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WORCRA SMELTING-CONVERTING, A NEW APPROACH TO CONTINUOUS DIRECT COPPER PRODUCTION[1]

by

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Australia

[1] The views and opinions expressed in this paper are those of the author and do not necessarily reflect the views of the Secretariat of UNIDO.

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We regret that some of the pages in the microfiche copy of this report may not be up to the proper legibility standards, even though the best possible copy was used for preparing the master fiche.

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SUMMARY

After reviewing briefly other processes used for copper extraction, the paper outlines a new approach to the continuous direct production of metal from sulphide concentrates in which the operations of smelting, matte conversion and slag clean-up are combined in one furnace but in separate, communicating zones or branches. The closely integrated unit operations include concentrate drying, bath smelting, dispersed phase refining, a type of hot solvent extraction and slag conditioning and settling.

The WORCRA process differs from established "jet" or "suspension" smelting processes (which in themselves are continuous) in that, (a) it produces metal, not matte; (b) most of the exothermic reactions are generated and continued within the liquid bath (hence the description "bath smelting"); (c) the bath in the smelting and converting zones is turbulent and continously flowing, and (d) the slag is caused to move generally countercurrent to matte in the converting branch, then to pass through the smelting zone and to emerge finally into a separate relatively quiescent slag conditioning and settling branch from which it is tapped continuously.

As the slag moves countercurrent to matte, into and through the slag conditioning and settling branch, its oxygen activity and its copper content are progressively lowered and on tapping it has a composition not basically different from conventional reverberatory slags. Even in small pilot furnace trials, copper-in-slag values as low as 0.3 per cent have been achieved over extended periods of continuous operation. Dust losses are also low. In full scale WORCRA plants overall recoveries of copper at least as high as the best modern reverberatory practice are expected. The metal produced may contain between 98.8 and 99.7 per cent copper depending on the amount of air (oxygen) lanced into the metal "reservoir" at the end of the converting branch.

Apart from slag and metal, the furnace produces continuously a high SO_2 tenor gas well suited for acid production. Sulphur dioxide levels may be within the range 9 to 12 per cent when straight air is used for lancing. When oxygen-enriched air is used in the converting branch the SO_2 tenor is proportionately higher. Over the past four years the method has been tested in various shaped pilot furnaces at the works of C.R.A.'s subsidiary, Sulphide Corporation Pty.Limited, at Cockle Creek, New South Wales, Australia. The method has been proved with four different concentrates fed at rates up to seven tons per day. Preparations are in hand to scale up operations to the semi-commercial phase with feed rates between 70 and 80 tons per day. This development is taking place at the works of The Electrolytic Refining and Smelting Company of Australia Ltd., Port Kembla, New South Wales.

CONTENTS

	Page
Introduction	6
Some innovations of the last quarter century	6
Incentives to develop continuous smelting processes	8
Some excursions into continuous copper smelting or converting	9
Principles of WORCRA bath smelting-converting	10
Some furnace shapes	13
Some pilot plant results	13
Likely comparative economics	16
Patents	18
Acknowledgements	18
References	19-23

Figures

1	Diagrammic representation of: (a) Roasting-reverberatory-converter smelting; (b) Sintering-blast furnace-converter smelting; (c) WORCRA continuous smelting-converting	24
2	Relationship of different zones in WORCRA continuous smelting-converting furnace. Diagrammatic longitudinal sectional elevation	24
3	Diagrammatic representation of plan view of one straight line form of WORCRA smelting-converting furnace	25
4	Ternary diagram showing change in composition of matte as it is blown progressively to copper in a WORCRA smelting-converting furnace	25
5	Idealised spacial diagram illustrating changes in composition within the converter branch of a WORCRA copper smelting furnace	26
6	Diagrammatic representation of vertical section through one type of WORCRA copper smelter-converter	26

Figures (cont.)

		Page
7	U-shaped WORCRA continuous smelting-converting furnace	27
8	Showing how a reverberatory furnace could be modified to form a straight line WORCRA smelting-converting furnace	27
9	Photograph of feed and smelter zone end of a U-shaped WORCRA copper smelting pilot plant at Cockle Creek, New South Wales	28
10	Photograph of the tapping end of U-shaped WORCRA pilot furnace at Cockle Creek	28

Tables

		Page
1	Composition of concentrates smelted in WORCRA pilot furnace at Cockle Creek	14
2	Some WORCRA slag compositions in pilot plant trials	15
3	Possible comparative capital costs of copper smelters	17
4	Possible comparative treatment costs	18

Introduction

1. The principal methods of extracting copper from its ores and concentrates have undergone little basic change, except in scale and degree of mechanization, during the whole of this present century. By far the greatest tonnage of (sulphide) concentrates (raw or pre-roasted) is smelted to matte in reverberatory furnaces (pioneered by Welsh metallurgists over a hundred and fifty years ago (1)1/) and the matte is separately air blown to blister copper in barrel type (Peirce-Smith) converters. Both operations are carried out batchwise with ladle transfer of matte from the reverberatory furnace to the converter and a reverse transfer of "revert" copper-bearing slag.

2. A smaller though significant tonnage of matte has been produced in blast furnaces and electric furnaces and the matte converted to blister copper in either barrel type or upright (Great Falls) converters. Another approach which had its origins in an earlier century (at Rio Tinto, Spain, for example) is acid leaching of heaps of ore followed by precipitation (cementation) of the copper from the leach liquors on scrap iron and steel. It is not intended to attempt a complete review of all the methods which have been tried for copper production but in the next section brief mention will be made of some of the significant innovations in copper extraction metallurgy over the past twenty years or so.

