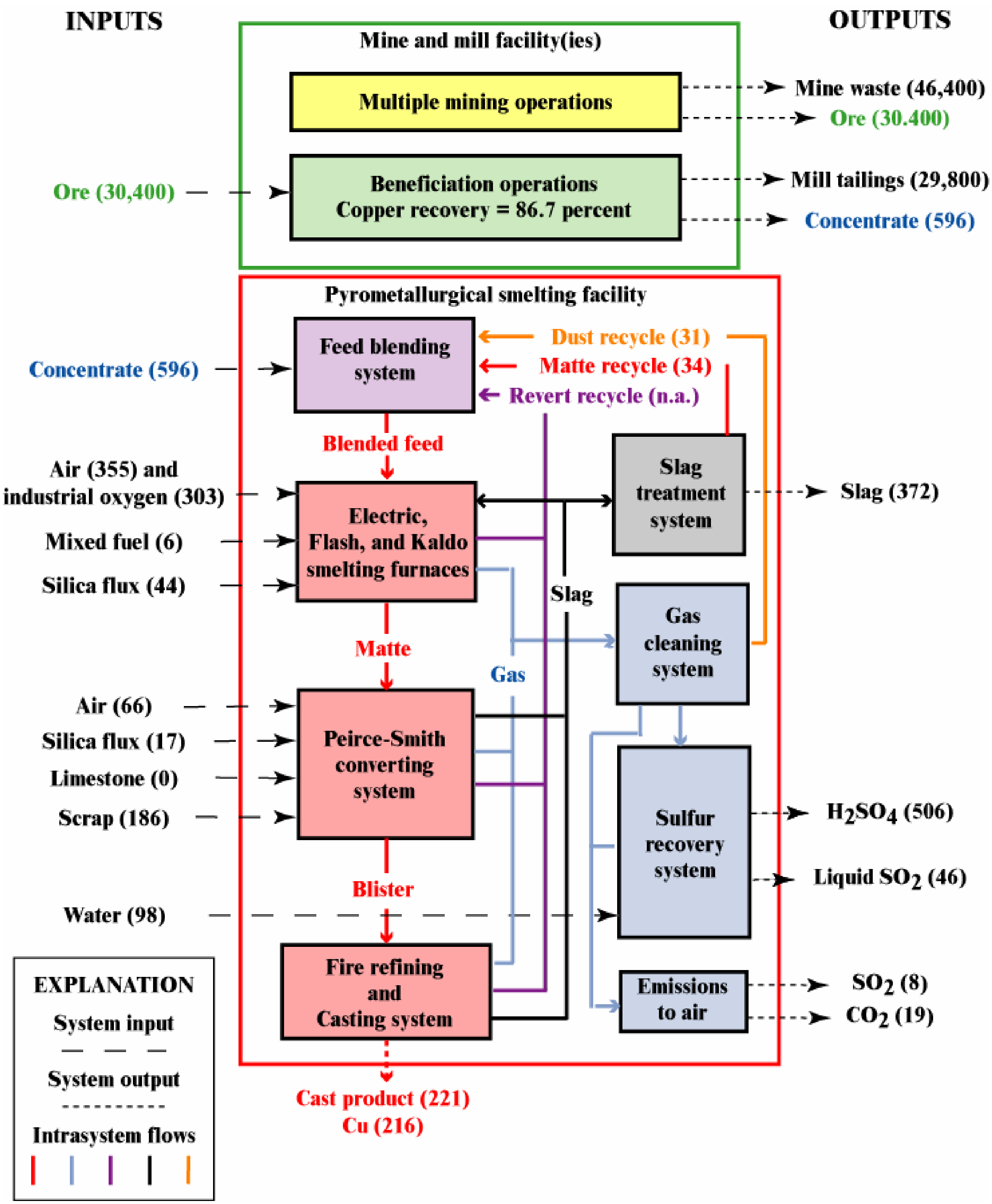

Figure 67. Gross flow diagram of the Ronnskar smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Saganoseki

Figures 66 and 67 show selected material flows for the Saganoseki smelter in Japan. The smelter is located in Oita (Kyushu), Japan (lat 33.24°N., long 131.87°E.). It is owned and operated by Nippon Mining & Metals Ltd. of Tokyo, Japan. It imports and smelts foreign concentrate and annual capacity is rated at 470,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Saganoseki smelter were extracted from the following sources: AME Mineral Economics 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Gossling, 2001; Hirai, Yasuda, and Hoshi, 1999; Mechanical Engineer's Handbook, 5th edition, 1951; MBendi, 2002; Mining Australia, 2003; Mining Technology, 2001; MMAJ, 1998; Nippon Mining and Metals, Ltd, 2001; Ogasawara, Kamegai, and Maedo, 2003; and World Mine Cost Data Exchange, 2004.

