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Energy saving and pollution control for short rotary furnace in secondary lead smelters

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Abstract

This work discusses a method to suppress the fugitive emissions of total solid particles (TSP) and save energy for industrial lead smelters. Pilot scale experiments simulating the industrial short rotary furnace (SRF) in lead smelters were studied. An energy study was manifested on a typical lead smelter. Factors affecting the objectives of this work have been investigated.

The results obtained revealed that the rate of fuel consumption of heavy fuel (mazout) is highest in the early period of smelting. The flue gases in the existing small lead smelters are heavily loaded, with TSP outweighing the constrains given by law 4/94. About 60% of the energy input in the SRF escapes to the environment causing pollution hazards of TSP and spreading out excessive heat. Applying clean technology including pelletization of battery paste saved about 35% and 12.5% of heat and total energy consumption, whereas fugitive TSP decreases by about 67%. A theoretical model explaining the lead recovery process is given. It is based on heat and mass transfer and the thermodynamic properties of the species and reactions involved. Prediction of the findings of this model has been experimentally verified with a marginal accuracy of 4%. On an economic basis, nearly 14% of the plant turnover is saved annually. © 2001 Published by Elsevier Science Ltd.

Keywords: Energy saving; Pollution control; Acid lead battery recycling; Environment management

1. Introduction

Due to the widely changing nature of the regulations, lead smelters brought additional pressure on the Environment Affairs Agencies EAA to use other techno-

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logies. These pressures, combined with the failure of the Agencies' technology efforts, led to the expanded use of stabilization technologies [1,2]. Moreover, poor experience in commercializing treatment technologies have spurred the search for simpler and cheaper facilities to deliver the planned economics. One direction is to find ways to recover lead in useful forms [3].

Schenker [4] reported that the starter battery scrap and subsets of plates were crushed, screened and sink-float-separated. Lead oxides and metallics were then separately reduced and molten campaignwise in a rotary kiln to low-antimony (<1% Sb) or antimony-rich (2.5–3.5% Sb) lead bullion. Extensive, automatically operated effluent treatment with a capacity of 70 m³/h was connected to the battery treatment plant. Industrial waste water was also transported for sedimentation and pH adjustment before recycling. A dedusting system installed with 250 kWh electric power for a short rotary furnace (SRF) was used. Schenker showed that clean backwater was collected and partly re-used, while the remainder was fed into the river with constant pH and quantity. Reynolds et al. [5] showed that Engitec Impianti, SPA of Milan, Italy, had successfully designed and constructed battery breaker systems in two European locations and a third in Toronto, Ontario, Canada. The system crushes the whole batteries, separates and desulphurizes the battery paste. Plant data also indicates an increase in furnace productivity of about 25–30% using feed from the CX system.

Worcester and Moenster [6] showed that battery paste could be treated with sodium carbonate to produce lead carbonate paste for smelting in a reverberatory furnace. The slag from such a furnace would be campaigned through a traditional primary blast furnace to produce hard lead. Conversion of battery paste into lead carbonate was carried out in reaction vessels constructed of 316 stainless steel. Lead carbonate so formed was then transported without pelletization to a reverberatory furnace, together with coke, for smelting. The reverberatory furnace was designed for a 24,000 CFM at 150°F process gas offtake. The gas was vented to the process trail from the furnace to the baghouse. No cost analysis for running this cleaning system was given. Moriya [7] in his paper showed that blast and reverberatory furnace types are disappearing in favor of direct smelting processes

Newly developed lead smelting processes include QSL [8,9], KIVCET [10,11], ISASMELT [12,13], Outokumpo's flash smelting [14], and Boliden's Kaldo [15]. These authors reported that it was permitted to charge the recently implemented QSL or ISASMELT furnaces with moist green pellets, continuously and directly into the melt of the oxidation zone through ports in the top. Dried feed preparation required investment in an additional dryer and complex cooling system and as a result greater energy consumption. The ultimate pollution problem for lead extraction and recycling was both the emissions of toxic dust and fumes and sulphur dioxide gas to the environment and the workplace. The authors said "the entrance of the 21st century will be a vary exciting period during which a revolution will be made in lead smelting". In line with that, Davey [16] showed that lead ore or concentrates and recycled material could be introduced into the process without preparation, briquetting or drying, so that sintering was unnecessary.

Forrest and Wilson [17] reported the use of a short rotary furnace (SRF) for lead

recycling. The feedstock included lead dross, battery plates and even whole batteries. Pickles et al. [18] reported a process for the recovery of metal lead from battery residue. The process involved pelletization of the residue with sodium carbonate and moisture. The process minimized the sulphur dioxide emission. Gaballah et al. [19] described a new approach for the characterization and extraction of strategic metals, such as (Nb and Ta)₂O₅ based on combined hydro- and pyrometallurgical processes. The planning of successive alkaline and acid leaching of semi-pilot slag based on the “pseudo-structure” of these amorphous materials permitted selective dissolution of the economic metals, lower consumption of chemical reagents, less toxic residues and a high recovery rate ($\geq 85\%$). Habermann and Rao [20] showed how flue dust and sludge of an arc furnace could be mixed with a carbonaceous material. The mixture was then pelletized and heated at 600–1150°C to recover the lead, zinc and cadmium. Rabah [21] reported that abating 1 ton of TSP from iron foundries using a SRF furnace would cost US\$1000–1500.