Some innovations of the last quarter century

3. All three of the classical branches of extractive metallurgy - pyrometallurgy, hydrometallurgy and electrometallurgy - are well represented in the fields of copper production and there have been innovations in each branch during the past twenty-five years. A comprehensive bibliography of the extensive literature on copper production up to 1960 is included in the book, Extractive Metallurgy of Copper, Nickel and Cobalt, edited by Paul Queneau (2). More recently other relevant and complementary reviews have been made by Toguri, Themelis and Jennings (3), Bailey (4) and Kuxmann (5), all of whom, incidentally, refer to the possible advantages of continuous processing.

4. In the following listing of some of the more significant process innovations there is no implication of relative importance in the order of presentation; the developments have been arranged more or less in the order in which papers of substance describing them appeared in the technical press. As the writer has more ready access to papers appearing in Western journals it is likely that some important innovations which have occurred in the Union of Soviet Socialist Republics and Eastern countries have been overlooked.

1/ Numbers in parentheses refer to references.

(a) The development of large electric furnaces for matte production, stemming largely from Norway and Sweden (6, 7, 8);

(b) The introduction of mechanical tuyere punchers on barrel type convertors by large American companies (9, 10, 11);

(c) The first successful (vertical) "jet" flash smelting to matte, at Outokumpu, Finland, resulting from the pioneering work of Bryk and his colleagues (12);

(d) The development of techniques of pressure leaching by Forward and his colleagues (13) in Canada and by others (14, 15, 16) and the successful commercial application of these processes along with gaseous reduction of metals from solution (17, 18, 19) at Sherritt Gordon, Canada;

(e) The successful commercial application of oxygen flash (suspension) smelting by INCO staff at its Copper Cliff plant in Canada (20);

(f) The development of "cyclone" suspension smelting to produce matte and volatile fumes, stemming from the pioneering work of A. Lange (21) in East Germany and of Dr. A.V. Tonkonogii and his colleagues (22) and others (23, 24) in the Union of Soviet Socialist Republics;

(g) Improvements in the efficiency of blast furnace smelting to matte accompanied by the possibility of SO_2 recovery by applications of the new feeding concepts of Dr. R. Momoda and his colleagues (25) of Sumitomo Metal Mining Co. Ltd. in Japan;

(h) The speeding up of converter operation by the use of oxygen enrichment of the air blast, a concept advanced by the Russian Tonakanov (26) back in the early nineteen thirties but not economically viable until cheap tonnage oxygen became available in the nineteen fifties and then tried on a commercial scale first in Russia (27) later in the United States (28) and elsewhere;

(i) The development by Nippon Mining Co. Ltd. at their Hitachi smelter in Japan of direct smelting in a converter using oxygen enriched air (29). This, of course, is a logical extension of (h) and is also a derivative of concepts which were explored before the advent of cheap tonnage oxygen. (See for example Newton & Wilson (30)). The high copper-content slags are treated in a slag dressing (grinding-flotation) plant for copper recovery;

(j) Improvements in the techniques of roasting (particularly by the application of fluidization methods), leaching and electrowinning and their application in combination as the "R.L.E." process (31,32);

(k) The recognition in the late nineteen forties and early nineteen fifties by metallurgists and biologists in many countries of the role of bacteria in the leaching of sulphides and the considerable increase in the scale and efficiency of heap leaching particularly as applied to ores too low in grade to be treated by conventional milling and flotation (33, 34, 35, 36);

(l) The development of greatly improved methods of recovery of copper from leach liquors by precipitation on particulate iron or steel (37, 38, 39);

(m) The application of solvent extraction to the recovery of copper (as well as many other metals) from leach liquors (40, 41);

(n) The successful application to refractory oxidised copper ores of the principle of "segregation" (42). Of particular interest in this connection is the TORCO process developed by metallurgists of Anglo-American Corporation (43);

(o) The development at Hoboken in Belgium of the "siphon" converter to avoid the dilution of gases from the converting operation and also to minimize atmospheric pollution (44).

5. There are many in the industry who feel that despite the several new process innovations of the last two decades, the combination of reverberatory smelting and separate matte conversion in barrel type converters remains the most efficient large tonnage method of extraction of copper, that is, at annual productions over 30,000 tons. There are others who have felt for some years that because of the relatively high fuel requirements of reverberatory furnaces (4.5 to 5.5 million BTU per ton for wet charging or 2.3 to 3.5 million BTU per ton with charges made up mostly of hot roasted concentrates) and also the high capital cost of the big furnaces and the materials handling systems inherent in the batch-wise conveying of matte, copper and slags (including "revert" slag), the time is ripe for some processing of concentrates right through to blister copper. (Continuous operations are, of course, the rule rather than the exception in hydrometallurgical operations).

Incentives to develop continuous smelting processes

6. The author has for several years been advocating the advantages of closely integrated sequences of continuous operations in pyrometallurgy (45, 46). The basic principles governing the several WORCRA processes (for continuous smelting-refining of metals such as copper, nickel, lead, tin, iron) were outlined in a paper (47) presented to the 1967 Symposium "Advances in Extractive Metallurgy" organized by The Institution of Mining and Metallurgy, London. It will be appropriate to repeat here some of the arguments and concepts presented in that earlier communication and grateful acknowledgement is made to the Institution for permission to do that and also to reproduce some of the illustrations. Incentives for the evolution of highly

integrated continuous copper smelting-converting operations in which maximum use is made of gravity flow of liquid mattes, metal and slag include:

(a) Reduction in capital costs for any given productive capacity arising from the smaller furnaces needed to handle the continuously flowing reactants and products, simplified materials handling (with virtual elimination of big cranes and ladles), the smaller foundations, buildings and site requirements generally;

(b) Lower operating costs resulting from reduced fuel consumption, less recirculating load (in such forms as "revert" slag, flue dust and internal metal scrap), lower maintenance costs, less skilled labour and the opportunity for straightforward metallurgical controls;

(c) Ability to secure high credit for recovery of sulphur (or other valuable volatile components) eliminated continuously during the smelting;

(d) Reduction in size of economically viable production plants.

