The 2004 Extraction and Processing Lecture
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Converting an Idea into a Worldwide Business Commercializing Smelting Technology

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Pyrometallurgy is an ancient art which has defined significant stages of human development. Today, new opportunities for improvements in the economic, environmental, and workplace costs of metal production continue to provide challenges for the profession and industry. Top-submerged lancing technology for the high-temperature processing of a range of metals and wastes is an example that has been taken up by many companies around the world. The furnace system now marketed under the names of Ausmelt and Isasmelt was, in the early stage of its 33 years of development, known as Sirosmelt. The voyage from the original idea through theoretical, laboratory, pilot plant, and commercial developments to establishment of a worldwide business has been both stimulating and rewarding.

I. STATUS OF TOP-SUBMERGED LANCING TECHNOLOGY

THE Top-Submerged Lancing (TSL) system was developed over more than 30 years by CSIRO (where it was called High-Temperature Submerged Combustion, then Sirosmelt), Ausmelt, and Mount Isa Mines (Isasmelt). Isasmelt now forms part of Xstrata Technology. At present, there are in operation or under design and construction 35 furnaces in 23 locations in 14 countries. Capacities of units range from less than 10,000 tons per annum (tpa) to more than 800,000 tpa of feed, with a total processing capacity of about 6 million tpa. The reactor is used for mainstream smelters or for by-product or waste treatment in production of tin, copper, nickel, lead, platinum-group metals, zinc, and aluminum. The furnace is tightly sealed and feeds require little or no pretreatment, which makes the system particularly suitable for improving the environmental performance of smelting and for the recycle of hazardous wastes. Plants in Korea, Japan, and Australia process metallurgical waste material to recover values and produce useable waste products, and in Seoul a plant is being built to process municipal waste incinerator ash.

Ausmelt has adapted the TSL approach to a new process called AusIron for smelting iron ore and wastes to produce iron. A demonstration plant in South Australia has been operated successfully at an iron production rate equivalent to 15,000 tpa, and commercial developments are being considered.

II. OUTLINE OF THE TSL SMELTING SYSTEM

The TSL system is a bath smelting technology which employs an upright cylindrical furnace with a central lance injecting fuel air and oxygen into a slag bath. The lance can be operated under oxidizing, neutral, or reducing conditions

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The Extraction and Processing Lecturer Award honors an outstanding scientific leader in the field of nonferrous extractive metallurgy with an invitation to present a comprehensive lecture at the TMS Annual Meeting.

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to provide for control of the slag chemistry at the lance tip and gas-rise region of the slag bath. The slags used for nonferrous processing applications generally are solutions of the oxides of iron, calcium, silicon, and aluminum. The composition is controlled primarily to remove the unwanted components in the feed to the furnace, with fluxing employed to provide the required viscosity at the chosen temperature of operation.

Figure 1 illustrates the features of the Ausmelt TSL technology. In operation, the lance is splash-coated with a solidified layer of slag before lowering into the slag bath and then is operated with a submergence of about 100 to 500 mm in a bath of 800 to 2000 mm depth, depending on the requirements of the application. Feed material is usually passed through a sealed port in the top of the furnace. The system can accept lump, fine, dry, or wet feed, so that feed preparation requirements are minimal.

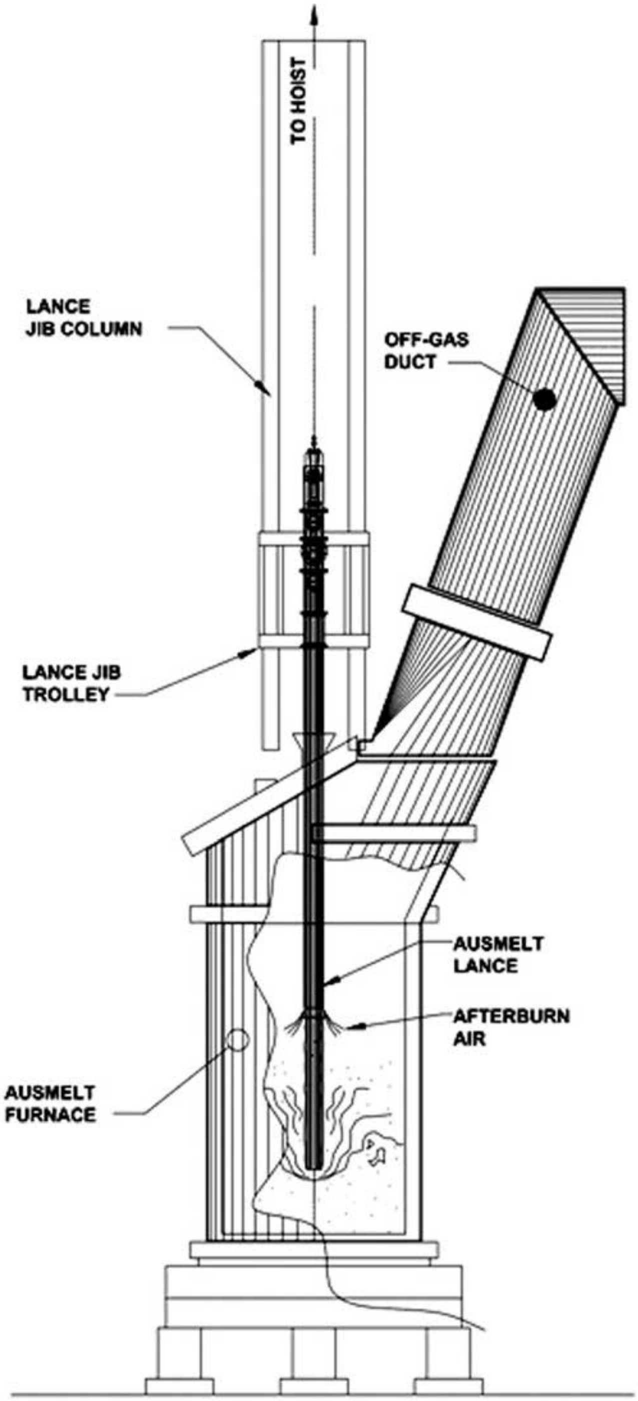


Fig. 1—Schematic of Ausmelt furnace.

The furnace possesses essentially five different reaction regions.

(1) The combustion region at the tip of the lance, where the gas and fuel (and sometimes feed) are injected downward into the slag bath. As mentioned earlier, this region can be oxidizing, reducing, or neutral, depending on the rates of fuel air and oxygen supplied to the lance.
(2) The gas-rise region above the tip of the lance, where gases generated and any solid unreacted feed material at the lance tip further react with each other and the surrounding and entrained slag.
(3) The splash-cascade region, where liquid slag ejected above the bath by the rising gas volume falls back into the slag bath and carries out physical and chemical processes with the material fed from the top of the furnace.
(4) The postcombustion region, where air and/or oxygen is injected into the splash region of the gas space above the bath.
(5) The bath region significantly beneath the lance-tip level, which is relatively quiescent compared with the violently agitated top region of the bath.

The TSL furnace has other features and facilities in common with other furnace systems—flue offtake, various ports, tapholes or tapping weirs, refractory or cooled containment systems, *etc*.

The capability of removing the lance, or of adjusting the depth of submergence of the lance in the bath, allows the operator to control the degree of turbulence in the bath and the extent of splashing of the slag cascade above the bath. The operator can also stop and start the furnace operations with little or no delay. The furnace can be put on standby at any time for as long as required by removing the lance and starting the standby burner system. This burner system is also used to initially heat the furnace at the start of a campaign and to cool the furnace under controlled conditions.

III. USES OF TSL TECHNOLOGY IN METAL EXTRACTION

As already described briefly, the operating conditions in the TSL furnace system are readily controllable by the operator. Assuming that ancillary facilities are designed and engineered appropriately, the furnace can be operated under conditions which are in the range of strongly oxidizing, through neutral, to strongly reducing. Furthermore, the operator is able to operate at least three regions in the furnace under different conditions: the lance tip, the postcombustion region, and the surface region, where feed materials are reacting with the slag in a cascade of liquid slag. The furnace can also be operated over a wide range of temperatures.

TSL furnaces have been established for both continuous operations under steady-state conditions in one furnace, such as for clean copper-concentrate smelting, or in two furnaces in series, as in copper smelting and converting and in processing zinc leach residues or slags. It can also be used for batch operations involving two or more different stages operated under different conditions, for example, in tin smelting and tin slag reduction.

The ability of the furnace to be operated under this wide range of conditions has given the technology a broad range of applications.

The metal producer with by far the greatest number of operating TSL furnaces is Korea Zinc Company, with five plants processing wastes or intermediate material from the zinc smelter at Onsan, Korea. The metals recovered in these Ausmelt Technology systems are mainly zinc, lead, and copper, but minor metals and steam production are significant in the economic balance. The ability of the Onsan plant to avoid waste production by recycling the heavy metals and producing a clean, useable slag product is a pointer to the way ahead for the industry in managing the environmental impact of base metal smelting.

Table I gives details of the various Ausmelt TSL furnaces used commercially (or under construction) for processing of primary and secondary materials in the production of tin, copper, lead, zinc, nickel, and platinum-group metals. Also seen in Table I are plants for processing hazardous wastes.

More plants are built every year, and most of the recently built lead, copper, and tin smelters have employed TSL technology. The technology offers a number of advantages over existing and alternative technologies, including the following:

(1) low capital and operating costs;
(2) the flexibility to handle different feeds;
(3) tight environmental controls;
(4) operable in batch, semibatch, or continuous operations with one or more furnaces; and
(5) efficient and easily operable on a large scale (*e.g.*, greater than a half million tpa of feed) and a small scale (*e.g.*, less than 10,000 tpa of feed).