Queneau et al. [22] and Kammer et al. [23] gave particular attention to optimizing matte and slag compositions. Because the input waste contained significant quantities of magnesium, aluminium and chromium, avoiding the formation of viscous, high melting-point slag was of particular concern. Soda ash slag was used in the SRF-smelting, similar to the rotary kiln-smelting at Oker. Faced with the problem of handling and dumping soda ash slag, other slag types based on CaO–SiO₂–FeO were used. Fowes [24] showed that the free energy of adhesion was strongly related to the adhesion of an adsorbed water layer on metal oxides. Humphris et al. [25] showed that 60% reduction in SO₂ emissions from the Copper Cliff smelter had been achieved through the use of high strength gas streams using innovative technology. The development of quench systems has been successful in overcoming spray system plugging problems and coarse solids separation. The Dynawave gas scrubbing and cooling systems have functioned well following some adjustments to the furnace froth column plate arrangement.

In order to save energy in industrial facilities, primary and secondary resources such as solar, geothermal, waste process water and cooling systems have been reported [4,26–28]. Several techniques for saving energy have been designed and tested. These include heat exchangers, heat pumps, chemical redox reactions and, more recently, updating the process technology of the industry.

The aim of this study is to discuss a method for saving energy and controlling the emissions of total solid particles (TSP) in the lead industry. Factors affecting energy consumption and concentration of TSP emissions for a lead smelter have been studied on laboratory and semi-pilot scales.

2. Experimental and methodology

2.1. Materials

Sample of acid lead battery paste were obtained from El-Messrya Co., Cairo, Egypt, for smelting, refining and shaping lead. The battery paste was separated from

the battery grids by wet grinding for a short time in a ball mill, followed by wet sieving. The process water was decanted and then filtered for re-use. The paste cake so obtained was left to dry in an ambient sunny climate. Laboratory scale and semi-pilot scale experiments were carried out using 5 and 100 kg of the lead battery components, respectively. The chemicals used in this work were of a technical pure grade. Hydrochloric and nitric acids, hydrogen peroxide solution (30% volume), sodium carbonate and ammonium hydroxide were used for leaching operations. Double distilled water was used for chemical analysis. Tap water of the town network was used for other purposes. Spent active charcoal obtained from the beverage industry was used as a reducing agent in the smelting process. Soda ash and lime were used to attain a basicity suitable to decrease the melting point of the formed slag and to help free the movement of the molten lead droplets towards the bottom of the SRF.

2.2. Description of the suggested method

Battery paste was carbonated to convert the lead sulphate to hydrocerussite (carbonate) by leaching with sodium carbonate solution. The solid product was rinsed with water and left to dry naturally. It was then blended with carbon, iron chips, soda ash and lime in a kneading machine fitted with double Z arms. Molasses was used for binding. Pelletization was carried out using a lab pelletizer, 45 cm in diameter.

2.2.1. Smelting experiments

Smelting experiments were done in a silicon carbide-heated chamber furnace at 1600°C, type 246/MRK42 VEB Elektro Frankenhäusen (MLW), Germany. The process was carried out using a 2 l salamander (silicon carbide) crucible. The furnace had an opening in its roof, allowing access for a mechanical stirrer driven by a 0.75 kWh motor. Smelting was carried out within the temperature range 900–1100°C for periods of up to 1 h.

2.2.2. Leaching experiments of the smelting slag

Slag so formed was skimmed and leached using a hot hydrochloric/nitric acid mixture. In some experiments, hydrogen peroxide was used to enhance metal dissolution. The metal content in the leachant was filtered and determined by an atomic absorption spectrophotometer. The metals were then separated by applying the method given by Abdel and Rabah Basir [26].

2.2.3. Melting of the battery grids

Melting of the isolated battery grids was performed in a muffle furnace, the top of which had an opening providing access for a mechanical stirrer. The grids were first pressed under 100 ton compression load in a hydraulic press to form solid blocks 10×10×5 cm³ in dimension. A Si–C crucible was inserted into the furnace hearth. When the furnace with the crucible was equilibrated to the required temperature, grid blocks were fed into the crucible. A smothering or fluxing agent was sub-

sequently added. After melting of the lead grids, the mixture was stirred at 500 rpm for the programmed period. At the end of each experiment, the formed slag was skimmed and the molten lead was poured into a suitable receiver and weighed when cold.

2.3. Measurements of the physico-chemical properties

2.3.1. Particle size measurement

Particle size measurement was carried out using a SediGraph 5100 particle analyzer, Micromeritics, USA. Computerized Philips X-ray diffraction equipment, model PW/1710, with Ni-filter, Cu radiation ($\theta=1.542$) at 40 kV, 30 mA, and scanning speed $0.02^\circ/\text{s}$ was used to identify the intermediate and end products of the leaching experiments. The diffraction charts and relative intensities obtained were compared with JCPDS files. The compositions of the metal products were analyzed by an emission spectrophotometer type 3460-880 ARL, Seuces. Lead, was determined as a chromate, while tin and antimony were determined titrimetrically with 0.05 M iodine-potassium iodide solution.

2.3.2. Determination of TSP level

Quantification of the total concentration of solid particles of lead smelting dust TSP in mg/m^3 was performed gravimetrically, applying the method given by Rabah [21]. External emissions that may contribute to the measurement of TSP (such as vehicles or other plants) were separately measured and considered.