It is felt that all of these conditions are met in the WORCRA process to be described. Before dealing specifically with this new development it is proper that mention be made of other work trending in the same direction.

Some excursions into continuous copper smelting or converting

7. In the last few years several groups around the world have reported plans or preliminary pilot furnace trials aimed at the development of continuous smelting or converting operations. The various "jet" or "suspension" smelting operations (12, 20, 21) like the blast furnace and electric furnace are continuous matte producers, but insofar as the matte is tapped intermittently into ladles they are all treated as if they were batch processes.

8. In their work on "cyclone" smelting, however, the Russian metallurgists such as Tonkonogii (22), Penzimonzh (23) and Onajew (24) have made clear their aim to develop truly continuous operations presumably with the intention ultimately of linking the matte producing stage with a continuous converting process. This latter concept has been under investigation by their fellow countrymen, Diomidovski and Shalygin (48) and others. In this field of continuous converting, notable contributions to both theory and experiment have been made by Holeczy, Schnalek and Schmiedl (49) in Czechoslovakia. Both the Russian and Czech workers have chosen top jetting methods for the converting operation. Brittingham (50) has proposed a method whereby the principles inherent in the Outokumpu and Copper Cliff "flash" smelters might be adapted and extended for the continuous production of white metal (Cu_2S) and copper.

9. In a sense the Japanese Hitachi process (29) is moving in the direction of a semi-continuous operation but, without considerable alterations in both furnace design and operation it would seem difficult to achieve truly continuous tapping of copper and slag from the converter. It is appropriate to mention here that a collaborative agreement exists between Conzinc Riotinto of Australia Limited and Noranda Mines Limited (of Canada) which company is also developing a truly continuous method for direct smelting-converting of copper concentrates. The Noranda process involves the use of a tilting furnace somewhat like an elongated Peirce-Smith converter. The converting and slag clean-up gases are blown in via tuyeres; copper is to be tapped from a central region and slag at the end remote from charging (51).

Principles of WORCRA bath smelting-converting

10. The objective of the several WORCRA smelting-converting operations is to seek to maximize energy conservation by a high degree of integration of individually efficient continuous unit operations and at the same time to turn to advantage the finely particulate nature of concentrates, presenting as they do a high surface area for reactions with gases, liquids and other solids. In their fully developed form the WORCRA concepts seek to combine in one furnace with separate but communicating zones or branches (a) a continuous melting-smelting stage; (b) a continuous converting stage, and (c) continuous slag conditioning and settling.

11. Figure 1 depicts diagrammatically the differences between the WORCRA approach to copper extraction and the conventional batch smelting processes using either reverberatory furnace and converter(s) or blast furnace and converter(s) with ladle transfers of liquid matte and slags. Figures 2 and 3 show diagrammatically the spacial relationship of the different zones in the WORCRA furnaces. "Zonalisation" in a horizontal plane is a feature of all of the furnace shapes.

12. The WORCRA operations are to be distinguished from established "jet", "cyclone" or "suspension" smelting processes in that

(a) They produce metal rather than matte, directly from concentrates;

(b) Most of the exothermic reactions are generated and continued within the liquid bath, hence the description "bath smelting";

(c) The bath in the smelting and converting zones is turbulent and continually flowing;

(d) Slag is caused to move generally countercurrent to matte or metal, through the converting zone and then mixed with the matte in the smelting zone to emerge finally into a separate relatively quiescent slag conditioning and settling zone. (This is analogous to the mixer-settler systems of the chemical engineer).

13. Unlike conventional reverberatory smelting, where reactions between slag and matte or slag and metal have to take place predominantly at a single (horizontal) interface, the WORCRA processes seek by the method of injecting particulate solids and gases into the bath to maintain within the smelting and converting zones the maximum area of surfaces for reactions in the liquid phases. The converting zone particularly is maintained in a state of vigorous turbulence with the air jets thoroughly stirring and dispersing slag and matte. It is appropriate therefore to describe the converting reactions as dispersed phase refining. Furthermore, the fact that the slag is caused to move generally countercurrent to matte enables a type of continuous hot solvent extraction to be achieved. Unwanted non-volatile components in the matte, particularly iron, are continuously being transferred (after oxidation) to the slag and under conditions where mass action and temperature effects are most favourable for the transfers. Conversely, valuable copper in the slag can be caused to revert to the matte phase by interaction with ferrous sulphide in the matte.

14. In the separate but connected slag conditioning and settling zone or branch, appropriate conditions may be maintained or additions made to achieve both optimal separation and settling of entrained matte and its continuous return to the smelting zone via a backward sloping hearth. It is also possible to alter the composition of the slag, free of any risk of upsetting the metallurgical balance in the smelting and converting zone, to fit it better for easier disposal or for some profitable end use, that is, for iron recovery, glass production, the making of abrasion resistant tiles or bricks etc. The progressive changes which occur in the slowly flowing matte stream as it is sequentially lanced to white metal (Cu_2S) and finally to metallic copper are indicated in a general way in the ternary diagram of figure 4.