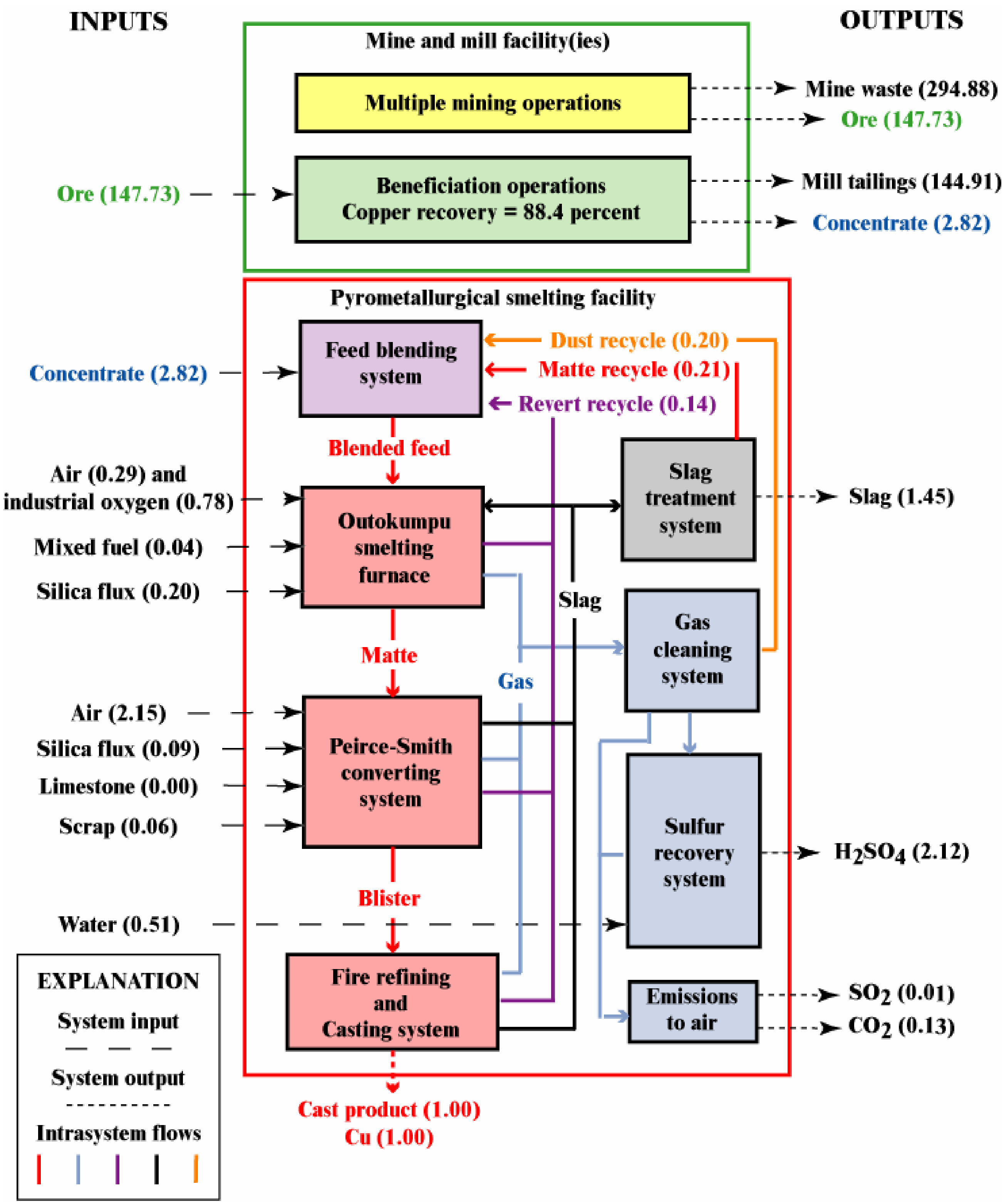

Figure 68. Copper-specific flow diagram of the Saganoseki smelter.