Table I. Ausmelt Commercial TSL Plants around the World

Client	Location	Starting Year	Feed Type	Annual Throughput (t/y)	Product	Temperature Range (°C)	Fuel
Star Project	Chelyabinsk, Russia	2004	Cu concentrates	500,000	Cu matte	1180	natural gas
Hindustan Zinc Limited	Chanderiya, India	2004	Pb concentrates	85,000	Pb bullion	1050 to 1200	light/heavy furnace oil
Korea Zinc	Onsan, South Korea	2004	Cu residues	70,000	Cu matte	1180	coal
MAPO Project	Seoul, South Korea	2004	Municipal Waste Incinerator Ash	10,000	Zn fume	1200	coal
Birla Copper (two furnaces)	Dahej, India	2003 (F1)	Cu concentrates	~350,000	Cu matte	1180	coal
		2003 (F3)	Cu matte	~160,000	blister Cu	1250	coal
Anhui Tongdu Copper	Tongling City, China	2003	Cu concentrates	330,000	Cu matte	1180	heavy furnace oil/coal
Amplats (two furnaces)	Rustenburg, South Africa	2002 (F1) 2004 (F2)	granulated Ni/Cu/PGM matte	213,000	high-grade Ni/Cu matte	1300	coal
Korea Zinc (two furnaces)	Onsan, South Korea	2003 (F1)	Pb tailings	100,000	Pb fume	1200	coal
		2003 (F2)	F1 slag (liquid)	80,000	Pb/Zn fume	1250	coal
Yunnan Tin Corporation	Gejiu City, China	2002	Sn concentrates	50,000	Sn metal	1150 to 1250	coal
Korea Zinc	Onsan, South Korea	2000	Pb concentrates and secondaries	100,000	Pb bullion and fume	1000	coal
Zhong Tiao Shan (two furnaces)	Houma City, China	1999 (F1)	Cu concentrates	200,000	Cu matte	1180	coal
		1999 (F2)	Cu matte	60,000	blister Cu	1250	coal
Portland Aluminum/ Alcoa	Portland, Australia	1997	spent-pot lining	12,000	$AlF3$	1250	natural gas
Minsur	Pisco, Peru	1996	Sn concentrates	70,000	Sn metal	1150 to 1300	bunker C oil
Metaleurop	Nordenham, Germany	1996	battery paste/ Pb cons	200,000	Pb bullion	950 to 1250	natural gas
Korea Zinc (two furnaces)	Onsan, South Korea	1995	zinc leach residue	120,000	Zn/Pb fume	1250 to 1300	coal
		1995	F1 slag (liquid)	100,000	Zn fume	1250 to 1300	coal
Mitsui (two furnaces)	Hachinohe, Japan	1993 (F1)	ISF slag	80,000	Zn fume	1300 to 1350	heavy oil
		2002 (F2)	F1 slag (liquid)	80,000	Zn fume	1300 to 1350	heavy oil
Korea Zinc (two furnaces)	Onsan, South Korea	1992 (F1)	QSL furnace slag (liquid)	100,000	Zn/Pb fume	1300	coal
		2001 (F2)	F1 slag	90,000	Zn fume	1300	coal
Rio Tinto Zimbabwe	Eiffel Flats, Zimbabwe	1992	leach residue	7,700	high grade Cu/Ni matte	1250 to 1350	coal

IV. DEVELOPMENT PHASES OF THE TECHNOLOGY, THE MARKET, AND THE COMPANY

A. *The Idea—Late 1970 to Mid-1971*

As with all developments, TSL started with an idea, and, as with many ideas, this one started with a problem.

Dr. T.R.A. (Ron) Davey of CSIRO in Melbourne wrote to me in the late 1960s at Imperial College, London, while I was completing my Ph.D. research into oxygen diffusion in solid oxide electrolytes.[1] He told me that the trials of a rotary furnace tin smelting process he was developing had not achieved the reduction of liquid slag in small-scale trials or in full-scale tests in Germany. I had worked with Dr. Davey on the process[2] for a short period to earn enough money to travel to England to try for a Ph.D. place at Imperial College.

Although my Ph.D. research had no direct relevance to pyrometallurgy, I understood what Dr. Davey was attempting to achieve and wrote back to him suggesting that he try injection of gas into the liquid slag bath to improve mixing and, thereby, enhance the rate of reduction of dissolved stannous oxide. The idea stemmed from work by other Ph.D. researchers at Imperial College on improved mixing achieved by gas sparging into aqueous systems and the turbulence and surface agitation in top jetting during oxygen steelmaking.

In December 1970, I took up an appointment in CSIRO's Division of Chemical Engineering in Melbourne. Dr Davey was then on the staff of Colorado School of Mines, and the Chief of the Division, Dr. Clive Pratt, asked me to examine the tin smelting project to see whether the problems encountered could be overcome. The process hinged on the ability to reduce tin oxide dissolved in liquid slag to recover tin as a liquid alloy with the iron, which would also be partly reduced. The rotary furnace using solid carbonaceous reductants had failed to reduce sufficient tin to make the process viable. The rotation of the furnace did not give adequate mixing of the slag with the reductant, and I decided to try injection of reductants into the bath. Dr. Davey had not taken up my earlier suggestion, so testwork was needed to evaluate the idea. The division had recently moved to a new location, and smelting research facilities had not been set up. Most of the division's research effort was then aimed at mineral separation and concentration, and the small High-Temperature Processing Group was engaged in a promising refining process development. There were no funds available for me to take on an assistant, and I started out alone to set up facilities for crucible-scale test work. Figure 2 shows the simple test rig, in which initial experiments showed that the idea had promise.

Progress with the test work was slow because the division's analytical laboratory was already almost fully committed to other projects and could only provide the assay results for one experiment a week. The fashion in experimental design at that time was to establish a matrix of all possible experimental conditions, then to carry out all experiments in the matrix and evaluate the results statistically. I thought this unsuitable to my situation, since it would take many years before I could tell whether there was a potential process which might result from the idea. I therefore set up an experimental program which used the results of the previous experiments to guide the selection of conditions for further experiments and, by this technique, zero-in on the optimum conditions for the process. I estimated that this continuous targeting approach would still require about 60 experiments to evaluate all important variables and that, with the limited analytical capacity, it would still take 18 months before I could propose a feasible process. This slow progress toward a novel approach to tin smelting was not practicable, so I established my own titrimetric analytical facilities for tin, iron, and other components of the concentrates, slag, metal, and other phases involved in the work.

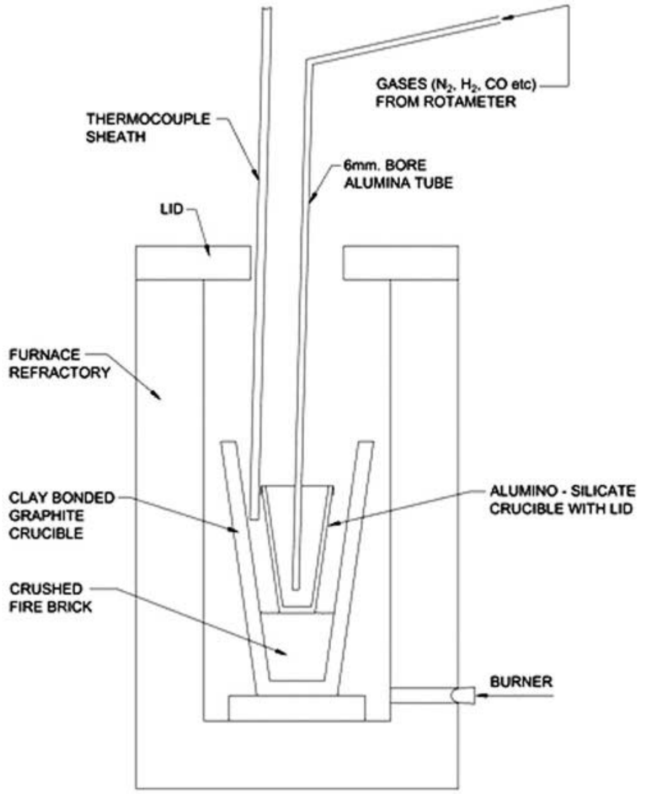


Fig. 2—Top-submerged lancing idea—testwork rig (500-g crucible apparatus).

I refined the time-consuming tin analytical procedure to decrease the time required from more than 1 day to one-half of a day, which allowed me to complete an experiment, including the critical assays, in 1 day. This allowed four or five experiments to be carried out each week.

In 6 months, I saw that the idea was feasible, and I needed to move to larger-scale test work to further evaluate a possible process. Funds were made available to recruit a Technical Assistant to help in the project, and we installed and commissioned the rotary furnace which had been in storage. Facilities, including ceramic injection tubes, were established to inject natural gas and entrained brown coal char into the 50 kg liquid slag bath of the rotary furnace.

The trials were unsuccessful. Injection of reductants through two ceramic lances from either end of the rotary furnace caused the reduction of tin in slag from about 10 to 15 pct to 5 to 10 pct in about 30 minutes, and then the reduction stopped.

The slag at the tip of the lances was over-reduced to produce solid high-iron, tin-iron alloy, and a high-melting-point slag, which was also solid. The remainder of the slag bath was not reduced further, because the reductants channeled through gas cavities in the solidified mass at the lance tips. The crucible-scale tests had not suffered from this problem, and it was apparent that the geometry of the rotary furnace bath, with a small depth and large surface area, was not suitable to achieve the necessary mixing of the whole bath by the injected gas.