15. They are represented in another way in the idealised longitudinal section of the converter branch shown in figure 5. Significant differences in specific gravity between slag, matte, white metal and copper aid in the separations. The increased depth at the copper tapping end also facilitates separation in that region.

16. Contrary to classical theory and batchwise converting practice, the production of copper takes place (continuously) under a flowing slag, which itself becomes charged with a mixture of prills of matte, white metal and copper. Near the copper taphole end the slag is naturally highly oxidized but as it moves back countercurrent to the matte stream its magnetite and copper contents are progressively lowered. Further chemical reduction and "stripping" of copper occurs as the hot slag enters

the circulatory smelting zone and comes into contact with (as well as transferring some of its heat to) freshly melting matte with much lower copper content and a high sulphur activity.

17. The denudation with respect to copper continues as the slag flows slowly through the slag-matte separation (slag settling) branch. Here reducing additives, such as pyrite, coal or other carbonaceous materials, can be gently stirred into the slag to effect a lowering of copper values to figures comparable to or better than are obtainable in reverberatory practice. The heat in outgoing furnace gases continuously emitted can be used for a variety of purposes, for example, drying and preheating ingoing fluxes and concentrates, preheating converter air, steam raising and for power generation. The degree to which ingoing solids or air are preheated by heat exchange from furnace gases will need to be determined in relation to the capital and operating costs of the heat exchange equipment and the cost of coal, oil or gas fuel which would be required to do the same work in the smelter in question.

18. Many sulphide concentrates can be smelted in WORCRA furnaces in a near autogenous manner and this is certainly so if a degree of oxygen-enrichment is used in the converter air. Indeed, if considerable enrichment takes place the excess heat generated in the converter branch may permit, even necessitate, the addition of "coolants" in such forms as cement copper, "dope", oxidised ore and possibly scrap.

19. Smooth and uniform smelting conditions and low dust carry-over are achieved by introducing the dry concentrates with appropriate momentum into the turbulent and flowing bath of slag and matte. The maintenance of circulatory flow ensures that there is no cold or "sluggish" region and it also contributes to the desirable thorough mixing of hot slag flowing back from the converter branch and freshly melted (highly reducing) matte. As pointed out before, these conditions facilitate reduction of both the magnetite and copper contents in the slag.

20. A secret of success is to maintain steady state conditions in the smelting and converting zones with appropriate temperature and composition gradients. The furnaces are so designed as to facilitate the maintenance of these gradients, not only in the horizontal plane but in a vertical plane as well, and particularly at the deeper copper tapping end.. There the vertical temperature differential may be of the order of 150°C. The nearer the bottom temperature approaches the freezing point of copper the lower will be the sulphur content in the metal flowing out into the metal reservoir via the channel at the deep end of the converting branch. (See left hand end of furnace in figure 6).

21. Naturally, however, the temperature of the copper continuously collecting in the deep end of this zone must be maintained high enough to ensure that the metal will flow continuously. This means that the metal flowing into the reservoir contains between 0.8 and 1.0 per cent sulphur. The sulphur level can be reduced to any desired value by jetting an oxidising gas or flame into the metal in the reservoir (shown at the extreme left side of figure 6).

Some furnace shapes

22. A wide variation in furnace shapes and sizes is possible to suit the smelter layout, type of concentrates being smelted and the required throughput of the plant. The simplest shape is the straight line form shown in figure 3 where the converting branch and slag settling branch connect on opposite sides with the smelting zone. The latter may be a circular "bowl" as shown but other smelter zone shapes with non-circular flow patterns for slag and matte may be employed.

23. This straight line type can be made either stationary, like a reverberatory furnace, or tiltable like a Peirce-Smith converter. In the latter case the converting air can be injected through a sequence of tuyeres, much like a conventional converter, but in the fixed type the oxygen-containing gases are preferably introduced through lances which may enter the furnace through either the roof or the walls. The manner and direction of lancing should be such as (a) to assist the desired flow of slag, and (b) to minimize refractory erosion.

24. In stationary furnaces the latter can be virtually eliminated (as in conventional reverberatory practice) by one or more of (a) banking the walls with concentrates, (b) banking the walls with siliceous flux, and (c) use of fluid-cooling in the brickwork at the slag line.

25. Furnaces with an L-shape, a U-shape and even with a complete annulus for the smelting region have been tested with satisfactory results. The U-shaped form depicted diagrammatically in figure 7 has some advantages, particularly in respect of site utilization and was selected for the extensive pilot plant trials at the works of C.R.A. subsidiary, Sulphide Corporation Pty.Limited, Cockle Creek, New South Wales. This shape (with some modifications) is also being used for the semi-commercial WORCRA plant now being built at the works of The Electrolytic Refining and Smelting Co. Ltd., Port Kembla, New South Wales, for further evaluation.

26. Figure 8 shows one of the possible ways in which a reverberatory furnace could be converted into a straight line WORCRA smelting-converting furnace to produce copper metal continuously. The projections delineating the central smelting zone can be made of refractory brickwork banked with concentrates, flux or other additive as may be appropriate.