2.3.3. Determination of recovery efficiency of the suggested method

- The weight percentage of the yield of metal lead from the battery paste (Y_{mr}) and that recovered from leached slag (W_{ml}) were determined gravimetrically. The extent of W_{ml} was computed from $(W_{\text{m}}-W_{\text{mu}})$, where W_{m} and W_{mu} are the weights of lead metal in the slag, as analyzed, and the unleached part, respectively.
- Extent of TSP escape as a percentage, W_{tsp} , was computed from the relation:

$$W_{\text{tsp}} = W_{\text{mp}}(1 - (Y_{\text{mr}} + W_{\text{ml}})) \times 100$$

where W_{mp} is the total metal weight in the input battery paste.

- Efficiency of lead recovery, $\Delta\epsilon_r$ was determined from

$$\Delta\epsilon_r = W_{\text{mp}} - (Y_{\text{mr}} + W_{\text{ml}})$$

using powdered and pelletized battery paste which were separately determined. The effects of pelletization of the battery paste on W_{tsp} and $\Delta\epsilon_r$ values were determined and the gain in plant turnover efficiency based on the suggested method was obtained from:

$$(\Delta\epsilon_r) = (\Delta\epsilon_r)_{\text{updated}} [1 - (\Delta\epsilon_r)_{\text{existing}}] \times 100$$

Table 1
The structure of the secondary lead industry in Egypt

Location	Type	No. of furnaces	Fuel type	Fuel/F (tons/day)	Product (tons/day)	Product (tons/year)
Greater Cairo	SRF	24	HFO	2.4	16–16.8	26,100
	VSR	2	HFO	0.6	7.0	1000
	K_r	11	Kerosene	0.4	Refining	
	K_{sh}	6	kWh	124	Shaping	
Alexandria	SRF	1	HFO	2.4	16–16.8	1150
	VSR	1	HFO	0.6	7.0	500
	K_r	1	Kerosene	0.4	Refining	
	K_{sh}	2	kWh	124	Shaping	
Other places	SRF	2	HFO	2.4	16–16.8	3250
	VSR	–	HFO	0.6	7.0	–
	K_r	6	Kerosene	0.4	Refining	
	K_{sh}	1	kWh	124	Shaping	
Total	SRF	27	HFO	64.8		32,000
	VSR	3	HFO	1.8		
	K_r	18	Kerosene	7.2		
	K_{sh}	9	kWh	1116		

3. Results

Two types of rotary furnace have been implemented in the existing lead smelters in Egypt: short (SRF, 5.4 m long) and very short (VS, 3.8 m long). Kettles for refining (K_r) and shaping (K_{sh}) are also in use. Tables 1 and 2 show the structure and types of products and the turnover of the secondary lead industry in Egypt, respectively. The production capacity of soft (pure) lead, antimonial hard lead and

Table 2
Types of lead products and annual turnover of a typical small lead smelter

Lead product	Annual turnover			
	tons/year	% of total	Unit price (L.E.)	Sub-total (million L.E.)
Pure lead ingots (blocks, pigs and links)	2560	8	3640	9.318
Hard lead bullion	3840	12	2850	10.944
Pipes and Fixtures	23,500	73.4	3100	72.850
Sn, Sb–lead alloy ^a	500	1.6	24,000 ^a	12.000
Lead oxides	1600	5.2	4200	6.720
Total	32,000	100		111.832

^a About 30% Sn (exchange rate, US\$1=3.3995 L.E.).

Table 3

The composition of 100 kg of spent acid lead battery and the pollution level in the existing lead smelters

Step	Battery components (kg)				Pollution level (kg/shift)		
	Acid	PE/PP	Grids	Paste	Liquid	In land	TSP
Handling	1.15						
Breaking	0.34	17.5	38.5	42.2	92	4	
SRF loading	0.01		38.2	41.7		8	
Losses			0.03	0.05			
Smelting						1	129.6
Ingot pouring						2	1.385
Slag pouring						200	1.00
Refining						3	
Shaping						0.5	
Total (wt%)	1.5	17.5	38.5	42.2	92	218.5	181.9

other lead alloys amounts to 32,000 tons per year. Table 3 shows the composition of the spent acid lead batteries and the fugitive TSP emissions.

Fig. 1 represents the suggested flow sheet of an updated clean technology process to recover antimonial hard lead alloys from spent acid lead batteries. The method includes 20 steps compared to only five steps in the existing dirty process. From an economic point of view and considering the skills of the man power of the existing plants, automatic, semi-automatic and manual processes are chosen for the industrial plants.

Fig. 2 shows the smelting temperature profile of a typical SRF for lead plants and the consumption rate of the heavy fuel used (mazout). It is seen that the furnace temperature drastically increases with time towards a maximum of 1450°C after 2 h, whereby a plateau is approached up to 6 h after which it slightly decreases to 1150°C. The rate of fuel consumption is highest during the starting period of the furnace and decreases towards a minimum after 6 h. Fuel consumption is shut off during pouring of the furnace load.