I concluded that a different geometry was required and that a vertical cylinder of 300 mm in diameter and 300 mm in depth, with a top-submerged injection lance, would be more appropriate. No reactor of this type was in use in the metallurgical industry, and I now had a much more challenging development project requiring design and trial of a submerged combustion system to provide the heat requirements of the process and to also provide the strong reducing conditions needed to reduce tin and some iron from tin smelting slags. These slags would be generated either in other conventional tin smelting furnaces (reverberatory, electric, or rotary furnaces) or in a new submerged concentrate smelting process in the new reactor.

B. *The CSIRO Development Phase—1971 to 1981*

This radical development proposal followed almost a year of work that had led to failure of trials in the rotary furnace. Clearly, the new proposal would be more demanding of resources funding, staff, and time, when divisional funding was still very limited for the smelting area. The expenditure of CSIRO resources in tin smelting was also brought into question because of the relatively small production of tin in Australia compared with other base metals and because the future of the tin industry was questioned by senior CSIRO staff after learning of the report to the Club of Rome entitled "The Limits of Growth."[3]

My reaction to this was to hold a meeting of interested CSIRO staff to show that the value of tin production to industry in Australia and to export earnings was sufficient to justify the development, provided the resources of time, people, and funds were not excessive. I also started work on evaluating the use of the technology for applications in the production of copper, lead, nickel, and other metals. Further work had to be done quickly, on a broader front, with minimal funds and without further staffing.

I built a pilot plant of the minimum size capable of sustaining its high-temperature operations by submerged combustion with submersible lance without the use of any external heating system (*i.e.*, a true pilot plant with all of the features needed in a commercial plant).

I used existing facilities and did as much work as possible myself. For instance, I found that the furnace shell size was the same as a 44-gallon drum (United States 55-gallon drum) and applied my previous experience as a bricklayer to install the refractory brick lining of the 44-gallon drum reactor. The first lances designed by me and made up in the Divisional Workshop were water cooled and used pure oxygen to combust the natural gas fuel and reductant. The gas handling and liquid-product handling system for the rotary furnace were used for the high-temperature submerged combustion reactor. Initially, the lance handling was done manually, with my own arm!

The first trial was successful in reducing the tin slag, and I was able to spend some funds on a simple lance-handling facility (Figure 3).

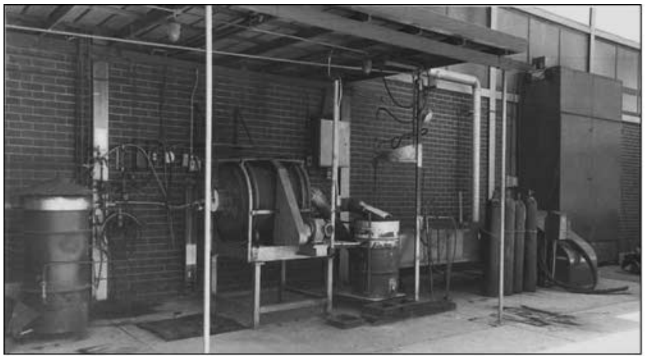


Fig. 3—First CSIRO pilot rig. The original rotary furnace is shown with, beside it, the 44-gallon drum furnace.

Results achieved with the rig were immediately encouraging, and I started looking for a route to commercialization. I wrote an article with a Chemical Engineer working on other projects in the division (Jim Thurlby) on the industrial use of the technology[4] and went to visit Associated Tin Smelters (ATS) in Sydney to discuss possible plant developments. The manager of ATS at the time regarded water and oxygen as dangerous in a tin smelter and told me that he would not allow water-cooled lances or oxygen injection to be used in his plant.

I redesigned the lance to provide cooling by injected air and operated the plant without oxygen in further developmental trials on the recovery of tin, copper, nickel, and lead from slags. By concentrating on slag processing, the technology could be used in smelting plants to improve metal recovery and to lower costs without the large investment and risk involved in replacing the primary smelting unit.

Further articles were written on tin smelting and other applications of the technology.[5–6] The CSIRO awarded Development Pool Funding for the project to assist in commercializing the development. These funds were used to employ an Experimental Officer, Mr. David Conochie, a Master Graduate from University of Melbourne and two Technical Assistants, one of whom, Mr. Brian Lightfoot, contributed to all stages of the technology and continues today to be involved with Ausmelt projects. The pilot plant facilities were also upgraded to improve the controllability and reliability of the system.

The work was becoming of interest to Australian industry, and we examined ways to assist smelters to allow larger or more relevant trials to be carried out at industrial sites. For this purpose we built a 50-kg rig which could be transported to smelters to allow greater involvement of smelter staff in trials on their materials.

I recognized the need for three areas of Research and Development (R&D) to achieve success in commercializing a new process. I established a work model for my team which involved each member having three areas of activity to be carried out, with time and opportunity determining the priority to be given to each. The following areas were to be given attention and progressed in parallel:

(1) theoretical and basic studies within CSIRO (*e.g.*, water modeling of flow and mixing), as shown in Figure 4;
(2) crucible or pilot plant work on technical and efficiency aspects of processes and equipment (*e.g.*, industrial plant evaluations in the transportable 50-kg rig), as shown in Figure 5; and

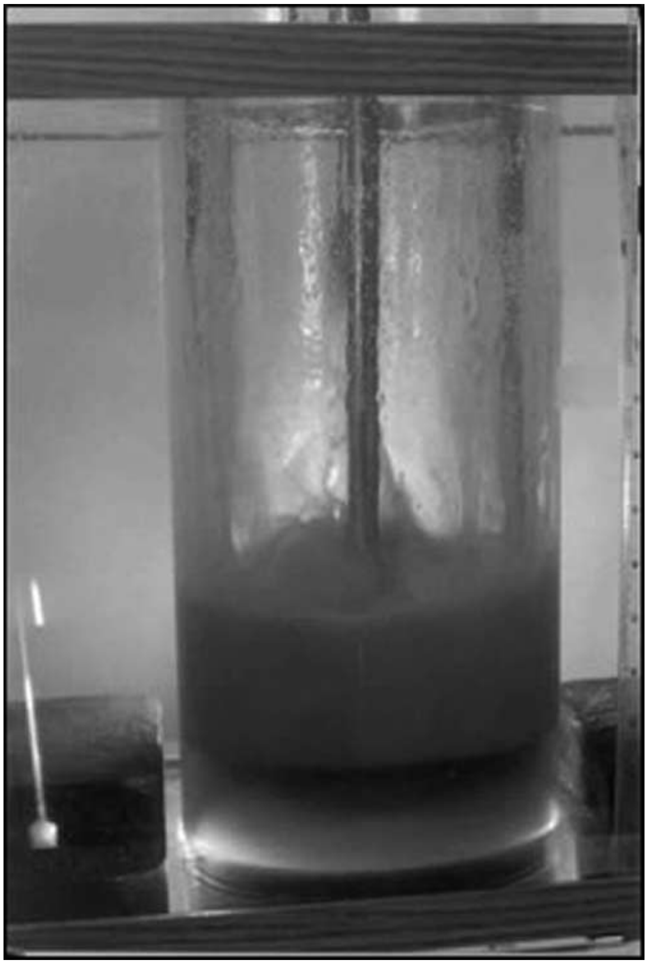


Fig. 4—Water modeling.

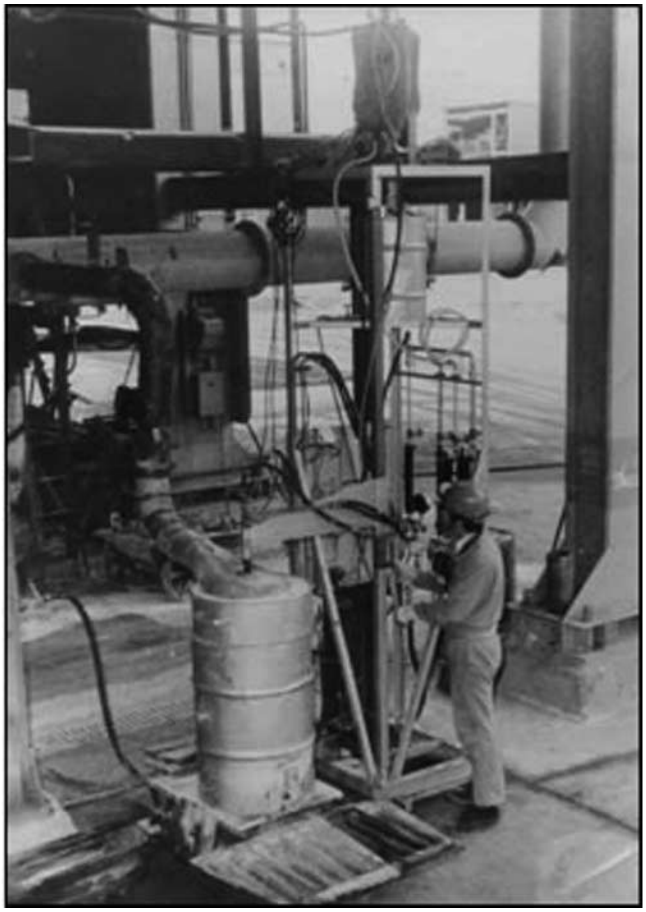


Fig. 5—Industrial evaluation in the transportable 50-kg rig.

Fig. 6—One-ton pilot-plant trials at ATS.

(3) commercial industrial evaluations of processes and equipment, as shown in Figure 6.