Some pilot plant results

27. Small pilot plant appraisals of the WORCRA continuous smelting-converting concepts commenced early in 1963 at the works of Sulphide Corporation Pty. Limited,

Cockle Creek. Over the past four and one half years much metallurgical data have been collected relating to the continuous smelting of ores of iron, tin, copper, lead and nickel. Insofar as copper is concerned, the process has been extensively tested in a U-shaped pilot furnace (shown in figures 7, 9 and 10) in eleven campaigns of up to seven weeks of continuous operation and with feed rates up to seven tons per day. The process has been demonstrated to work satisfactorily with a range of Australian concentrates from Mount Morgan (Queensland), Mt. Lyell (Tasmania), Rum Jungle (Northern Territory) and Cobar (New South Wales). Typical analyses of these concentrates are listed in table 1.

Table 1

Composition of concentrates smelted in WORCRA pilot furnace at Cockle Creek (percentages)

Component	Mt. Morgan	Mt. Lyell	Rum Jungle	Cobar
Copper	22.4	25.1	22.2	18.5
Iron	30.2	31.3	19.5	28.6
Sulphur	34.4	33.4	24.6	32.2
SiO_2	6.5	4.0	14.0	4.7
Al_2O_3	0.4	0.9	3.4	0.7
CaO	0.7	0.3	0.[illegible]	0.1
Zinc	0.3	0.1	0.1	5.5
Lead	0.02	0.1	0.03	2.7
Graphite	-	-	3.8	-

28. With each of these Australian concentrates it has been possible to produce copper within the range 98.8 to 99.7 per cent metal, depending on the degree of extra oxidation of residual sulphur which is effected in the metal reservoir at the end of the converting branch. Recovery of gold and silver is high. Conversely, the elimination of elements like lead, bismuth, antimony and arsenic seems to be better than in conventional batch processes. This is probably because the air-lancing starts while the sulphur activity in the bath is still quite high and elements with volatile lower valency sulphides begin coming off in the smelter zone and continue to be eliminated in the converter zone.

29. In the case of the Cobar concentrates with relatively high values of zinc and lead, quite high eliminations of both of these elements into the furnace gases has been achieved in the Cockle Creek pilot furnace. The WORCRA process could well join the "suspension" smelting processes in showing advantages for the treatment of con-

centrates containing valuable volatilisable components. In the semi-commercial plant now being built at Port Kembla to treat (mainly) Cobar concentrates, provision will be made to recover zinc (and lead) fume from the furnace gases.

30. While the elimination of elements such as zinc, lead and bismuth is high, dust carry-over has been found to be low, between 2 and 5 per cent of the total concentrate feed, the higher figure being for extremely fine concentrates. As more experience has been gained with the process, copper losses in slag have been progressively reduced until in the last campaign (No.11) values below 0.4 per cent were achieved over extended periods of continuous operation. Indeed, over several shifts values between 0.25 and 0.30 per cent were attained. With production furnaces, having longer converting and slag settling branches, there seems to be good prospects that copper-in-slag values as low as 0.20 per cent may be achieved. The U-shaped pilot furnace has operated satisfactorily with a wide range of slag compositions. Table 2 summarises the ranges which have been found to give good performance and low copper losses.

Table 2

Some WORCRA slag compositions in pilot plant trials

	Range %	Preferred %
SiO_2	32 - 40	38
FeO	38 - 54	50
CaO	1 - 8	6
Al_2O_3	nil- 5	1
Other	up to 10	5

31. There is every indication that the process can be applied to the full range of concentrates which can be smelted in reverberatory furnaces. There is no fundamental reason why this should not be so for the WORCRA chemistry is basically the same as that in conventional batch processes. The smelter bowl serves functions similar to the reverberatory furnace while the converting branch serves functions similar to the batch convertor. The great advantage thermally of the WORCRA process is that the excess heat liberated in the bath by the oxidation of iron and sulphur (in the matte) is immediately available to help melt incoming concentrates and flux.

32. The higher the sulphur and iron contents of the concentrate feed the more nearly autogenous the WORCRA process becomes, even with ordinary air injected in the converter branch. As pointed out earlier, the operations can be made completely

autogenous by enriching the converter air with a little oxygen. It has been found that the air pressures for lancing need be little if any higher than for conventional converting. Furthermore, "oxygen efficiency" in the pilot plant lancing operations has practically always been well over 100 per cent, probably due to some supplemental air inspirated through inspection ports in the walls of the pilot furnaces.

33. As pointed out earlier, SO_2 levels are likely to be in the range 9 to 12 per cent with normal concentrates and relatively small in-leakages of air. With appropriate draft control, conditions around the furnace are quite pleasant for operators and the fact that the gas offtake is integral with the furnace means that there is little or no dilution of the furnace gases going off to the acid plant via boilers, or other heat exchangers, electrostatic precipitators or bag house, as the case may be. There is potential for high recovery of the sulphur values in the concentrates.

Likely comparative economics

34. It is too early in the development of the WORCRA processes to give firm estimates of capital and operating costs. However, reasonably reliable predictions of the economics of the new continuous copper smelting operation can now be made on the basis of (a) four years experience with the pilot plants at Cockle Creek; (b) the known cost of the semi-commercial plant (with a potential capacity of about 6,000 tons of copper per year) now being built at Port Kembla; (c) knowledge available within the Rio Tinto-Zinc Corporation group of companies, which includes close association with the Rio Tinto Co., Spain (with its recently modernized blast furnace), Palabora Mining Co. Ltd., South Africa, (with its highly mechanised reverberatory-converter complex) and other copper producing companies.

35. It seems that when compared with reverberatory and blast furnace practice, the WORCRA process holds the potential for significant savings in both capital and operating costs over a wide tonnage range. As a one-furnace, one-gas, one-slag, continuous operation, there is potential for considerable savings in smelter site requirements, foundations and buildings. Labour and maintenance costs should also be significantly lower than for conventional batch smelters.