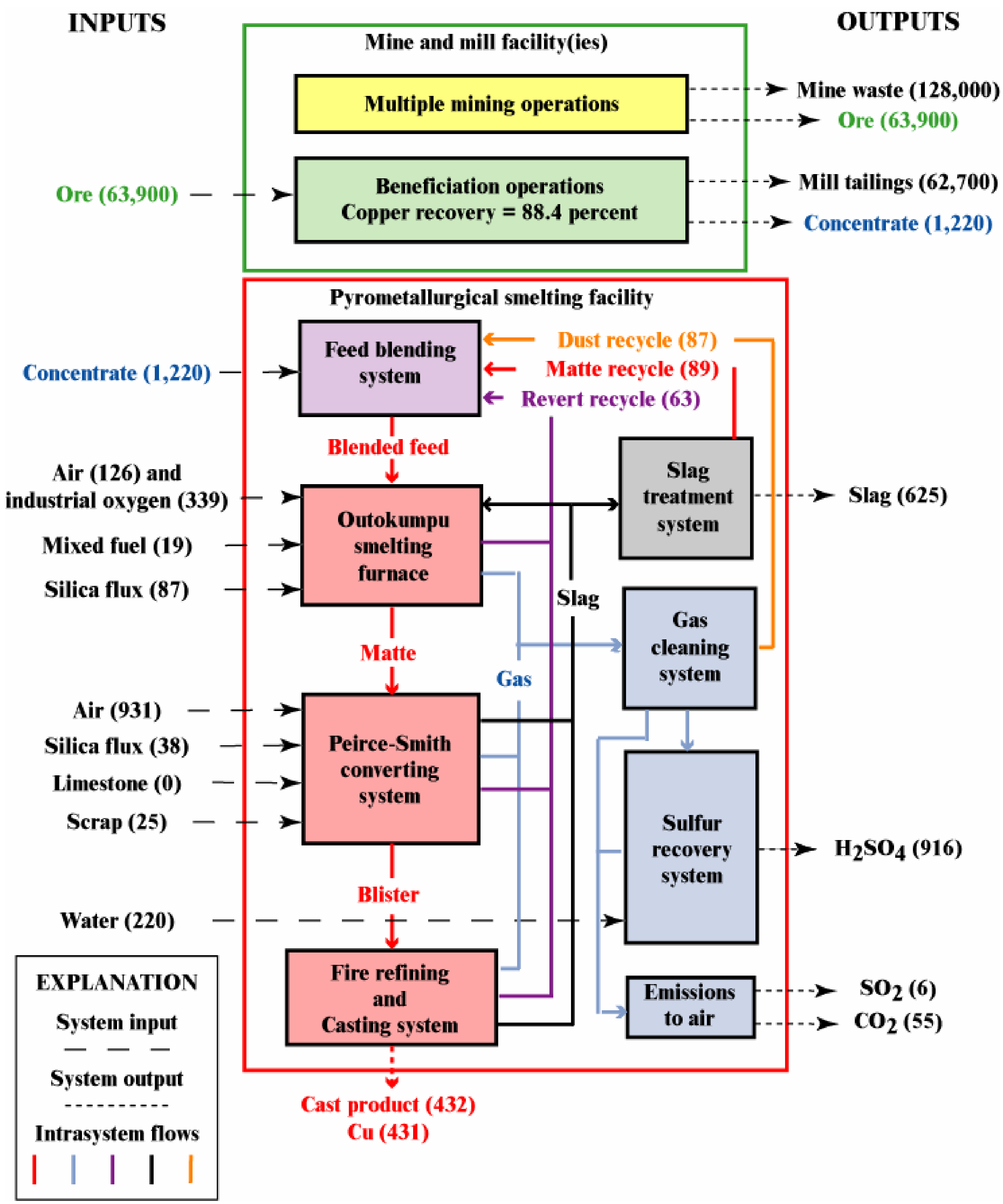

Figure 69. Gross flow diagram of the Saganoseki smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Tamano

Figures 70 and 71 show selected material flows for the Tamano smelter in Japan. The smelter is located in Okayama, Japan (lat 34.48°N., long 133.93°E.). It is owned and operated by a consortium that includes: Furukawa Electric Company Limited, Mitsui Mining & Smelting Co. Ltd., and Nittetsu Mining Co. Ltd., all of Tokyo, Japan. It imports and smelts foreign concentrates and annual capacity is rated at 263,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Tamano smelter were extracted from the following sources: AME Mineral Economics 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Maruyama, Furui, Hamamoto, and Sunamoto, 2003; Maruyama, Saito, and Kato, 1998; Mechanical Engineer's Handbook, 5th edition, 1951; Ojima, 2003; Shibata, Abe, and Uekawa, 1991; World Mine Cost Data Exchange, 2004; Wu, 2002.