Patents were taken out on the lance system and some of the processes developed in order to assist in protecting the intellectual property.[7,8,9]

Pilot plant and commercial developments were pursued with the CSIRO team working at a number of metallurgical plants in Australia.

Broken Hill Associated Smelters, Port Pirie, South Australia—1974. The transportable 50 kg-rig was taken by truck and set up at Broken Hill Associated Smelters (BHAS), Port Pirie, to take liquid antimony–lead slag from the softening furnace and reduce it in two stages to produce lead bullion for recycle and lead-antimony alloy for marketing. The plant operated successfully in its two weeks of operation and demonstrated good control and very good separation of antimony and arsenic from the lead circuit.[10]

Associated Tin Smelters, Sydney, New South Wales—1974 and 1977. Tin-slag reduction work in the pilot plant in CSIRO was successful;[11] however, we needed to prove the system in an industrial environment. The tin smelter in Sydney had a new, young, and enthusiastic manager in Rod Tolley. Rod saw the potential for what we were doing and in 1974 agreed to let us on his plant as long as it did not require investment by his company or cause interruption to his production. He had a refractory-lined ladle used for transporting tin-iron alloy in the plant, which he loaned to us for a two-week period while the No. 4 reverberatory furnace was being relined. At that time there was a baghouse we could use and enough ducting in the store yard to connect it to a trial furnace at the crane aisle of the No. 4 furnace.

Back at CSIRO, the team designed and built a lid for the ladle with ports for three lances, a feed entry, and a flue offtake. Lances for oil and coal combustion and appropriate lance controls and handling gear were designed and built. The plant was then assembled at Associated Tin Smelters (ATS) with the help of their staff and workers and operated successfully over a 1-week period to reduce tin from liquid slag and prove the process and equipment.[11]

Figure 6 shows the plant in operation at the end of the aisle of the No. 4 reverberatory furnace. Three lances (Figure 7) were used for the plant to provide the required turbulence in the reactor, since the loaned ladle was of larger diameter than was suitable for operation with a single lance.

This work was followed in 1977 by the design, construction, and successful operation of a 6-ton-capacity commercial plant processing batches of liquid slag from the existing reverberatory furnaces[12] (Figure 8). Mr. Bill Edwards was then the manager of the plant, and I am greatly indebted to him for being the first person responsible for establishing a commercial TSL reactor. The plant had a second furnace built to increase capacity, and the slag reduction continued as part of the plant until it was closed after the collapse of the tin price in the mid-1980s.

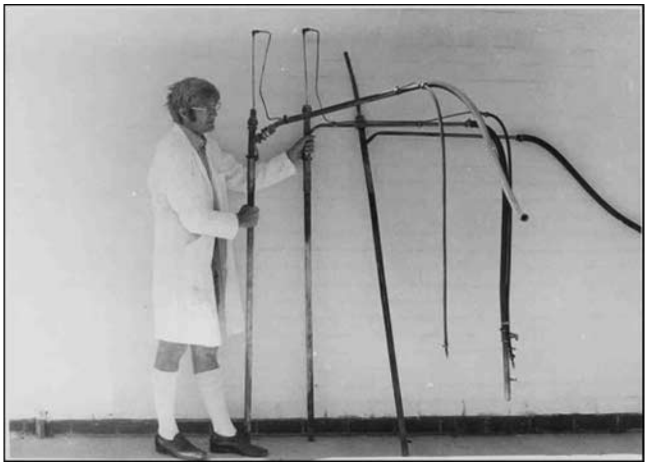


Fig. 7—Three lances used in the ATS pilot plant to give sufficient mixing in the large-diameter ladle used for the furnace.

Fig. 8—Commercial tin slag reduction plant at ATS.

The Electrolytic Refining and Smelting Company (ER&S), Port Kembla, New South Wales—1975. A 1-ton-capacity rig was built in the Peirce–Smith converter aisle of the ER&S copper smelter and used to demonstrate the reduction of copper from batches of liquid slag from the converters. Both copper and zinc were recovered efficiently from the slag after some modification of the rig and process to solve early difficulties. This was the first purpose-built larger pilot plant, and a single lance was used. Scale-up of the lance required significant modifications during the trials. Figure 9 shows the furnace being filled with converter slag from the ladle in the converter aisle.

Copper Refineries, Townsville, Queensland—1976. The transportable 50-kg rig was installed in the refinery and successfully used to produce copper metal for recycle from anode furnace slag. A 1-ton-capacity pilot plant was subsequently built and operated successfully at the Townsville refinery.[13]

Mount Isa Mines, Mount Isa, Queensland—1978. Mount Isa Mines (MIM) relocated the 1-ton-capacity plant from Townsville to Mount Isa to carry out successful trials on cleaning of converter slag in the converter aisle.[13]

Fig. 9—Filling the ER&S 1-ton plant with liquid-copper converter slag.

Aberfoyle Limited, Kalgoorlie Nickel Smelter, Western Australia—1978 and 1979. Following three successful 50-kg trials at CSIRO,[14] Aberfoyle Limited built a 4-tons/hour pilot plant at Kalgoorlie Nickel Smelter (Figure 10(a)) to fume tin from a pyritic ore. This plant was operated through to 1982 and achieved good results for both pyritic ore and a copper-sulfide concentrate containing significant levels of tin.[15]

MIM, Mount Isa, Queensland—1980. Following successful crucible-scale development of a lead smelting process using MIM concentrates at CSIRO, MIM established a 120-kg-capacity pilot plant to further investigate the lead smelting process.

My CSIRO team was closely involved in all of these plant designs, constructions, and operational planning and performance. Over the same period there were also a wide range of other processes investigated in the crucible and pilot-plant rig in CSIRO, including copper concentrate smelting and matte converting to blister copper. The small pilot plant was successfully operated on direct smelting of chalcopyrite concentrate to blister copper, as well as three-stage processing to matte, then white metal, then blister copper.[16]

(*a*)

(*b*)

Fig. 10—(*a*) Aberfoyle 4 ton/h tin matte fuming plant built and operated at Kalgoorlie Nickel Smelter. (*b*) Olympic Dam pilot plant used to produce a range of slags while smelting to matte, then for converting the matte to blister copper.

An incident which caused a temporary halt to development in the pilot plant should be mentioned, since it led to the spotlight being put on the project and would have caused problems for CISRO people responsible for risks and costs of development work.

While working on the pilot plant, the lance became blocked at the tip, and the subsequent series of events caused me to be hit by a liter or so of burning fuel oil. Quick action by Brian Lightfoot extinguished the flames and I was not burnt. The incident demonstrated that our safety clothing and procedures were effective. An analysis of this series of events indicated a very low probability of a repeat episode. Nevertheless, it was incumbent on us to carry out a thorough safety check and to put in modifications to the system. This was costly and caused a halt to pilot work for a number of months before trials were restarted on the upgraded and improved rig.

I was very happy with the CSIRO working environment and with the industrial collaboration achieved and was pleased with the progress being made in the industrial use of the technology. I thought that the establishment of a successful industrial plant using a revolutionary new smelting process which I had thought up, tested, patented, and developed in a period of 6 years was a good outcome. The other processes being developed in laboratory and pilot plants and trialed in commercial plants bode well for the future of the technology. The first 10 years of the development of TSL was described in more detail in an article by Floyd and Conochie.[17]

Table II lists the people in CSIRO and industry who were most significant in helping me to achieve success in the CSIRO development phase.

My work was criticized by some senior technical people in the industry in Australia who believed that there was no company in Australia capable of commercializing a new smelting development. It was regarded as too expensive and too long-term for our industry. I was also criticized by the Chief of my division of CSIRO for working too closely with industry. We advertised for an Australian company to take up the rights to develop and commercialize the technology. There was only one interested party, and he would only take it up if CSIRO would second me to his site and continue to pay my salary. The Chief would not agree to this and told

Table II. The Most Significant Contributors to Success During the CSIRO Development Phase—1973 to 1981

Mr. Brian Lightfoot	CSIRO team and Aberfoyle tin fumer
Dr. David Conochie	CSIRO team and Aberfoyle tin fumer
Mr. Rod Tolley	ATS Managing Director—tin slag reduction pilot plant
Mr. Bill Edmonds	ATS General Manager—commercial tin slag reduction plant
Mr. Doug Gallagher	ER&S R&D Manager—copper slag reduction pilot plant
Mr. Denby Ward	BHAS R&D Manager—antimonial slag pilot work
Mr. Kevin Foo	Aberfoyle Development Metallurgist—process development and 4-ton/h tin fuming plant
Mr. Jim Fewings	MIM R&D Manager—copper slag cleaning and lead smelting pilot plants

Table III. Main Plant and Process Developments during the CSIRO Development Phase

	Patent	Lab	50-kg Rig	Large Pilot Plant	Commercial
1. Plant Developments					
A. Top-submerged lance reactor system		√	√	√	√
B. Water-cooled lance for submerged injection of oxygen/fuel			√		
C. Air-cooled lance for submerged injection of air/oxygen/fuel	√		√	√	√
D. Submerged combustion systems fired with:					
1. Natural gas		√	√		
2. Light fuel oil			√	√	√
3. Fine coal		√	√	√	
4. Heavy fuel oil			√		
5. LPG			√		
E. Multiple lance furnace				√	
F. Lances in reverberatory furnace					√
2. Process Developments					
2.1 Tin slag reduction	√	√	√	√	√
2.2 Tin concentrate smelting	√	√	√	√	
2.3 Tin ore or concentrate fuming	√	√	√	√	
2.4 Reduction of antimonial slag in two stages		√	√		
2.5 Lead slag reduction	√	√	√		
2.6 Lead concentrate smelting	√	√	√		
2.7 Copper smelter and converter slag cleaning		√	√	√	
2.8 Anode furnace slag reduction		√	√	√	
2.9 Copper concentrate smelting		√	√		
2.10 Matte converting to blister copper		√	√		
2.11 Nickel slag reduction	√	√	√		

me that if there was no other group prepared to fund the development, I would have to stop the Sirosmelt work and find a new research project.