36. The indications are that with normal air used for lancing the fuel requirements of WORCRA furnaces will be between 20 per cent and 40 per cent that of the equivalent reverberatory furnace practice. This considerable saving in fuel is possible because (a) most of the heat of oxidation of sulphur and iron is achieved where it is most needed, in the bath; and (b) the heat generated in the converting stage supplements the heat available in the smelting stage.

37. Each smelter will need to determine the degree to which it will pay to preheat air and ingoing solid feed materials by heat exchange from outgoing furnace gases. In many cases it may pay to generate steam with the continuously emitted hot gases and to use some supplemental oil or gas for pre-drying of concentrates.

38. Although, as already mentioned, "oxygen efficiency" in lancing is expected to be high, the power requirements for a WORCRA smelter may be a little greater than for an equivalent capacity batch smelter, because the lancing of the matte begins at somewhat higher sulphur levels. (The likely bonus from this is better elimination of impurities such as As, Bi, Pb, Sb and Zn).

39. Perhaps one of the most significant attractions in WORCRA smelting today, when greater attention must be given to sulphur utilization and reduction of atmospheric pollution, is the potential which the process has for high overall sulphur dioxide recovery; well over 90 per cent of the sulphur in the concentrates is expected to be recoverable as acid. Table 3 summarises some comparative estimates which have been made of likely capital costs (modern reverberatory-converter complex taken as 100) at two levels of production, namely, 30,000 tons per year (tpa) and 80,000 tpa.

Table 3

Possible comparative capital costs of copper smelters

(excluding off-site and acid plant capital)

Copper production tpa	30,000	80,000
Reverberatory	100	100
Modern blast furnace	90	110
Flash smelting	92	93
WORCRA process	85	85

40. A feature which the above table does not make apparent is that the Momoda blast furnace, modern flash smelting and the WORCRA processes should all be economically viable at tonnages much below 30,000 tpa, which is often regarded as the lowest level at which it would be economic to install a reverberatory-converter complex. Treatment costs seem likely to be even more favourable to the WORCRA process. The anticipated comparative treatment charges calculated for Australian conditions with no sulphur recovered are listed in table 4.

Table 4

Possible comparative treatment costs

Copper production tpa	30,000	80,000
Reverberatory	100	100
Blast furnace	130	150
Flash smelting	110	105
WORCRA process	72	75

41. The potential for high recovery of sulphur dioxide from the "one gas", continuous WORCRA furnaces should put this process even further ahead of conventional reverberatory and blast furnace operations. Indeed, within Australia, at the 80,000 tpa copper production level, and with sulphur credited at $(Aust.)35 per metric ton, but with costs (including capital charges) of the necessary gas cleaning deducted, smelting could result in an overall credit of between $(Aust.)13 and $(Aust.)15 per ton of copper produced (= approximately $US15 to $US18). These evaluations, incidentally, are based on new smelting plants. The economics of converting existing smelters to the WORCRA process have not yet been fully examined. As implied in the brief comment related to figure 8, these could be quite attractive.

Patents

42. The WORCRA processes for continuous smelting and converting are protected by patents and patent applications in forty countries of the world.

Acknowledgements

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51. Canadian Patent No. 758,020 assigned to Noranda Mines Ltd. also Personal Communications.

Figure 1

Diagrammatic representation of (a) Roasting-reverberatory-converter smelting; (b) Sintering-blast furnace-converter smelting, and (c) WORCRA continuous smelting-converting.