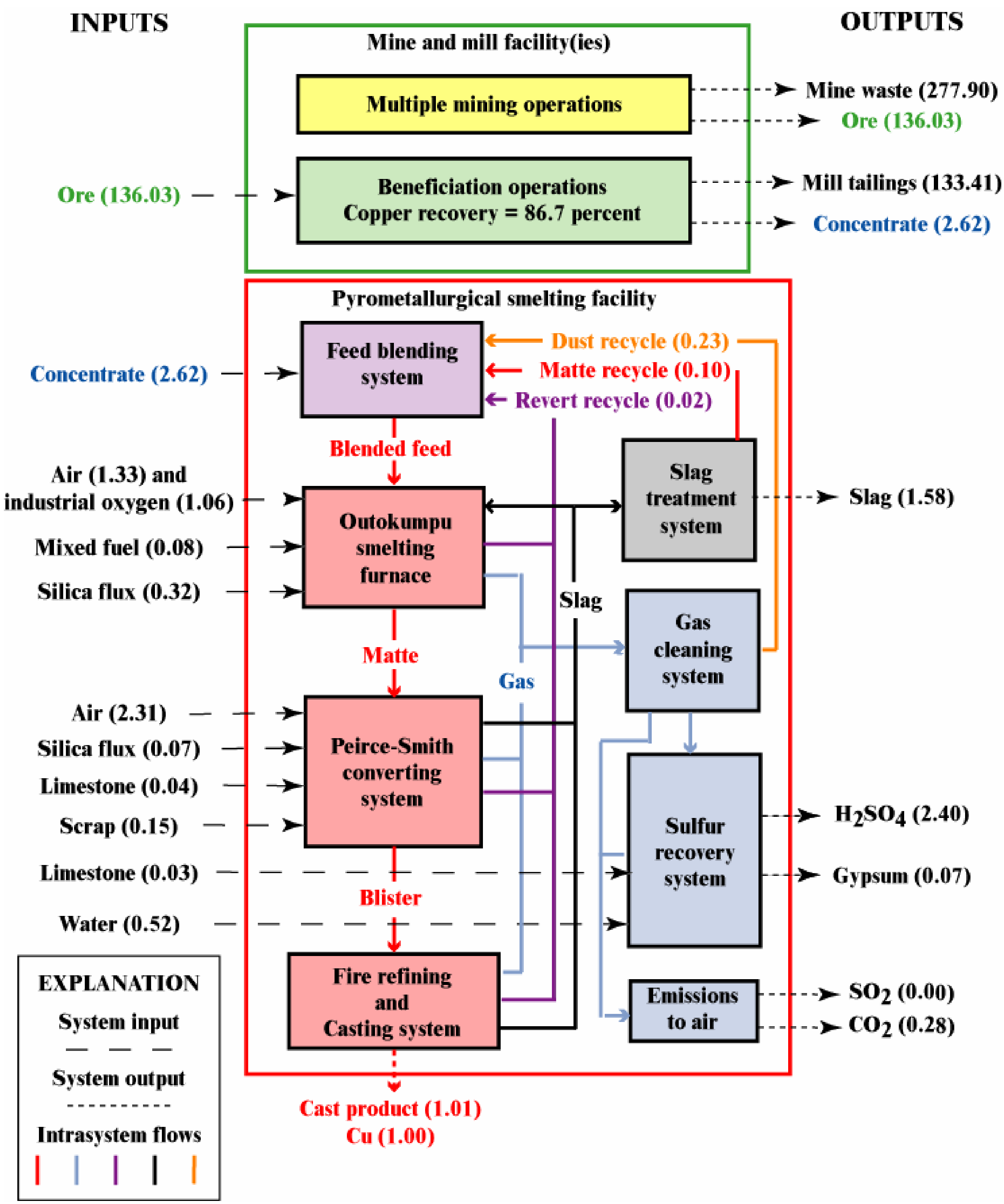

Figure 70. Copper-specific flow diagram of the Tamano smelter.

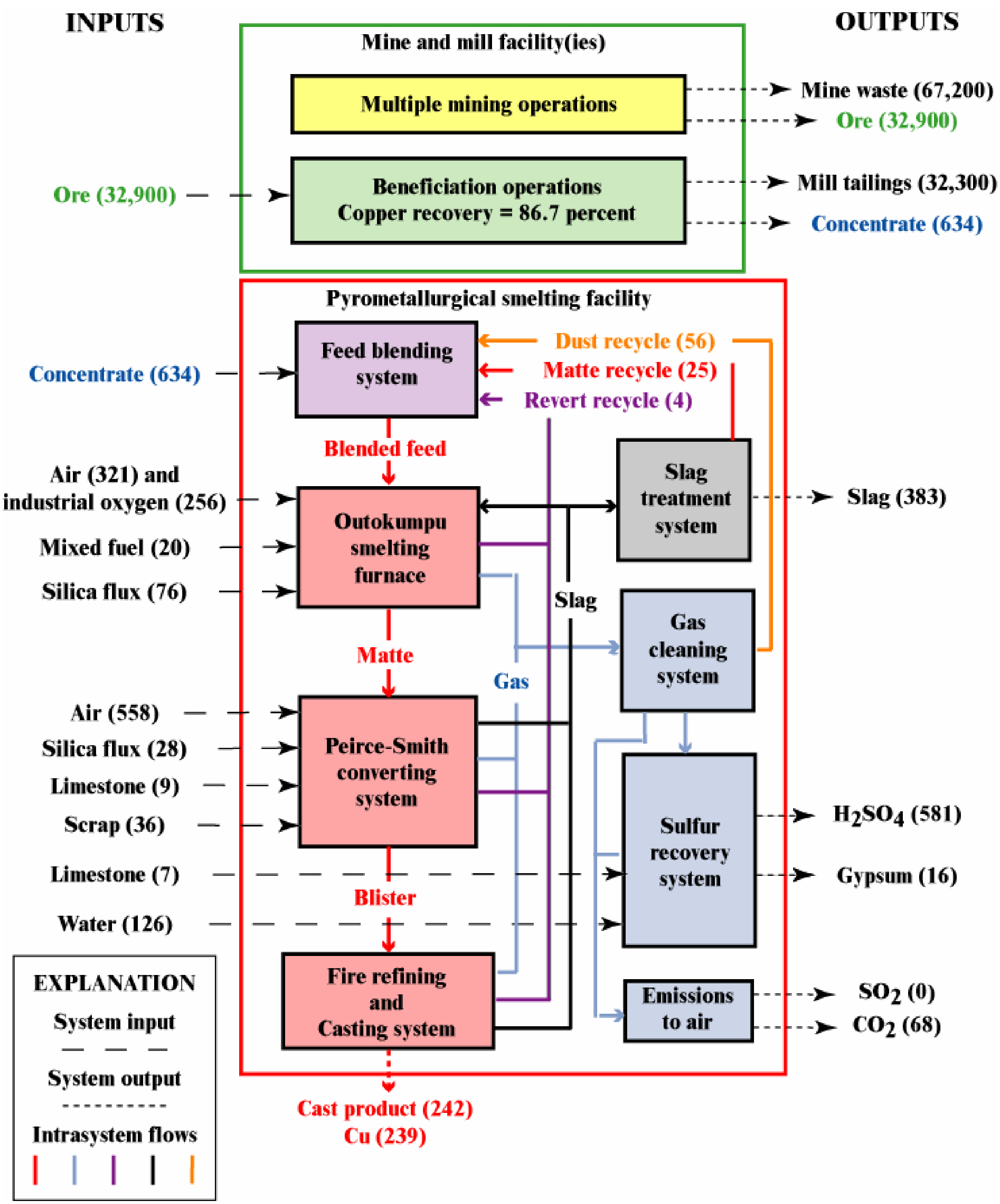

Figure 71. Gross flow diagram of the Tamano smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

Toyo (Besshi)

Figures 72 and 73 show selected material flows for the Toyo smelter in Japan. The smelter is located in Besshiyama, Japan (lat 33.88° N., long 133.32°E.). It is owned and operated by Sumitomo Metal Mining Co. Ltd. of Tokyo, Japan. It imports and smelts foreign concentrates and annual capacity is rated at 300,000 metric tons of cast copper products.