Table III lists the main plant and process developments carried out during the CSIRO development phase.

C. *Ausmelt Development Phase—1981 to 1990*

On June 30, 1981, I resigned from CSIRO, and on July, 17, 1981 my wife, Carolyn, and I registered Ausmelt Pty Ltd. I set out to develop and commercialize the technology as an independent consultant to industry. Our plans included the establishment of our own TSL pilot plant, with the ultimate aim to set up our own commercial operations for processing secondary and problematic materials which were being stockpiled at smelters. By cashing in my superannuation, we could plan on surviving for about 6 months if my services were not needed by industry.

I wrote to CSIRO to request the rights to market and develop the technology, and, after prolonged consideration, they gave me a letter giving me the nonexclusive rights to provide the technology to third parties, who would have to take out a license from CSIRO.

In the interim, I had received notification that CSIRO would continue to provide laboratory, pilot-plant testwork, and advice on TSL to anyone who requested them. The CSIRO position was that they would not provide any help to Ausmelt, they would assist anyone to compete, and, in fact, CSIRO would compete directly with Ausmelt in providing services. This was not an auspicious start for the enterprise.

The change from a secure and permanent position in a large government R&D organization to working for myself in private enterprise was not a step I took lightly. My wife, Carolyn, supported me completely and assisted in the operations and development of the company. We undertook this, despite the lack of financial backing and with little money in the bank to support the business, as well as having a family with four young children: the youngest, Eliza, was only 1 year old. Without the full support of Carolyn, it could not have worked.

We did achieve the transition. In the process, we had the satisfaction of seeing great technical achievements over the years, as well as seeing the company mature to a successful public company with an international presence and recognition, as demonstrated by a number of awards given to the company and to me.

The first year or so of Ausmelt's business involved me consulting to the three companies then involved in the technology: ATS, Aberfoyle Limited, and MIM.

These three companies were continuing work done in the CSIRO development phase and, according to the agreement CSIRO had reached with Ausmelt, all had the same marketing and development rights as Ausmelt. It would make great sense to form a consortium with these companies to jointly carry out the marketing and development of the technology, and I called a meeting of them and CSIRO to this end. All declined to form a consortium because they did not regard technology marketing and commercialization as their business. CSIRO regarded it as contrary to their policy; ATS and Aberfoyle were only interested in their own use of the technology; and MIM said they did not regard the process as having promise for commercial use and were only using the development work by their R&D group to keep abreast of developments in technology by overseas companies.

The first overseas assignment was with Bamangwat. Concessions Limited (BCL), Botswana, where a lance was tried in the bath of the nickel flash smelter to remove accretions and assist in cobalt recovery.

Greenbushes Tin operated a tin mine and small smelter in Western Australia, and we were given a contract to develop and supply a small Ausmelt reactor to assist in processing tin concentrates containing tantalum and antimony.

Roxby Management Services (RMS) was developing the processing plant for the South Australian copper-uranium mine at Olympic Dam. Ausmelt was employed to evaluate the technology to smelt their concentrates to produce a range of slags simulating those which would be produced if RMS installed a smelter using one of a number of possible technologies, such as Outokumpu, Noranda, Electric Furnace, *etc*. Ausmelt Technology was chosen for this evaluation because of its flexibility, but was excluded from consideration for the commercial smelter because there was no copper smelter then in operation using the technology at commercial scale. The aim of the work was to produce a range of slags for pilot-plant evaluation of a uranium leaching process. Laboratory-scale tests and 50-kg pilot-plant trials (in the CSIRO rig leased to Ausmelt) successfully smelted the concentrates to produce high-grade matte and the range of slag compositions required. The pilot work was also extended to convert the matte to blister copper. One trial of direct smelting to blister copper also showed that the technology could be used in this mode of operation for the Olympic Dam concentrates.

A large pilot plant was designed, built, commissioned, and operated for several months at Olympic Dam using Ausmelt's services.[18] After production of the required range and tonnage of slags for the leaching trials, the matte produced, averaging approximately 70 pct Cu, was converted through to blister copper in the Ausmelt reactor. Figure 10(b) shows the pilot plant in operation. Figure 11 shows the slag-coated lance being raised from the furnace.

While these projects were in progress, I become involved in lecturing to the last classes of metallurgy to pass through the Department of Mining and Metallurgy at the University of Melbourne. The University had closed the department in 1981, and I was contracted for one day a week, giving chemical and extractive metallurgy courses and supervising postgraduate students. In 1983 the University established a new position of Professorial Research Fellow to provide leadership in continuing extractive metallurgy industrial research links with the Chemical Engineering Department. The Extractive staff, including Dr. Neil Gray and Dr. Madhu Nilmani, had transferred to the department, and Australian industrial leaders had urged the University to provide for ongoing research activities. I was appointed to this position on a four-day-week basis. I spent the remainder of my time on Ausmelt business. The University provided only the position and a modest initial equipment grant, which I used to establish a versatile induction furnace experimental facility to add to the substantial equipment from the old department, housed in a "hot laboratory." Funds from industry and research granting bodies were used to take on staff and postgraduate students, and we formed the G.K. Williams Research Laboratory for Extractive Metallurgy.[19]

By 1987, there was external funding of nearly 1 million dollars per year for the research work of the laboratory, which housed about 25 five staff and students carrying out research into metal extraction equipment and processes. The University laboratory had become a viable entity, and I returned full-time to Ausmelt's development. Dr. John Rankin took up the leadership of the laboratory and achieved Co-operative Research Centre status with CSIRO as a partner.

Fig. 11—Slag-coated lance being raised from the Olympic Dam reactor.

On taking on the University research development task, I asked Brian Lightfoot, who was then with Aberfoyle Limited, to take on the management of Ausmelt. He joined the company as its first full-time employee and has been involved in the company's expansion and development ever since then.

Australia lacked a venture capital industry before the 1980s, and the federal government initiated a scheme (the MIC Scheme) to encourage companies to become involved in providing capital for start-up companies to achieve a viable scale of operation.

The Pratt-Group MIC Company, Australian Pacific Technology, invested about a quarter of a million dollars to add to equity funds from myself and Brian Lightfoot to build a pilot plant in Dandenong, Victoria. The pilot plant was started up in 1985 and was used for extensive process and equipment developments during the 1980s and 1990s. It was also used for commercial operations on precious-metal recovery from intermediate and waste materials and for commercial-scale testing of the treatment of hazardous wastes. The plant has been modified and improved over the years and, in its present form, simulates closely the operability and controllability of commercial plants.

The wide range of uses for Ausmelt Technology developed in this plant is described in various articles.[20, 21, 22]

In the mid-1980s, Western Mining Corporation's Kalgoorlie Nickel Smelter was suffering problems due to a build-up of solid material in the bath of the flash furnace beneath the flue offtake. All efforts to remove the build-up had failed, and the blockage was soon to shut down the smelting operation. Ausmelt was given the job of supplying and installing a lance to be lowered through the roof to inject fuel and air into the slag bath. The cascade of splashed slag produced by the lance rapidly dissolved the build-up and allowed the flash furnace to continue in operation for a number of years.

An Ausmelt plant for cupellation of 1,200 tpa retort bullion at the BHAS lead smelter in Port Pirie was designed and installed in 1989. This plant was the major precious-metal recovery unit for the smelter until the late 1990s.[23]

Sulphide Corporation engaged Ausmelt to trial the fuming of zinc from their imperial smelting furnace (ISF) slag, and a commercial-scale plant was built in 1988 to process 90,000 tpa of liquid slag.[24] The project suffered from insufficient funds being allocated to provide reliable ancillary equipment. Although it achieved good recovery and costs of processing, it suffered from frequent stoppages and operations were not continued.

Hollandse Metallurgische Industrie Billiton (HMIB) contracted Ausmelt to develop, design, and commission a 10,000 tpa tin concentrate smelter for their plant[25] in Arnhem, The Netherlands (Figure 12). The smelter was started in 1989 but closed in the early 1990s because of environmental problems with the secondary lead operations using rotary furnaces at the same site.

Throughout these developments, Ausmelt's preferred path for process and plant supply for clients included the following steps.

(1) Theoretical evaluation of the technical feasibility and the optimum chemistry and process routes to be used.
(2) Laboratory-scale studies of the technical feasibility and the optimum chemistry and process routes to be used.
(3) Pilot-scale trials of the technical feasibility of incorporating submerged combustion with the proposed fuel and air/oxygen level.
(4) Prefeasibility engineering and a costing study, including evaluations relating to environmental and commercial suitability of the project.
(5) Larger-scale pilot-plant trials where required by a new process relating to scale-up, engineering limitations, or materials issues.
(6) Feasibility study prior to a decision to invest in the commercial plant.
(7) Design, engineering, supply of special components (*e.g.*, lances), procurement, construction and start-up of the commercial plant.


Fig. 12—HMIB commercial tin smelter.