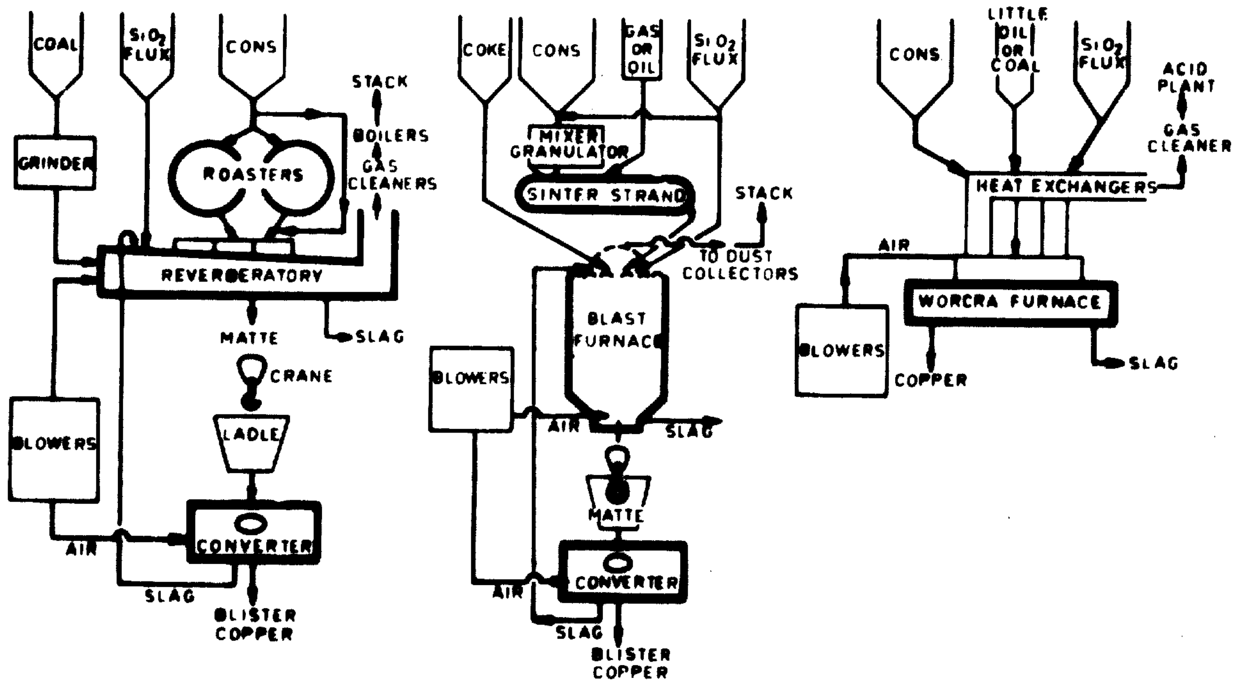

Figure 2

Relationship of different zones in WORCRA continuous smelting-converting furnace. Diagrammatic longitudinal sectional elevation.

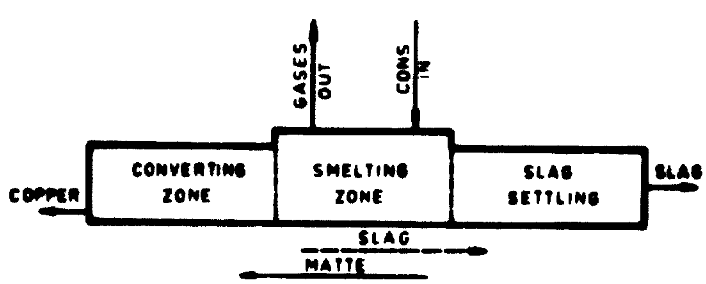

Figure 3

Diagrammatic representation of plan view of one straight line form of WORCRA smelting-converting furnace.

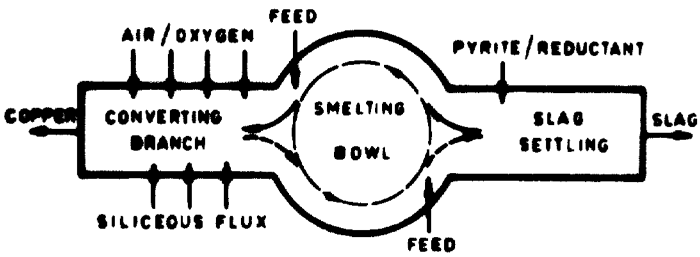

Figure 4

Ternary diagram showing change in composition of matte as it is blown progressively to copper in a WORCRA smelting-converting furnace

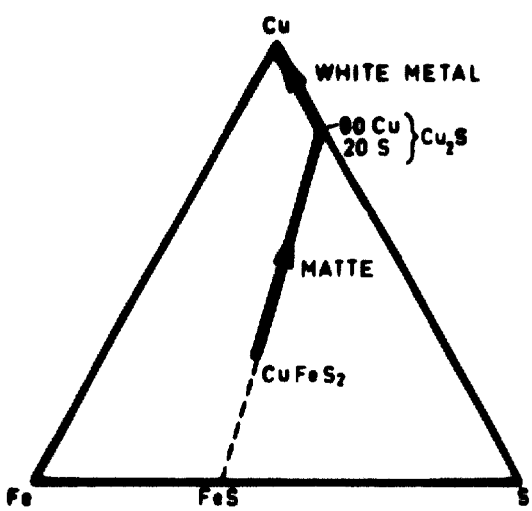

Figure 5

Idealised spacial diagram illustrating changes in composition within the converter branch of a WORCRA copper smelting furnace.

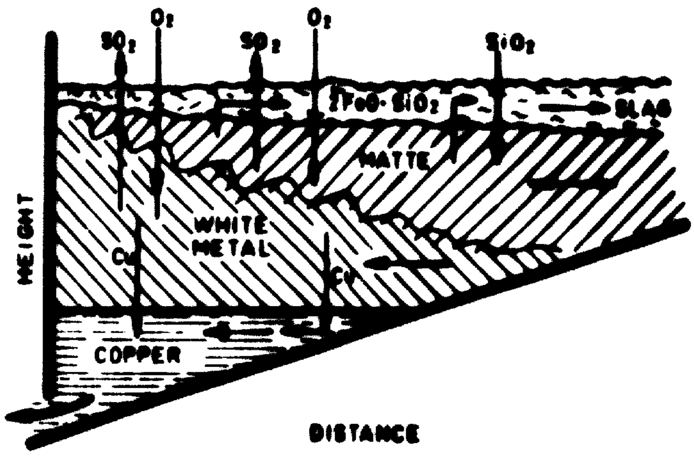

Figure 6

Diagrammatic representation of vertical section through one type of WORCRA copper smelter-converter.