The data that populate the material balance, which underlies the graphics for the Toyo smelter were extracted from the following sources: AME Mineral Economics 2001; Biswas, and Davenport, 1980; Davenport, Jones, King, and Partelpoeg, 2001; Inami, Baba, Kurokawa, Nagai, and Knodo, 1991; Mechanical Engineer's Handbook, 5th edition, 1951; Ojima, 2003; Sumotomo Metals Mining, Inc., 2003; World Mine Cost Data Exchange, 2004; Wu, 2002.

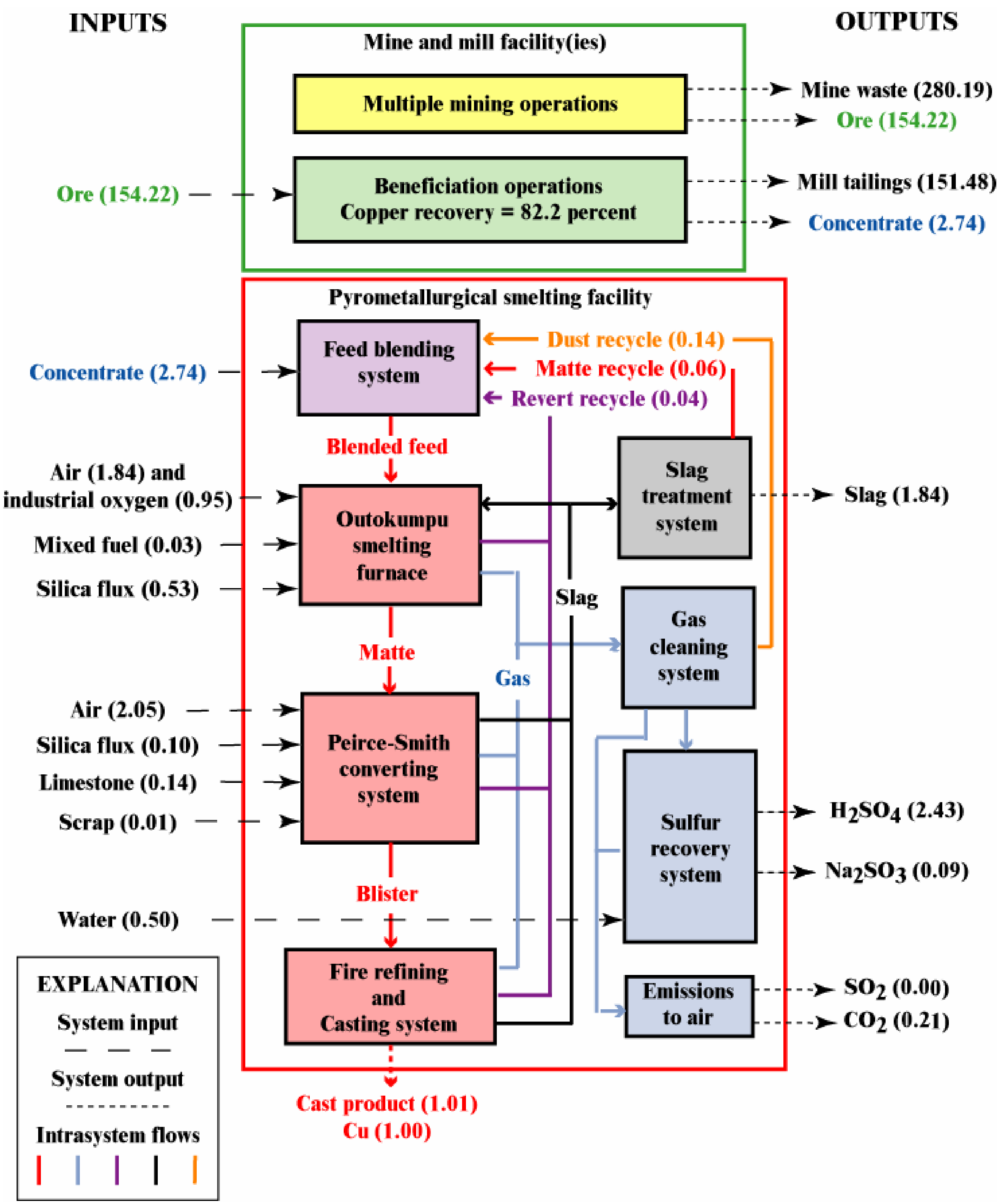

Figure 72. Copper-specific flow diagram of the Toyo smelter.