In forming Ausmelt in 1981, I had planned to establish our own industrial operations using the technology. In order to give impetus to that development in 1987, Triako Resources bought 20 pct of the company's shares for 1 million Australian dollars. Verbal agreement on the deal had been reached the day before a major stock market crash. Despite the considerable financial problems and uncertainty that the crash caused, Triako's Barry Fairley went ahead with the agreement, becoming a Director of Ausmelt and a great supporter of the technology. Triako continues as a substantial shareholder in Ausmelt today. A subsidiary company, Ausmelt Equity Ventures, was formed to pursue the development of this business area.

In 1989, CSIRO issued a license to develop and market TSL smelting technology to MIM, who had been carrying out their own commercial developments in lead and copper smelting. They had not been involved in marketing the technology previously, and it came as a surprise that CSIRO would undermine Ausmelt's position in this way.

CSIRO subsequently gave Ausmelt what it said were equivalent rights, but which were later found to favor MIM for larger-scale plants. This new agreement, however, gave Ausmelt the right to license the technology to end-users and, in that respect, was an improvement on the original agreement of 1982.

I regret that CSIRO did not support Ausmelt's technology wholeheartedly during the crucial initial years of the development of the markets and commercialization of the technology. By competing with Ausmelt and being involved in licensing, they confused the market. After more than eight years of Ausmelt succeeding in a range of commercial plant establishments and new process developments with clients in Australia and overseas, CSIRO's licensing MIM in competition with Ausmelt did not make commercial sense. Now, we had two Australian companies fighting head to head for each client that wanted to use the technology for copper or lead smelting.

If collaboration and assistance had been provided to Ausmelt by CSIRO and if an effective working relationship had been achieved with MIM, I think that the commercialization would have been achieved more efficiently to the benefit of CSIRO and MIM as well as Ausmelt. The licensees of the technology would also have benefited from a clearer path and more robust single source of the technology.

I want to emphasize that I do not feel any bitterness concerning these events. I am pleased to hear that CSIRO is now aware of the need to assist "spin-off" organizations. CSIRO workers were under great pressure through the 1980s to supplement their government funding with industrial grants, and this undoubtedly contributed to the situation that

Table IV. Plant and Process Developments During the Ausmelt Development Phase

	Patent	Theoretical	Lab	Small Pilot Plant	Large Pilot Plant	Commercial
1. Plant Developments						
1.1 Shrouded lance system	√	√		√	√	√
1.2 Jet pump powder injector	√		√		√	
1.3 Continuous flow through reactor						√
1.4 Lances in flash furnaces						√
2. Process Developments						
2.1 Smelting tin concentrates with Sb and Ta		√	√	√		√
2.2 Copper concentrate smelting (with uranium)		√	√	√	√	
2.3 Copper matte converting				√	√	
2.4 Nickel concentrate smelting		√	√	√		
2.5 Nickel matte converting/desulfurizing		√	√	√		
2.6 Laterite nickel smelting	√	√	√	√		
2.7 Precious metal smelting		√	√	√		√
2.8 Cupellation of retort bullion		√	√	√		√
2.9 ISF slag fuming	√	√	√	√		√
2.10 Smelting complex copper-gold ore		√	√	√		
2.11 Zinc concentrate smelting	√	√	√	√		
2.12 Tin concentrate smelting			√	√		√
2.13 Antimony-gold smelting	√	√	√	√		
2.14 Smelting complex ores, residues, and concentrates		√	√	√		
2.15 Recycling zinc leach residues	√	√	√	√		
2.16 Smelting zinc silicate ore		√	√	√		

Ausmelt had to work through. We all know that competition is good in a free market and survival of the fittest is the way of the world. Ausmelt has not only survived, but has prospered and is diversifying into other areas of application of the technology.

Table IV lists the plant and process developments achieved in the Ausmelt development phase.

Table V lists the people who contributed most significantly in helping me to develop Ausmelt and the technology in the 1980s.

D. *Ausmelt Commercialization Phase—1990 Onward*

The list of plants in operation and under design and construction (shown in Table I) is extensive, and these have been the main visible achievements of the Ausmelt commercialization phase of TSL Technology Development since 1990.

In 1994, Ausmelt was floated successfully on the Australian Stock Exchange and was referred to by some analysts as the star performer during its first year as a public company. There have been difficult years as well as star years for the company over the last 14 years.

Some of the highlights have resulted from the recognition of the breadth of operations which can benefit the environmental and sustainability features as well as costs of operation of the technology in the metal extraction industry.

The Korea Zinc Company, a world-leading zinc producer, has built at the Onsan smelting complex five plants using eight Ausmelt furnaces to process five different intermediate materials: QSL lead smelter slag,[26] zinc leach residues[27] (Figures 13 through 15), lead-rich residues and concentrates, lead-zinc tailings from the processing of zinc concentrates by direct atmospheric leaching, and copper dross from lead pyro-refining. These plants allow recovery and production of metals from various residues and intermediates of the Onsan plant. The final slag from the Ausmelt plants is saleable to cement producers.

Table V. The Most Important Contributors to Ausmelt Technology and Corporate Growth in the 1980s

Ms. Carolyn Floyd	Ausmelt Company Secretary & Director
Mr. Ivan Storey	Ausmelt Accountant and Financial Director
Mr. Brian Lightfoot	First Employee, Manager, Managing Director, and Director
Mr. Ross Muller	Roxby Management Services Copper Smelter
Mr. John Bultitude–Paull	Greenbushes Tin Smelter, then Ausmelt Operations Manager
Mr. John Leckie	Australian Pacific Technology Venture Capital
Mr. Barry Fairley	Triako Resources Investment and Director
Mr. Christian Dor	HMIB Tin Smelter

The Ausmelt copper smelters for Zhong Tiao Shan[28] (Figure 16) and Tongling (Figure 17) in China, Birla Copper in India, and the Star Project in Russia are substantial mainstream smelters.

The Zhong Tao Shan and Birla plants include Ausmelt copper matte converting units, which provides an important new market for the technology.

The big lead smelter at Nordenham in Germany (Figure 18), operated by Metaleurop, was installed to solve a pollution problem. Dust and fume escaped to the atmosphere during processing of concentrates and secondary lead materials in the old sinter-plant/blast furnace. The original production target of 90,000 tpa lead produced from a mixture of concen-

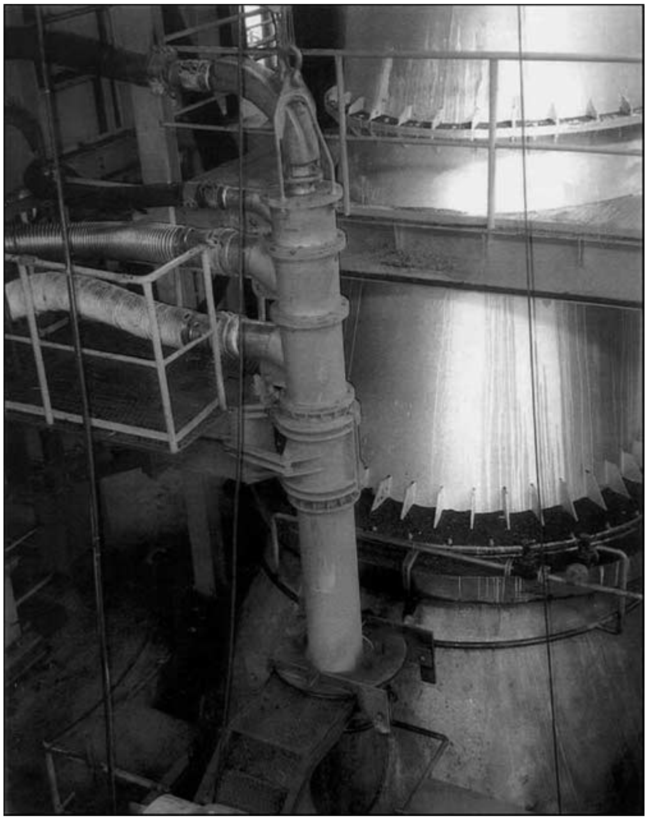


Fig. 13—Lance in Korea Zinc Co. Slag Fuming Plant furnace.

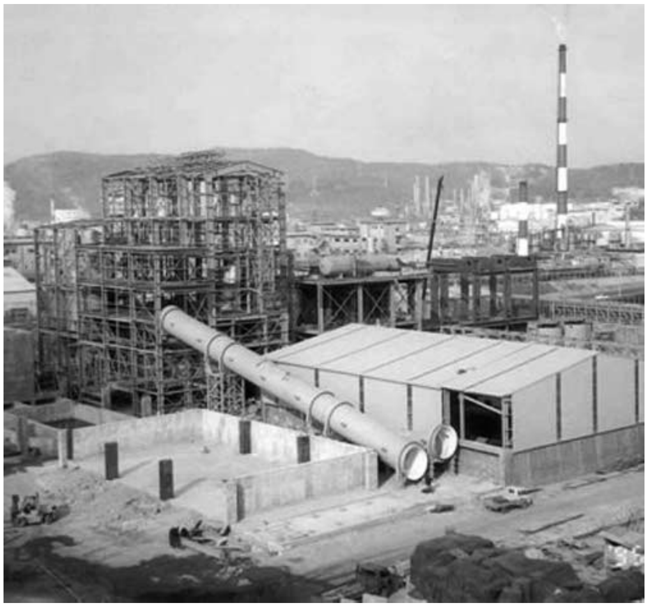


Fig. 14—Korea Zinc Co. Residue Fuming Plant during construction.

trates and battery paste[29] is now being significantly exceeded. The production costs and energy requirements are significantly lowered compared with the old system, and the emissions have been drastically decreased.

The Hindustan Zinc Limited (HZL) plant under design and construction in India will have both environmental and cost benefits by use of Ausmelt lead smelting.