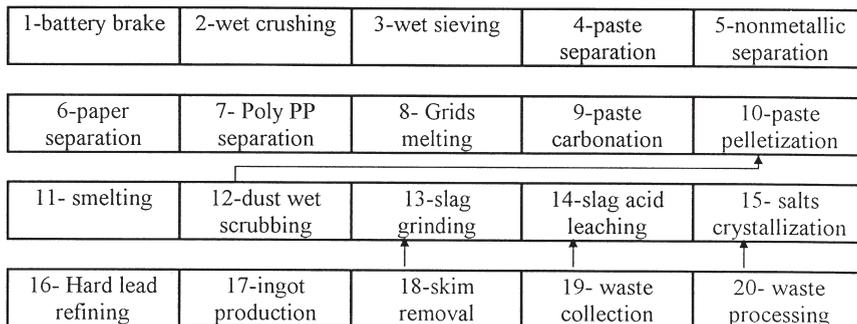


Fig. 1. The suggested process flow sheet of the updated clean technology to recover hard antimonial lead bullion from spent batteries.

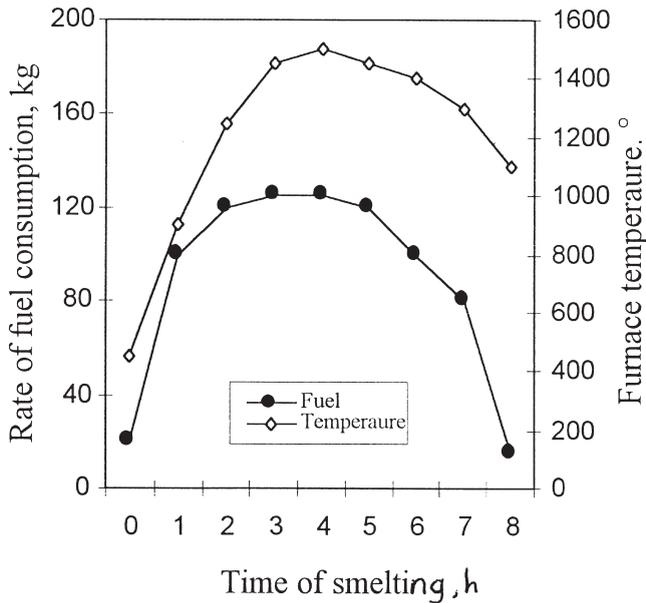


Fig. 2. Temperature profile of the SRF furnace and the rate of fuel consumption (mazout) as a function of time.

Fig. 3(a, b) show the uncontrolled TSP emission purging from SRF as a function of smelting temperature. TSP emission levels monitored at 1000 and 1200°C amount to 3510 and 2750 g/m³, and 1150 and 960 g/m³ with powder and pellets of 10 mm diameter, respectively. However, none of these levels complies with the standard level as specified by the law 4/94 (200 and 100 ppm for old and new plants, respectively). It is also seen in Fig. 3(b) that the TSP emission level complying with law 4/94 is only attained by smelting pelletized paste of 10 mm diameter at <1050°C. In other words, 65–67% reduction in fugitive TSP emission level is achieved by applying the suggested method. However, the scrubbed solids from this method are suitable feed for the pelletizer. Fig. 4 shows the mechanical strength of the pelletized battery paste as affected by molasses content. The mechanical strength value increases gradually with an increase in the molasses percentage, towards a maximum value with 12.5% molasses. The standard strength is achieved with pellets having a diameter of 10 mm. Fig. 5 shows the yield of metal lead (Y_{mr}) as a function of smelting temperature using powder and pelletized paste having different diameters. It is seen that Y_{mr} increases with an increase in both the smelting temperature up to 1100°C and the pellet diameter up to 10 mm. The maximum value of Y_{mr} is attained at 1050°C.

Table 4 shows the cost of capital expenditure and running (utilities, direct and operating) costs of a pilot plant having different capacities. The costs increase with an increase in the annual capacity. A pelletizer with a capacity of 5000 metric tons per annum (mt pa) (taken from 13,150 mt scrap batteries) is found to be most econ-

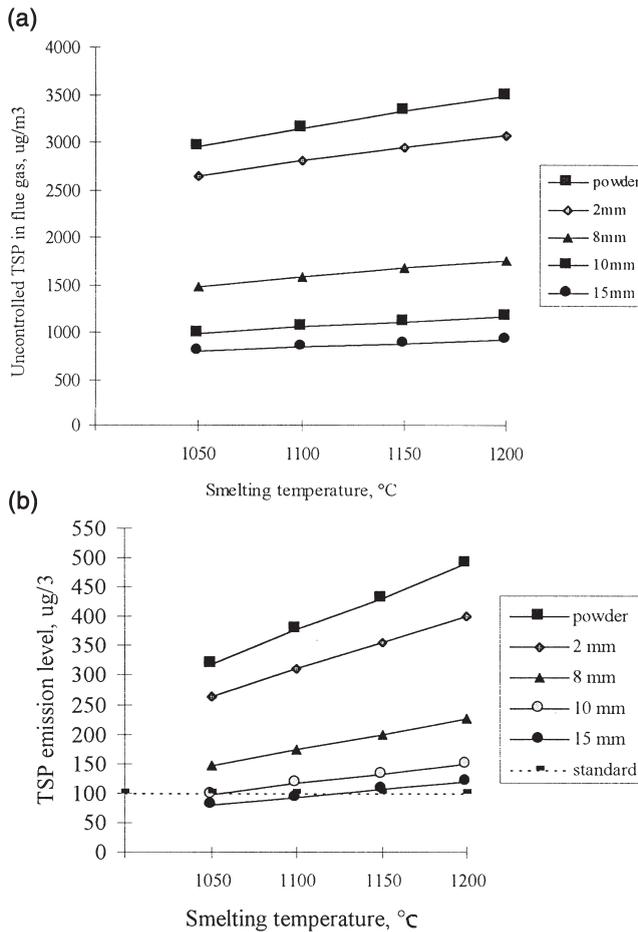


Fig. 3. (a) The uncontrolled TSP emission level using powder and pelletized battery paste as affected by the smelting temperature. (b) The controlled ESP emission level of the updated technology using powder and pelletized battery paste as affected by smelting temperature.