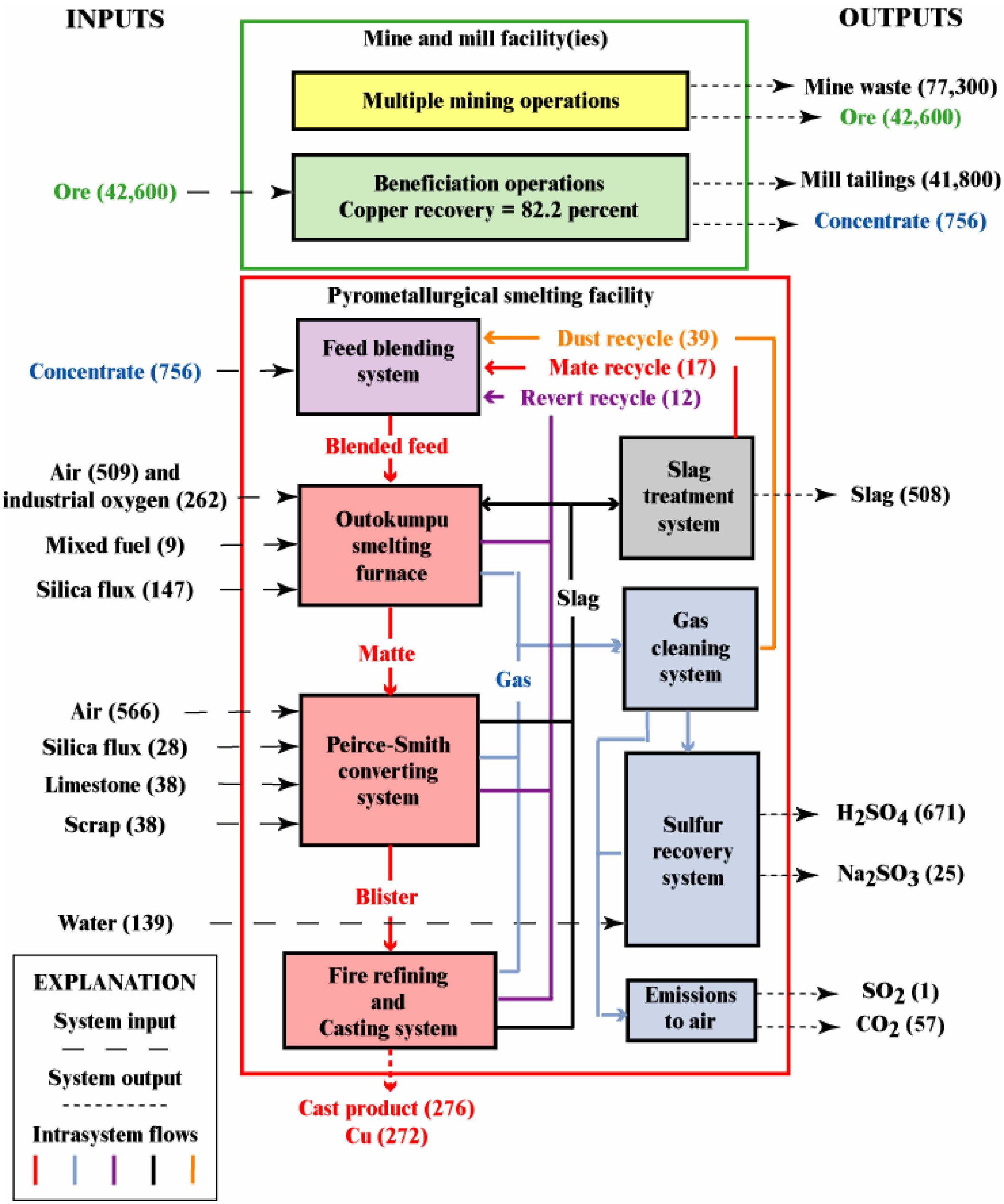

Figure 73. Gross flow diagram of the Toyo smelter.
[Gross flow estimates are thousand metric tons per year, based on the assumption of a 92-percent capacity utilization rate.]

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Appendix II

Glossary of Smelting Terminology

Introduction

This glossary of smelter terms is for the non-technical reader. It is not exhaustive and is not intended to be. The definitions in the glossary are the author's.

Terms

Acid plant

Acid plants take cleaned (particulates removed and recycled) gas streams that contain sulfur dioxide (SO_2) and convert the SO_2 to sulfur trioxide (SO_3) over a catalyst. The SO_3 is reacted with water to make sulfuric acid (H_2SO_4), which is diluted to 98, or 93 percent acid with additional water. Acid plants require rich (more than 5 percent) SO_2 streams to make acid. Lean (less than 5 percent) SO_2 streams can be treated to produce gypsum. Flash furnaces have become popular because rich SO_2 streams are generated, and the heat from sulfur oxidation contributes to energy conservation.

Anode

The anode is the negatively charged half of an electrolytic cell. In an electrolytic copper refinery, the anode is composed of 99.5+ percent copper material, which has been cast at the smelting facility into a specifically designed shape to fit easily into the cell, where they dissolve. The dissolved copper deposits on the cathode, which is 99.99 percent copper, and the residuals deposit on the bottom of the cell as slimes. The slimes are treated for their metal content, which is often very valuable (gold, osmium, platinum, rhenium, selenium, silver, tellurium, and others).

Arsenic trioxide

Arsenic is often associated with copper ores [enargite (Cu_3AsS_4)]. During copper smelting, arsenic partitions mainly to the gas phase with the SO_2. Arsenic is detrimental to the making of H_2SO_4 because it contaminates the catalyst used in the acid plant. Therefore, it is removed prior to the gas entering the acid plant. If the quantity is sufficiently large to generate an income stream then the arsenic is captured with a special technique to make arsenic trioxide.