Fig. 15—Korea Zinc Co. Residue Fuming Plant feed. Little or no feed preparation is needed for Ausmelt furnaces.

Fig. 16—Copper smelter and converter at Zhong Tiao Shan Copper (Houma City, China).

Fig. 17—Ausmelt copper smelter at Anhui Tongdu Copper (Tongling City, China).

The Amplats furnaces in South Africa provide close metallurgical control of the product matte, needed for the subsequent refining for platinum group metal (PGM) production.

The technology replaces Pierce–Smith converters for tighter environmental performance. Similar benefits are provided at a smaller scale by the Rio Tinto Zimbabwe plant at Eiffel Flats,[30] which replaced an electric furnace.

The tin smelter of Funsur in Peru[31] (Figure 19) originally had an installed capacity of 25,000 tpa concentrates. This has subsequently been increased by various means, including oxygen enrichment and installation of a second furnace to a smelting capacity of 70,000 tpa concentrates, producing more than 35,000 tpa of tin.

The tin smelter of Yunnan Tin Corporation in China (Figure 20) was built with an installed capacity of 50,000 tpa tin concentrates and, since its hot-commissioning start-up in

Fig. 18—Lead smelter, Metaleurop (Nordenham, Germany) during construction and on the operating floor during smelting of lead concentrates and battery paste.

Fig. 19—View of the Funsur tin smelter and the control room during operations.

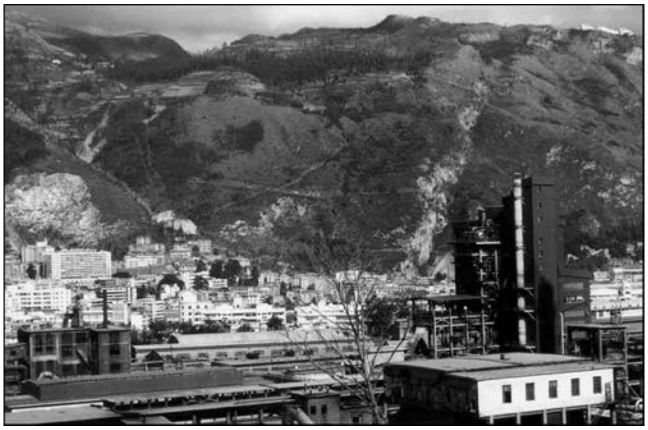


Fig. 20—Tin smelter of Yunnan Tin Corporation (Gejiu City, China).

a record time of 3 weeks in mid-2003, has expanded capacity to more than 60,000 tpa concentrates (30,000 tpa tin metal).

Between them, these two smelters produce over a quarter of the world's annual tin requirement.

Other plants built for processing of waste materials to recover valuable components and produce a useable waste product illustrate the capability of the technology in processing hazardous or toxic waste materials. Note that the technology applied to waste does not involve combustion reactions and, therefore, cannot be considered as a high-temperature incinerator. The carbon or hydrocarbon components of waste fed to the furnace reacts with ferric oxide dissolved in the slag to produce carbon dioxide and water vapor and ferrous oxide dissolved in the slag. Ferrous oxide in slag is then reoxidized to ferric oxide by oxygen in the gases injected through the lance. The reactions involve indirect oxidation, and the iron oxide is effectively a catalyst. Ausmelt calls the reactor a Catalytic Waste Converter. The Spent Potlining plant at Portland[32] (Figure 21) is an example of this application, in which the recycled product is aluminum fluoride and the slag is accepted by the Environmental Protection Authority (EPA) (Victoria) as suitable for use in building materials.

Another waste application is the ISF Slag Fuming plant at Hachinohe.[33] The plant recovers zinc and lead from the slag for recycle to the ISF furnace, and the slag is used for sea retaining walls.

The Mapo project under construction in Seoul is yet another waste recycle application where the fly ash produced in a municipal waste incinerator will be processed to recover heavy metals such as zinc and lead and the slag waste will be suitable for use in cement manufacture.

Note that the fuels for the various plants in Table I vary depending on the requirements of the location. The Funsur tin smelter is an example of the flexibility of the technology. It started operations using light fuel oil, changed to heavy fuel oil when that fuel became available at the location, and is now being modified to operate on natural gas. The similar tin smelter of Yunnan Tin Corporation uses coal as the fuel, because that is the most economical in Gejiu City.

Ironmaking using TSL technology has been under development for some time. The first successful trials in the pilot plant at Dandenong were carried out for processing Aneka Tambang's Iron Sands from Java in the early 1990s.[34] Ironmaking has been further developed in a larger demonstration plant of nominal annual capacity of 15,000 tpa iron in Whyalla, South Australia,[35–38] as shown in Figure 22. The technology is being evaluated for projects in Australia, India, and China. Niche markets requiring 300,000 to 5000,000 tpa of pig iron provide the present opportunities. An example is the production of pig iron for liquid feed to electric-arc steelmaking plants, where greater capacity, energy savings, and substitution of iron ore for scrap are of major benefit.

The Ironmaking technological development has drawn on the successful commercialization of TSL in the nonferrous smelting market. Thus, many of the issues associated with scale-up have been addressed in the copper smelting plants with capacities of up to 500,000 tpa. The main differences to nonferrous metal plants is that postcombustion energy recovery to the slag bath becomes a major (rather than a minor) component of the energy balance, and the operating temperatures are higher in the region of 1440 °C to 1480 °C. The furnace uses multiple lances to achieved the degree of slag cascade needed for the postcombustion energy recovery and, with the high levels of oxygen enrichment of the combustion air that is used, the lances are cooled by water.

Fig. 21—SPL Recycle Plant at Portland Aluminum/Alcoa (Australia).

Fig. 22—Iron ore to pig iron demonstration plant (Whyalla, South Australia).

An R&D project was carried out with staff of University of Melbourne and Swinburne University of Technology to evaluate flow in and above the bath in the multiple-lance iron-smelting furnaces,[39,40,41] as shown in Figure 23.

Table VI lists the plant and process developments in the Ausmelt commercialization phase.

Table VII lists the people who have contributed the most to the Ausmelt commercialization phase of the technology since 1990.

V. PEOPLE AND FUNDING FOR TSL DEVELOPMENTS BY CSIRO AND AUSMELT

Table VIII gives a summary of the maximum team size and the funds invested in the development of the technology by CISRO and Ausmelt.

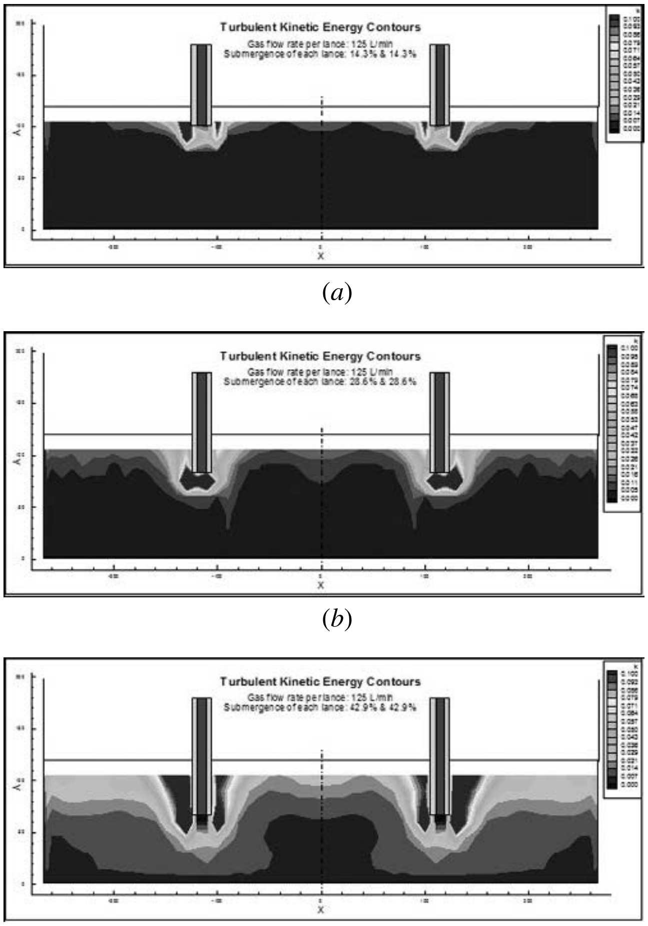
The quality of people and their technical and commercial competency is very significant in achieving a development of worldwide significance and succeeding in commercialization of the technology in competition with world-leading companies.

In both the CSIRO and Ausmelt teams, the selection, training, and professional development of staff was of critical importance and has been generally successfully achieved.

The cost of developing and commercializing any technology needs to be considered carefully. There are times and situations where costs must be minimized, but if cost cutting is used inappropriately, the integrity and effectiveness of the project can be jeopardized. For instance, if a commercial plant is built with unsuitable components of the feeding, gas-handling, product-handling, or other "ancillary" components, the plant will not achieve its capacity or product quality. The optimization of designing, fabrication, procurement, engineering, and construction of any plant requires engineers with high levels of skill and judgment.

Initially, the TSL development was achieved by process engineering specialists. For scale-up and commercialization of the technology, it became important to support process engineering expertise with high-quality design and project engineers covering the full range of engineering disciplines. Marketing, sales, and commercial capabilities of the engineering staff as well as the commercial and financial support staff is a critical requirement of the commercial and technical success of the enterprise.

For a project involving construction of a TSL plant for a client, the team required includes contractors, engineers, consultants, and the staff of the company building the plant. The success of the project obviously demands the professional and efficient performance of all members of the team. The performance of a very large group of people must be recognized in the successful commercialization of TSL technology.