omic in terms of capital and operating costs. Table 5 shows the energy consumption for 1 ton of spent acid batteries in a case study for an industrial plant in light of the suggested method compared to the existing technology. It is seen that the fuel used in the existing plants is switched to natural gas. Also, most of the steps are automatic in response to manual operations in the existing plants. The total energy needs for processing 1 ton of scrap batteries has been converted into kWh equivalent, whereby about 12.5% of the total energy requirement is saved. Table 6 shows the results of a previous economic study on the effect of pelletizing the battery paste on the annual turnover and production costs of a typical lead smelter. A plant with a capacity of 10,000 mt scrap batteries pa was taken as a model. Savings of 8.2% by weight of metal lead production and 4% of the running costs of the plant are achieved.

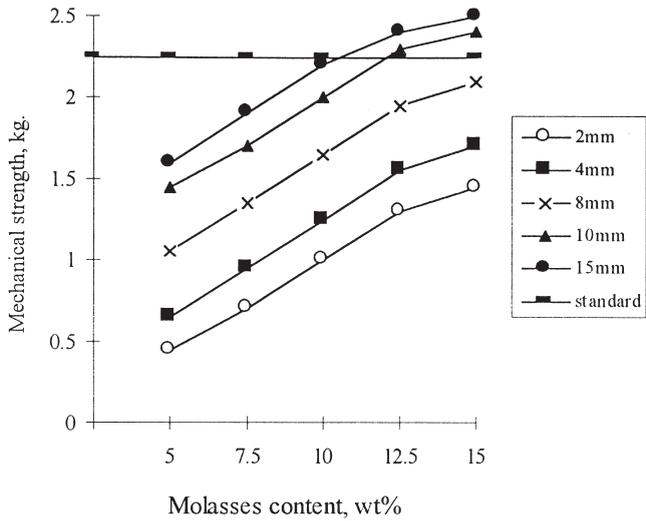


Fig. 4. The mechanical strength of the pelletized battery paste as a function of the molasses content.

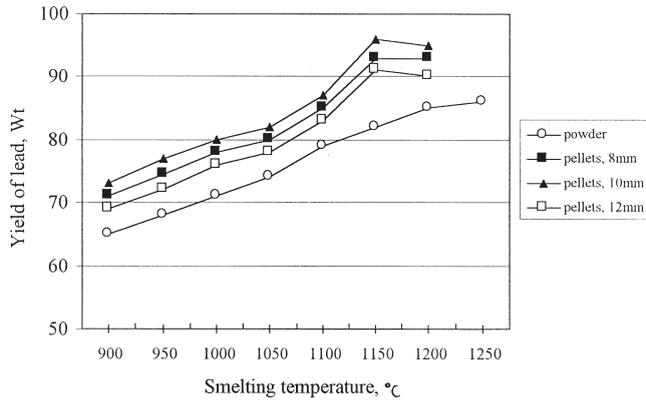


Fig. 5. The yield of lead as a function of smelting temperature (°C) using powder and pelletized battery paste, 8–12 mm in diameter.

4. Process economics

The methodology for estimating the running costs of a secondary lead plant is as follows.

4.1. The capital expenditures

The capital expenditures are for the studied plants and equipment that include the gas cleaning system, the treatment device for cleaning industrial waste water, and the ventilation system and fans to collect the fugitive TSP emissions inside the plant.

Table 4
Costs of capital expenditure of pelletizers using carbonated battery paste [29]

Pelletization capacity (mt pa)	Cost of capital expenditure, $\times 10^3$ L.E.				Cost/plant, $\times 1000$ L.E.
	Equipment	Land	Others	Total	
1000 separated from 2630 mt scrap batteries	450	50	–	500	500
3000 separated from 7900 mt scrap batteries	650	80	–	730	730
5000 separated from 13,150 mt scrap batteries	800	150	50	900	950
7500 separated from 19,125 mt scrap batteries	1350	150	100	1500	1600
Pelletizer capacity (mt/year)	1000	3000	5000		500
Capital cost (L.E./mt)	500	243.3	190		213.3

(Exchange rate \$US1=3.3995 L.E.).

Table 5
The energy consumption per recycling 1 ton of spent batteries, a case study in an industrial plant^a

Production	In existing plant				The suggested method			
	Manual	Automatic	Fuel ^b , F (kg)	kWh, E	Manual	Automatic	Fuel ^c , F (m ³)	kWh, E
1	2	3	4	5	6	7	8	9
Handling	×		–	–	–	×		1
Breaking	×		–	–	–	×		3
Crushing	–		–	–	–	×		6
Sieving	–		–	–	–	×		4
Carbonation	–		–	–	–	Semi	30	2
Grid melting pelletization	–		–	–	–	×	47	8
Smelting	–	Semi	112	42		×		42
Refining	×		20	12		×	53	12
Scrubbing		×		668		×	14	187
Shaping		Semi	30	8		×	–	8
Others	×	–	10	15		×	6	–
Total			172	645		–	6	273
\equiv kWh, $F+E$			172	9733			156	8516

^a %Saving in energy consumption= $\frac{\Sigma(5)-\Sigma(9)}{\Sigma(5)}$ =12.5%.