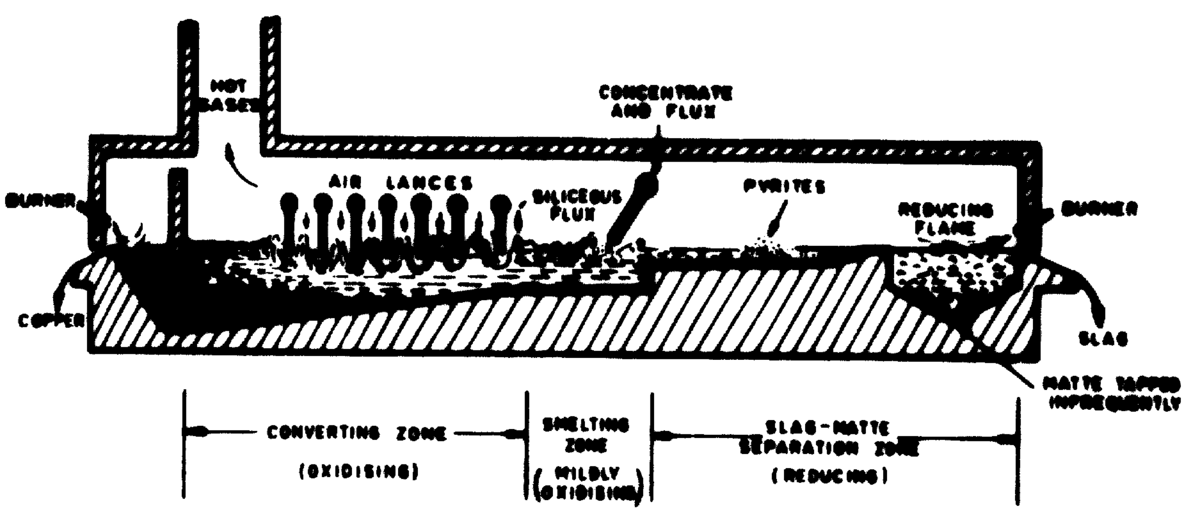

Figure 7

U-shaped NORANDA continuous smelting-converting furnace

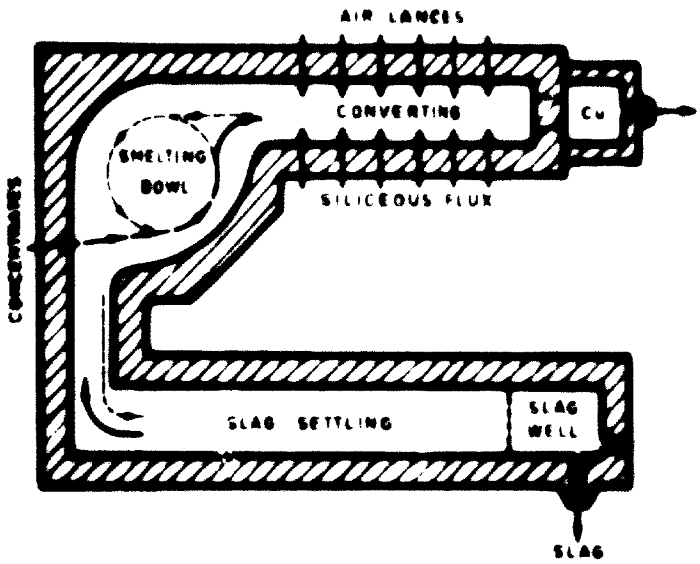

Figure 8

Showing how a reverberatory furnace could be modified to form a straight line NORANDA smelting-converting furnace.

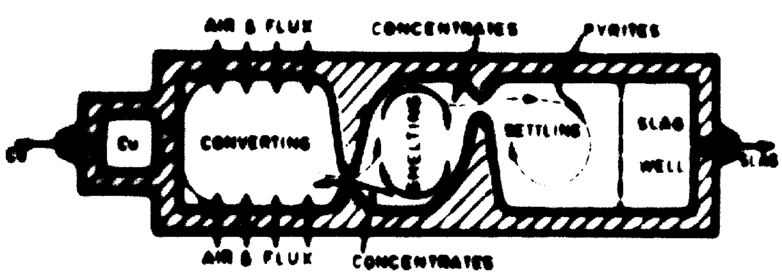

Figure 9

Feed and smelter zone end of a U-shaped WORCRA copper smelting pilot plant at Cockle Creek, New South Wales. Shows hoses and lances by which air-entrained concentrates, fluxes and a little fuel are fed into the furnace.

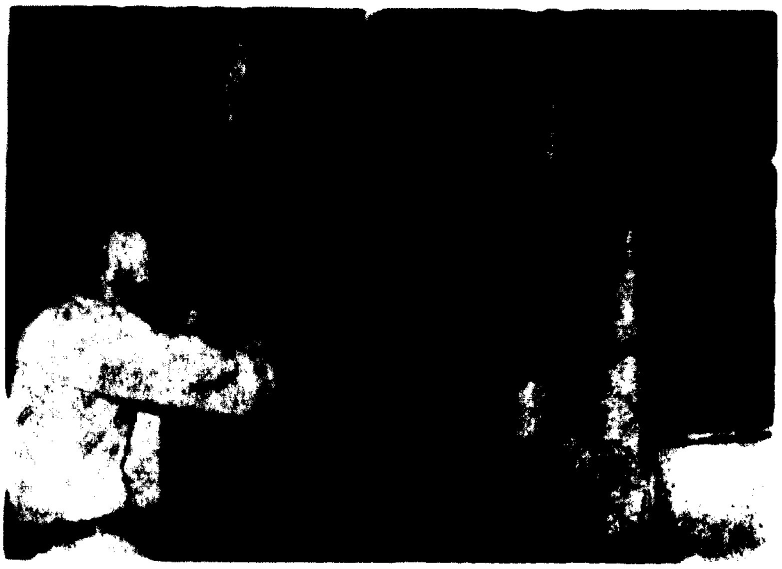

Figure 10

Tapping end of U-shaped WORCRA pilot furnace at Cockle Creek. Low copper content slag is flowing steadily in a thin stream into a granulating launder. The rate of copper production is barely sufficient to permit truly continuous tapping so it has to be spooned out at frequent intervals and cast into conveniently shaped "bricks".

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