(*a*)

(*b*)

(*c*)

Fig. 23—Computational fluid-dynamics modeling of multiple-lance furnace for ironmaking: (*a*) lance submergence of 14.3 pct, (*b*) lance submergence of 28.6 pct, and (*c*) lance submergence of 42.9 pct.

Table VI. Plant and Process Developments During the Ausmelt Commercialization Phase

	Patent	Theoretical	Lab	Small Pilot Plant	Large Pilot Plant	Commercial
1. Plant Developments						
1.1 Multiple furnace systems						√
1.2 Multiple lance furnace	√	√	√		√	
1.3 Water-cooled lances	√			√	√	
1.4 Submerged combustion fired by:						
1.4.1 Coal				√		√
1.4.2 Heavy oil				√		√
1.4.3 Natural gas				√		√
1.4.4 Autogeneous sulfide smelting				√		
2. Process Developments						
2.1 Iron making	√	√	√	√	√	
2.2 Spent-pot lining recycle	√	√	√	√		√
2.3 Mobile phone battery recycle		√	√	√		
2.4 Electronic waste recycle		√	√	√		
2.5 Zinc leach residue recycle						√
2.6 Nickel-PGM matte converting				√		√
2.7 Continuous copper matte converting	√			√		
2.8 Lead concentrate smelting				√		√
2.9 Lead secondaries smelting				√		√
2.10 Lead smelting slag reduction and fuming				√		√
2.11 Nickel leach residue smelting			√	√		√

Table VII. Ausmelt Commercial Development—1990 Onward

Mr. Brian Lightfoot	Ausmelt Technical Director and Manager of Ausmelt Equity Ventures
Mr. Peter King	Ausmelt Marketing Director
Dr. Ken Robilliard	Ausmelt Operations Manager, then Manager of Funsur Tin Smelter
Mr. Kevin Wong	Ausmelt Engineering Manager
Mr. Paul Markham	Rio Tinto Zimbabwe Smelter
Dr. C Y Choi	Korea Zinc Co. Recycling plants at Onsan
Mr. Barry Fairley	Floating the company
Mr. Terry Silverson	Chairman on Floating Ausmelt
Mr. Ken Hamilton	AusIron marketing and the South Australian Steel and Energy (SASE) Project
Mr. Ross Baldock	Ausmelt Process Engineering Manager
Mr. Gavin Swayn	Ausmelt Process Engineer, then Portland Aluminum Spent Pot Lining (SPL) Plant Manager
Dr. Harry Li	Ausmelt Business Manager-China
Mr. Paul Abbott	Ausmelt Managing Director
Mr. Mark Thompson	Ausmelt General Manager of Engineering
Dr. Joe Sofra	Ausmelt Sales and Marketing Manager

Table VIII. People and Funds for CSIRO and Ausmelt Development Phases

Phase	No. of People in Team (CSIRO & Ausmelt)	Time	Total Funding A$ (Including Plant Cost)
Idea	1	6 months	~20,000
CSIRO Development	1 → 4	10 years	~5 million (CSIRO ~1M)
Ausmelt Development	1 → 10	9 years	~10 million (Ausmelt ~3M)
Ausmelt Commercialization	10 → 60	14 years	~1 billion (Ausmelt ~100M)

VI. FAILURES

Ausmelt's TSL technology has not achieved complete success with every initiative undertaken. Not all plants have achieved continuing sustainable operation for clients. Fortunately, there are not many instances of failed projects.

Reasons for project failure are not always related to the performance of the plant itself, but may relate to the overall economic environment at the time. The downward swing of metal prices, a change in performance or ownership of mines producing raw materials, and alternative market arrangements for intermediates have all caused TSL projects to be discontinued. There have also been plants which have suffered technical difficulties because of problems with refractories, ducting, oxygen or air supply, and other external facilities. There have been a number of developments which have not yet proceeded beyond pilot plant work into commercial operations, but the reasons generally have not been that the results were not as expected. Commercial operations are being examined or envisaged for processes under development.

Two of the business initiatives of Ausmelt have not yet achieved sustainable operations, but they can still be successful in the future. One of these is establishing Ausmelt's own industrial production through Ausmelt Equity Ventures. Another is the Ausmelt Technology Corporation based in Denver, CO, aimed at developing and servicing the use of the technology for waste processing in North America.

VII. IMPORTANCE OF CONTINUING BACKGROUND R&D

Ausmelt has been successful in improving the hardware of TSL and in developing new applications. In my experience, commercial developments generally occur before R&D is carried out into the basic aspects of relevance to the new processes and/or equipment involved. I think that background R&D is best carried out by research organizations not directly involved in commercialization, because this encourages a more abstract and independent approach to the problem and brings in fresh minds with the potential for cross fertilization.

In the case of Ausmelt Technology, two organizations were able to provide R&D work in support of commercialization. CSIRO was crucial to getting the technology to production stage, but was of little benefit to Ausmelt over the past 23 years because of the competition for development funds and because of the competitive position with MIM, to whom they gave exclusive access to their research in the TSL area during the 1990s.

Universities were very helpful in supporting developments by Ausmelt and in generating ideas for improvements. Excellent working relationships were maintained with Dr. Neil Gray and his group at G.K. Williams Centre at University of Melbourne and with Professor Yos Morsi and his group at Swinburne University of Technology.

Areas still needing investigation include the following:

(1) flow patterns of liquids and gas in reactors and lances during injection;
(2) feeding solid materials beneath the surface of a liquid slag bath;
(3) measurements in furnace (temperature; oxygen potential; slag, matte, and metal surface position; and composition of liquid products from the furnace (instantaneous and continuous); and
(4) specific chemistry- and process-related issues for new applications.

VIII. THE FUTURE

The TSL technology is now a major component of the worldwide production of nonferrous metals. The cost, environmental impact, controllability, and versatility of the technology will continue to expand the number and capacity of production plants for smelting copper, tin, lead, nickel, precious metals, and PGMs.

The solution to the waste problems in the metallurgical industry such as zinc leach residues, zinc-lead slags, and alumina plant spent potlining are demonstrated by Ausmelt plants now in production, and, when environmental requirements dictate, there will be opportunities for industry to utilize these proven processes.

Environmental pressures to control dust and gas emissions from smelters will increase with time, and, in order for the industry to be sustainable in proximity to towns or agricultural production, those present smelting units which are intrinsically difficult to seal, such as Pierce–Smith converters, sinter plants, and rotary furnaces, will need to be replaced. Coke ovens, needed to produce the bed of a blast furnace for ironmaking, are another example of technology which causes significant environmental problems. There are examples of Ausmelt plants in operation now which can efficiently and cost-effectively solve these problems. Ausmelt copper matte and nickel-PGM matte converting is now proven technology. The lead-sinter plant/blast-furnace replacement at Nordenham demonstrates substantial cost savings as well as greatly reducing the environmental impact of lead smelting.

The AusIron pig-iron technology can accept any form of iron feed and most coal types as fuel and reductant and has been demonstrated to be cost- and energy-efficient for the production of iron. While there is a long way to go to replace blast furnaces producing many millions of tons per annum of iron, there are smaller-scale niche markets, at present, provided in the iron and steel industry. Ultimately, replacement of the huge blast furnaces by technology such as Ausmelt's can be expected.

There are also potential future metal markets for TSL based on extensive work which has been done on projects which did not go into commercial production. Examples are precious-metal production from a range of materials, smelting of nickel laterites, smelting ilmenite, antimony/gold processing, processing complex ores and concentrates, and recycling of secondary metals from residues and wastes containing valuable metals such as platinum, gold, cobalt, bismuth, *etc*.

The successful processing of hazardous wastes such as SPL and municipal waste incinerator ash demonstrates that the technology would be suitable to recycle hazardous industrial waste. The cost of recycling must be kept low, and the TSL technology is capable of low-cost operations if the scale is large enough, or if the products are of sufficient value.

Another way of enhancing the economics of waste recycling is to produce a high-value product from the slag. In the CSIRO development phase of TSL, we examined the production of tiles from Broken Hill Proprietory Company Limited (BHP) iron blast-furnace slags. This required a modification of the slag composition, which was very easily achieved in the TSL system.[42] As a side issue, I demonstrated the ease and controllability of the production of a foamed slag. The slag produced could have a density of less than 1 (it floated on water) and was extremely tough. A building material produced in this way might have many valuable applications and could be sold at a price much greater than slag used in cement, concrete, *etc*.

I think that TSL can also be developed to safely recycle municipal waste, and Ausmelt holds a patent in this area. Note that steam or power production are important valuable products from many of the Ausmelt plants shown in Table I and, for catalytic waste converters, this will be a significant aspect of the operations. The system has been shown to be effective in destroying and preventing emissions of complex halogenated hydrocarbons such as dioxins and furans.

IX. CONCLUSIONS

I am greatly honored that TMS has given me the opportunity to talk about TSL smelting developments which have taken place during my professional life. Taking an idea to worldwide commercialization has involved me in many areas, including technical, commercial, and corporate experimentation and development. Personally, I have moved from the role of postgraduate student to retired pyrometallurgist.

Our ancient art continues to provide a challenging and rewarding career path for young people with a technical bent who want to improve the commercial and community aspects of industrial production.

I see in my company and among the staff of clients and associates, a large number of people who are both well trained and highly motivated, with the technology, community, and family support structures needed to achieve great advances. Application of the present technology and further innovation, development, and commercialization of new ideas will continue the drive to provide sustainable, healthy, and well-appreciated processing of materials.

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