^b Mazout.

^c Natural gas.

Table 6

Effect of updating the recovery technology on the annual turnover and production cost of a typical lead smelter using SRF [29]

Item of economic analysis	Plant expenses	
	Before updating	After updating
1. Weight of input scrap (tons pa)	10,000	10,000
2. Weight of product (tons pa)	5330	5776
3. % Saving (tons pa)	–	8.2
4. Price of product (L.E./ton)	2950	2950
5. Price of product (million L.E. pa)	15.7	17.039
6. Metals by slag leaching (milliom L.E.)	–	0.19
7. Total price of products (5+6)	15.7	17.229
8. TSP ($\mu\text{g}/\text{m}^3$) in flue gas	3150	100
9. TSP (tons pa)	115.128	3.960
10. Expenses of scrubbing (pa)	0.345	0.249
11. Expenses of maintenance (milliom L.E.)	0.082	0.197
12. Annual plant gain (7–[8+11])	15.355	16.783
13. Saving due to pelletization (million L.E.)	–	1.428
14. Running costs of plant	14.050	14.811
15. Annual gain (% running cost)	9.29	13.31
16. % Saving/plant running costs	–	4.02

These capital expenditures have been converted into annualized capital costs using a 10% discount rate, assuming the normal life time of the equipment is 12 years.

4.2. The annual operating costs

The calculations take into account that the Egyptian authorities have reduced the high subsidies on energy prices. Nevertheless, the present energy prices are still subsidized by about 20%. The annual operating costs include:

1. labor (4 L.E. per hour), supervision, raw materials, energy, water, chemicals, maintenance, spare parts etc.
2. the average prices of energy are: heavy fuel oil (HFO) (mazout) is 100 L.E. per ton; kerosene is 500 L.E. per ton; natural gas is 200 L.E. per ton (equivalent to 0.3 L.E. per m^3) and the average price of electricity is 0.21 L.E. per kWh.
3. running costs for monitoring the emission level consist of:
4. (a) frequent measurements at six sites inside and outside the plant, and
5. (b) measurements at four sites from the stack and inside the plant two times a year.

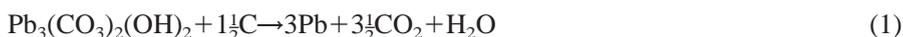
4.3. Additional costs

Additional costs are only given here as indicative estimates for representative “typical” plants. It has been possible to allow in the empirical analysis for prospective

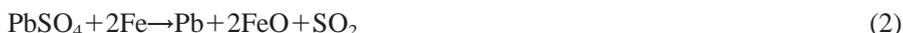
changes in technologies and the structure of the industry. However, the effects of a gradual rise in the charges are examined qualitatively and specific issues regarding possible changes before an economic instrument can be implemented are highlighted.

5. Discussion

In technical communities like Europe and the United States, the existing technology of the secondary lead industry involves 23 successive steps, including separating battery paste by breaking up scrap batteries followed by wet screening [27]. The latter step produces wet cake having about 22–28% moisture content. Partial drying is then manifested to decrease the moisture content down to about 8% prior to smelting in reverberatory or rotary furnaces. The traditional recycling technology of scrap battery paste involves the carbonation of lead sulphate to hydrocerussite, $Pb_3(CO_3)_2(OH)_2$ (desulphurized battery paste). Lead carbonate is then reduced by smelting at temperatures up to 1450°C. The reducing agents are carbon and iron oxide. In this study, carbon is used to display the following reduction reaction:



Iron chips are also used to reduce unreacted lead sulphate as follows



Most of these plants, apply smelting without paste pelletization. Problems encountered with pollution control of the industry are solved by installing powerful cleaning and ventilation systems. Although the running costs of these cleaning systems are relatively high, the running costs of the plant can sustain these overhead charges in the case of mass production. However, plants with small capacities and poor technologies cannot sustain the installation of expensive cleaning systems and so the applied technology is dirtier, poorer and the recovery efficiency is rather low (<86%).

The existing lead smelters in Egypt use SRFs. Heating is carried out using one burner working with HFO (mazout) and atmospheric air as the oxidizer. Field measurements show that the average fuel consumption rate amounts to 100 kg of HFO and 3600 m³ air per 1 ton of lead. During the initial period of smelting, a higher rate is matched to promote rapid heating of the furnace charge. The available hearth volume of SRF is 2.75 m³ (0.65 m² cross section × 4.25 m long). The projected flame moves at a velocity of 2.27 m/s and the tilting angle is about 10°. The main disadvantage of such a furnace design is that heating takes place mainly by radiation and partly by conduction whereby combustion products (heat energy and gases) smash into the furnace charge [4].

Rotation of SRF and the projection flow of the hot flue gases would drive out some of the materials in the furnace hearth. The pulp density of the flue gas is proportional to the rotation speed of the furnace, the smelting temperature, pressure and velocity of the HFO combustion products and inversely proportional to the

weight of the solid particles. Under these conditions, the flow of the flue gases is turbulent. Laden-flue gas dust is thus readily displaced and escapes as fugitive emissions in the environment. It becomes reasonable to suggest that the concentration level of fugitive dust in the air increases with a decrease in particle diameter.