Blister

Blister is the product of converting. With respect to copper, it is liquid copper saturated with residual sulfur and oxygen, which is soluble in copper at process temperatures. When blister cools, the oxygen solubility decreases, and the oxygen reacts with the residual sulfur to form SO_2 gas bubbles, which travel to the surface leaving the cooled copper with a blistered surface.

Cast (casting)

To cast is to pour liquid materials into molds of a specified shape where the material solidifies as the heat flows from the liquid to the mold.

Comminution

Comminution is the process of taking large fragments of materials, and reducing them into small particles through the application of mechanical energy, such as crushing and grinding. Smaller particles are more suited to flotation.

Converter (converting)

Liquid copper matte travels from the primary smelting furnace to the converter. Converting has generally meant another furnace, but new continuous converting systems have another chamber in the primary furnace where converting takes place. In the converting step, oxygen (carried by air) is added. The oxygen reacts with iron, and an iron-rich slag is formed, skimmed, and recycled. The oxygen also reacts with sulfur to form SO_2 gas. When the reactions have proceeded to the point that the liquid is principally copper sulfide (Cu_2S), the liquid is called white metal. After removing the slag, oxygen (carried by air) is again added to remove the remaining sulfur. When the reactions proceed further to the point where the liquid is principally copper, the liquid is called blister. Converting produces blister from matte.

Copper concentrate

Copper concentrate is the product of comminution and beneficiation of copper ores. Generally accomplished by sulfide flotation, the percentage of copper is increased from low levels (in ores) to much higher levels (in concentrates); for example, from 0.7 percent to 30 percent. Concentrate-to-ore ratios are about 0.02 to 0.10 in magnitude, which means that the greatest fraction of an ore is waste material, which is stored as tailings. Copper ores and concentrates made from them vary from mine to mine and mill to mill. A given smelter usually is charged with a blend of concentrates and sometimes other copper-bearing materials (primarily recycled dust and products of slag cleaning). The blend is referred to as "new metal-bearing materials."

Copper-specific

A copper-specific flow is the flow of material "m" in mass units of "m" per mass unit of copper contained in cast product from the smelting system (primary smelting, converting, and fire-refining).

Electrolytic process

An electrolytic process is one that passes electric current through an electrolyte (a chemical solution that conducts electricity) between electrodes (anode and cathode), such that positive ions travel to the cathode and negative ions travel to the anode. With respect to copper, the purpose is to purify copper metal to 99.99% copper, which is the internationally accepted standard. Purified copper has much better physical properties (for example conductivity and malleability) than less pure copper. Other valuable residuals, such as gold and silver, are recovered by processing electrolytic cell slimes in special recovery circuits. Slimes account for the difference between 99.7% copper in anodes and 99.99% copper in cathodes. These are outputs of the electrolytic process.

Fire refining (anode) furnace

The surface of blister copper is not sufficiently flat to make good anodes for electro refining, therefore blister is fire refined in anode furnaces prior to casting into anode forms. Additional oxygen is added to remove the residual sulfur as SO_2 gas, and then some form of hydrocarbon is added to remove the residual oxygen. The molten copper, which is about 99.7 percent pure copper, is cast into the shape of an anode for further processing at an electrolytic refinery, which upgrades the copper from 99.7 percent to 99.99 percent copper.

Flotation

Minerals that contain sulfur are amenable to treatment with organic chemicals, which adhere preferentially to the sulfides in water-based liquid slurries. The adhered particles float on the slurry mixture and are recovered as concentrate. The unwanted materials sink and are collected. The collected material (tailings) is transported to the tailings holding area.

Gas handling system

Gas is a significant product of copper smelting. Off-gas constituents may include hydrocarbon combustion products (carbon dioxide, water vapor), metal-oxide gases, metal sulfate dust, nitrogen, and SO_2. Dust and some metal-oxide gases are recovered from these gases by means of baghouses, venturi scrubbers, electrostatic precipitators, and mechanical cyclones. Sulfur dioxide is usually recovered in acid plants and/or other sulfur-fixing technology. Carbon dioxide, nitrogen, water vapor, and other unrecovered materials compose the largest portion of emissions.

Gypsum (calcium sulfate)

Many of the gas streams associated with the various steps of copper smelting contain only low concentrations of SO_2. In such cases, H_2SO_4 is too expensive to make because of insufficient sulfur. Where environmental controls are strictly enforced, some low percentage SO_2 gas streams are collected and processed in alkali scrubbers. One effective technology is to capture the SO_2 in wet scrubbers where a mixture of water and calcium carbonate ($CaCO_3$), or lime (CaO), reacts with the SO_2 to form calcium sulfite ($CaSO_3$), which can be further oxidized to gypsum ($CaSO_4$), which is sometimes a salable, if not always profitable, product. Gypsum is the principal component of wallboard and must meet purity specifications for that use. Where environmental controls are few or unenforced, other low percentage SO_2 gas streams are discharged directly to the atmosphere.

Matte

In a stepwise process to produce metal, matte is the product of the first pyrometallurgical step. For example, copper concentrate that contains perhaps 33 percent copper is processed in a primary furnace to produce a liquid matte that contains between about 50 and 75 percent copper, depending upon the primary process selected. This product is sent to another step (converting) to upgrade it further. Mattes are sulfide mixtures because the other materials (nonsulfides) have separated into a slag, which is removed. A copper matte is a stoichiometric mixture of Cu_2S and iron sulfide (FeS).