The capture of fugitive solids is conventionally carried out with the help of a wet scrubber. The function of this device is well reported in the literature [28]. The temperature of the flue gases at the furnace exit, under steady-state steady-flow smelting conditions, amounts to nearly 750°C. The temperature of the flue gas coming out of the wet scrubber exit (T_g) can be computed from:

$$T_g = [m_{\text{HFO}}C_{\text{vHFO}}T_{\text{HFO}} - ((m_wCp_w + m_aCp_a)T_a)] \quad (3)$$

where m , C_v , Cp and T are the mass flow rate, calorific value, specific heat and temperature of heavy fuel oil (HFO), sprayed water (w) and air (a). In the scrubber, a water film coats the laden flue gas particles, whereby capture of the dust can be achieved successfully.

The results obtained in this work show that updating the technology of secondary lead recovery has the following beneficial effects and advantages: (1) a high extent of lead recovery is achieved; a high extent of reduction reactions is manifested because reactants are more close to each other; (2) pellets are readily equilibrated in the furnace hearth in a short time and the smelting process takes place at a lower temperature, 1050°C compared to 1450°C in the existing technology; (3) savings of 12.5% of the total energy consumption per ton of lead; (4) a decrease in the volume flow rate of the flue gases and the laden flue gas dust by 65%; the concentration of the fugitive TSP emissions complies with the law; (5) a decrease in the running costs of the gas cleaning device.

The addition of alkalis such as soda ash, lime and silica to the pellet composition is essential. Soda ash and lime provide a basicity index of 0.8–0.9 to decrease the melting point of the slag so formed. This effect helps the molten lead droplets to freely diffuse through the porous texture of the reacted pellets, coalesce and sink to the bottom of the SRF hearth. It follows that a small portion of molten lead or other heavy metals go into the slag. In this context, pellets of 10 mm diameter are acceptable as they allow paths for the free movement of molten lead. However, pellets of about 10 mm diameter were found unsuitable as they trap an excessive quantity of metal in their pore systems.

In a previous study [21] we estimated the cost of abating 1 ton of TSP. It was found that the costs of abating TSP are directly proportional to the annual weight of TSP emitted, which approaches a value of 3000 L.E./ton TSP when the annual TSP emitted amounts to 6000–12,000 tons. However, with larger annual TSP quantities, a drastic increase in the costs takes place. For instance, with 14,000, 14,500 and 15,000 tons pa, the cost per 1 ton of TSP abated amounts to 3400, 6000 and 8000 L.E., respectively. The computed costs of abating the fugitive TSP of the lead smelters would thus be 4.5, 18, 39 and 120 million L.E. for 3000, 6000, 12,000 and 15,000 tons of TSP, respectively. Practically, the annual weight of TSP emissions of lead smelters in Egypt approaches the latter amount.

It was found that small lead smelters who are heavily polluting would not

implement any control options in response to a high charge per ton of TSP emitted. This cost may exceed estimates of these lead smelters to abate emissions. For plants with two or more SRFs using mazout, the target may be affected by installing and operating cleaning devices, comparatively low in price, such as a wet scrubber. Other cleaning systems such as bag filters are not acceptable on an economic basis. They would further increase the charge of abating emissions up to >8500 L.E. per ton of TSP. This type of cleaning system is only suitable for abating emissions in plants applying updated technology with high mass production.

Plant visits showed that the installation of cleaning and ventilation systems is based on the annual expenditure and running costs. Hence, it would be favorable to encourage lead smelters to update their technology and to implement and operate these controls. The total costs to all lead smelters in Egypt for both abatement costs and charge payments would be about 87 million L.E., which is about 32% lower than the total costs to all firms under the incentive charges of 6000 L.E. per ton of TSP. If the firms do not do this, their total costs would be substantially higher under the incentive charges scenario. Concrete proposals to help solve the TSP abatement problem in lead smelters in the country would suggest updating the technology of lead recovery. Reasonably, pelletization of battery paste would provide the dual benefits of TSP control and saving 4% of the running costs of the plant.

6. Conclusions

Saving energy and pollution control in lead smelters are achieved by updating the technology of recycling the spent acid lead battery paste prior to smelting. The following challenges have been achieved.

1. High extent of lead recovery.
2. Pellets are readily equilibrated in the furnace hearth at 1050°C in a short time compared to 1450°C in the existing technology.
3. Saves 12.5% of fuel the total energy needs.
4. Decreases the volume flow rate of the flue gases and the laden-flue gas dust by 65%. The concentration of the fugitive TSP emissions thus complies with the law.
5. Decreases the running costs of the gas cleaning device(s).
6. Saves nearly 4% of the annual production cost of the plant.