Mercury

Mercury is a toxic metal often found in small quantities in sulfide ore deposits. During copper smelting, residual mercury partitions mainly to the gas phase. Mercury is likely to be found in acid plant residues. If the amount of mercury is high enough to warrant recovery, it can be recovered with a retorting process. Otherwise, it is likely to be treated as a hazardous waste.

Oleum

Oleum is a corrosive solution of SO_3 in H_2SO_4 and is another possible byproduct of copper smelting. Oleum is a chemical precursor in the chemicals industry.

Primary smelting furnace

The primary smelting furnace receives (wet/dry) concentrate, and/or scrap, and other materials, adds heat by means of electricity or chemical oxidation, and produces copper matte and slag. Subcategories include the following:

- Flash furnaces: Use air and industrial oxygen to oxidize fuels and/or sulfur and iron in the concentrate, to generate sufficient heat to melt the products. The concentrate is delivered to the furnace as a coarse powder.
- Electric furnaces: Use electrical energy delivered through electrodes to melt the concentrate charge and infiltrated air to oxidize the sulfur and iron in the concentrate.
- Reverberatory furnaces: Use organic fuels and oxygen to melt the charge and oxygen to oxidize labile (most easily reacted) sulfur and a small percentage of the iron sulfide in the concentrate.
- Blast (shaft) furnaces: Packs agglomerated copper-bearing materials and carbon-bearing reductants into a shaft and introduces oxygen-bearing gases through tuyeres (opening) at the bottom of the furnace, which percolate upwards through the charge.

Reducing agent (reductant)

In the context of fire refining, a reducing agent is a substance that chemically reacts with the excess oxygen in solution in the charged copper blister. The reducing agents used in this process are generally hydrocarbons; such as natural gas or wood. In slag cleaning operations, coal is added to slag to "reduce" Fe^{+3} to Fe^{+2}; that is, from insoluble magnetite (Fe_3O_4) to soluble iron oxide (FeO).

Revert

Revert is material generated during the entire smelting-to-anode process. It consists of spills from the various batch segments of the process and material frozen in transfer ladles and furnaces that is generally collected during refractory relines. The material approximates the chemistry of matte and is returned to the process during the actual smelting stage. For the purpose of calculating the mass balance for any given smelter, the author assumed that total revert input for the year is equal to total output for the year.

Slag

Slag is a mixture of metallic oxides, which is liquid at process temperatures, and solidifies upon cooling. Slag generally contains unwanted materials and elements from the smelting process. In copper smelting, the slag contains virtually all of the iron separated from the copper in the concentrate. When copper concentrates, which typically contain roughly one-third each of copper, iron, and sulfur, are smelted, the generated slag quantities are greater than the copper produced. Iron oxides must be associated with either silica or CaO and other oxides in order for them to separate properly from the melt. Slag is an immiscible liquid that floats on top of the metal phase. It is poured off the furnace melt to be further treated or solidified. Some kinds of slag are suitable for use as construction material; others are stored, awaiting a possible future use. In copper smelting, converter slag contains high amounts of copper and is returned to the primary smelting furnace to recover as much as is practicable. A high-copper slag might be treated in an electric slag-cleaning furnace or ground and returned to a flotation mill. When either occurs, the portion of the slag that is recovered and recycled very closely approximates the chemistry of the matte generated by the smelting step. This recycled material is what is referred to in this study as "matte recycle" and is sometimes a relatively large quantity. The economic decision for routing slag for treatment is related to the reducing capability of the primary smelting furnace and the quality (magnetite concentration, less than 10 percent) and variability of converter slag.

Sulfide ores

Minerals where sulfur is the principle anion. Typical sulfide ore minerals include bornite (Cu_5FeS_4), chalcocite (Cu_2S), chalcopyrite ($CuFeS_2$), covellite (CuS), and enargite (Cu_3AsS_4).

Sulfur

Sulfur is an element that readily combines with certain metals to form sulfide minerals and ores. Principal metals that form sulfides include copper, iron, lead, molybdenum, nickel, and zinc. When the metal is desired, sulfur must be removed. The principal way to accomplish this is to chemically react it with oxygen to form SO_2 gas. Gas streams emitted to the environment that contain SO_2 are potentially toxic and when combined with atmospheric water vapor produce sulfurous acid (H_2SO_3), a potentially toxic substance.

Sulfuric acid

Sulfuric acid is a principle co-product of sulfide ore smelting. It is a valuable co-product when it can be used, for example, as a leaching agent in copper hydrometallurgy. It is also one of the fundamental substances used in the chemical industry. It is relatively costly to manufacture from metallurgical gas streams and contains more impurities than would chemical-grade acid made directly from sulfur. Environmental legislation is a primary motivation for the production of metallurgical co-product H_2SO_4.

Sulfur dioxide

Sulfur dioxide is a gas formed by copper smelting when oxygen is added to the melted concentrate. If not recovered, it is emitted to the air, where it combines with water vapor to form H_2SO_3, which is potentially harmful to the environment. Sulfur dioxide is treated in acid plants and/or other sulfur-fixing processes to prevent it from going into the atmosphere. The acid product is either sold or used locally to recover copper from waste and low-grade oxide ores