References

- [1] EEAA (Egyptian Environmental Affairs Agency). Government of Egypt, law no. 4/94, 1994.
- [2] Schreifer J. The challenge of electric furnace dust. In: *New steel.*, 1995:28.
- [3] Moser WS, Mahler GT, Knepper TR, Kuba RW, Pusateri JF. Metals recycling from steelmaking and foundry wastes by Horesehead resource development. In: *Electric Furnace Conference Proceedings*, ISS, 1992:145.
- [4] Schenker G. Lead recycling from battery scrap and other raw materials in MetalEurop's lead smelting

- plan in Oker. In: Mackey TS, Prengaman RD, editors. *Lead-Zinc'90*. Pennsylvania, USA: The Minerals, Metals & Materials Society (TMS), 1990:979–1000.
- [5] Reynolds RM, Hudson EK, Olper M. Advances in lead-acid battery recycling: Engitec's automated CX breaker system. In: Mackey TS, Prengaman RD, editors. *Lead-Zinc'90*. Pennsylvania, USA: The Minerals, Metals & Materials Society (TMS), 1990:975–96.
- [6] Worcester AW, Moenster JA. The DOE run company's quick resource recovery facility. In: Mackey TS, Prengaman RD, editors. *Lead-Zinc'90*. Pennsylvania, USA: The Minerals, Metals & Materials Society (TMS), 1990:1023–44.
- [7] Moriya K. Lead smelting and refining, its current status and future. In: Mackey TS, Prengaman RD, editors. *Lead-Zinc'90*. Pennsylvania, USA: The Minerals, Metals & Materials Society (TMS), 1990:23–38.
- [8] Fischer P. The present status of development of the QSL lead process. *J Metals* 1982;6:60–4.
- [9] Pollaert TJ. Lead production by the QSL process. Germany: Lurgi GmbH, 1986.
- [10] Ferri PF, Perillo A. The new lead smelter of Portovesme. In: *Extraction Metallurgy'85 Symposium*, Sept. London: I.M.M., 1985:891–3.
- [11] Perillo A, Carminati A, Schuermann P, Berger N. The KIVCET lead smelter at Portovesme: commissioning and operating results. In: Mackey TS, Prengaman RD, editors. *Lead-Zinc'90*. Pennsylvania, USA: The Minerals, Metals & Materials Society (TMS), 1990:903–18.
- [12] Errington WJ. Status of the Isasmelt lead smelting process. In: 11th AIME Annual Meeting, March 1; New Orleans, 1986:15.
- [13] Asteljoki J et al. Outokumpu flash-smelting method and its application for nickel and lead production. In: I.M.M Conference, Kunming, China, Oct, 1984:171–86.
- [14] Sychev AP, Poljakov IP. The current state and prospective of implementation of autogenous processes in lead production. *Tsvetnye Metally* 1981;8:9–12.
- [15] Asteljoki J. Outokumpu flash-smelting method and its application for nickel and lead production. In: I.M.M Conference, Kunming, China, Oct, 1984:171–86.
- [16] Davey TRA. Towards AD 2000. In: Mackey TS, Prengaman RD, editors. *Lead-Zinc'90*. Pennsylvania, USA: The Minerals, Metals & Materials Society (TMS), 1990:39.
- [17] Forrest H, Wilson JD. Lead recycling utilizing short rotary furnaces. In: Mackey TS, Prengaman RD, editors. *Lead-Zinc'90*. Pennsylvania, USA: The Minerals, Metals & Materials Society (TMS), 1990:971–8.
- [18] Pickles CA, Smith D, Tomlinson V, Toguri JM. Sulphur dioxide emission from soda ash smelting of scrap lead acid battery residue. In: *Proceedings of Conference on Primary and Secondary Lead Processing*, Aug 20–24; Halifax, Nova Scotia, Canada, 1989.
- [19] Gaballah I, Ferreira S, Djona M. Recovery of metals contained in spent catalysts using a thermal treatment followed by selective chlorination. *Rev Metall* 1995;31(4):215–21.
- [20] Habermann JH, Rao YK. Chemical dissolution of lead blast furnace accretions with potassium carbonate in the presence of carbon. *Canadian J Metall* 1988;24:36–47.
- [21] Rabah MA. Cost effectiveness of abatement options for emissions control in Egyptian iron foundries. *Waste Manage J* 1999;19:283–92.
- [22] Queneau PB, Douglas EC, Douglas KM. Optimizing matte and slag composition in rotary furnace smelting of lead residues. In: *International Symposium on primary and secondary lead processing*, Halifax, Nova Scotia, Aug 20–22, 1989.
- [23] Kammer U, Schenker G, Wieden HO. Secondary lead smelting using a silica slag. In: Hager JP, editor. *EPD Congress*, New York, 1993:917–23.
- [24] Fowes FM. Calculation of work of adhesion by pair potential summation. *J Colloid Interface Sci* 1968;28(3-4):493.
- [25] Humphris MJ, Liu J, Javor F. Gas cleaning and acid plant operations at Inco Cliff smelter. In: Diaz C, Holubec I, Tan CG, editors. *Pyrometallurgical operations, the environment and vessel integrity in nonferrous smelting and converting*. Nickel Cobalt 97 CIM Conference, vol. III, 1997:321–35.
- [26] Abdel Basir SM, Rabah MA. Hydrometallurgical recovery of metal values from brass melting slag. *Hydrometallurgy* 1999;53:31–44.
- [27] Reynolds RM, Hudson EK, Olper M. Advances in lead-acid battery recycling: Engitec's automated

- CX breaker system. In: Mackey TS, Trengaman RD, editors. *Lead–Zinc’90*. Pennsylvania, USA: The Minerals, Metals & Materials Society (TMS), 1990:1015–7.
- [28] Gordon M, Peisakhov I, editors. *Dust collection and gas cleaning techniques*. Moscow: MIR Publication, 1972.
- [29] Rabah MA. Effect of pelletization of battery paste on control of total solid particles (TSP) in secondary lead industry. *Waste Manage.* (in press).