Supporting Information

State-of-art of recycling e-wastes by vacuum metallurgy separation

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Supporting Information Content

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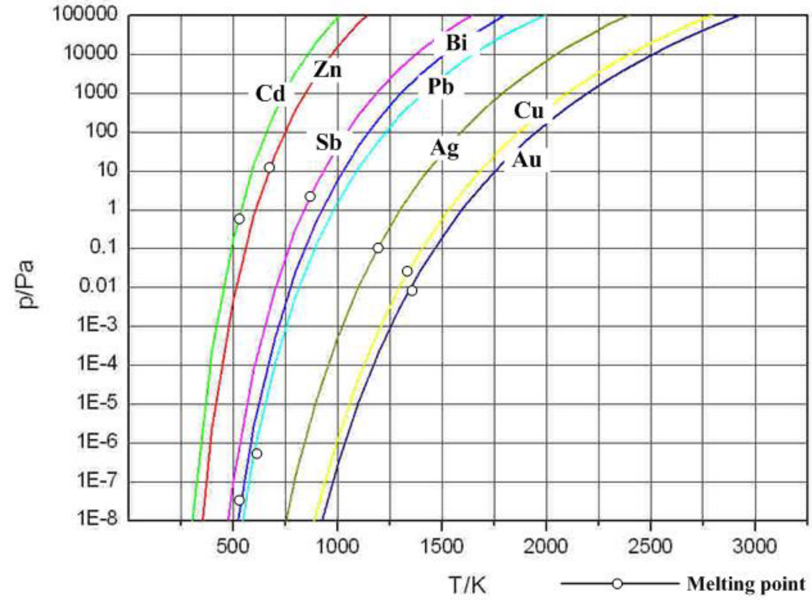

FIGURE S1 The relationship between the saturation pressure and temperature of metals (37).

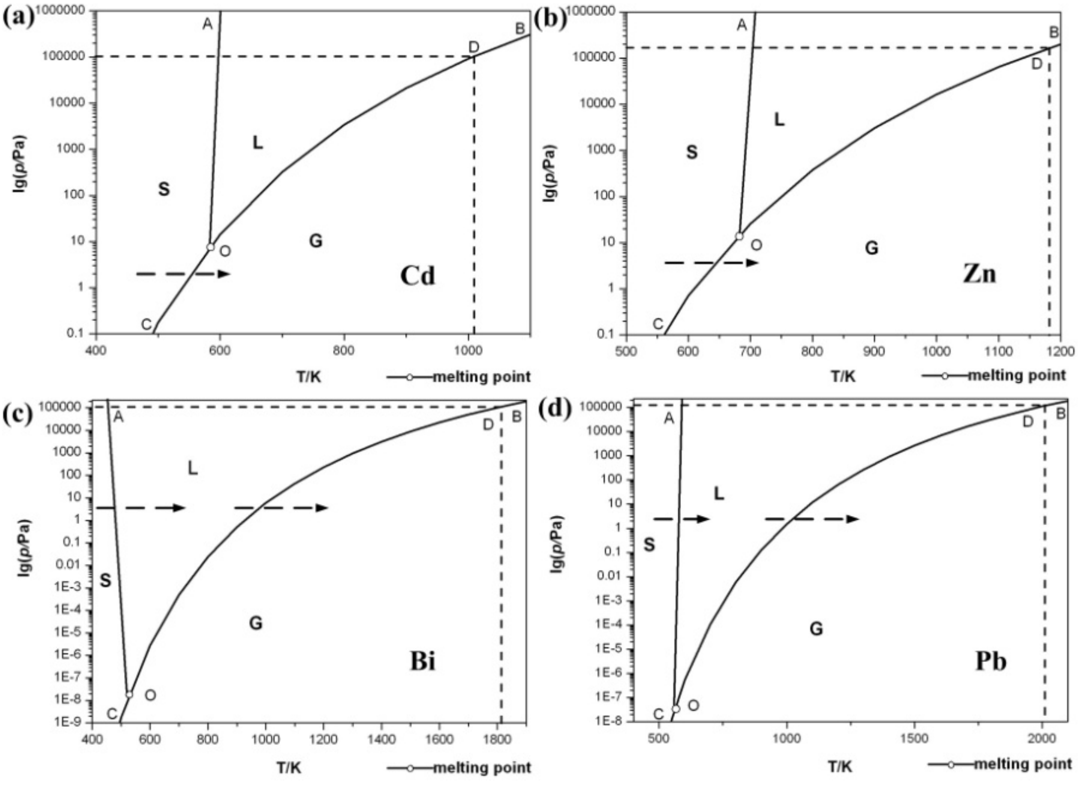

Figure S2. The triple phase equilibrium graphs of metals (38).

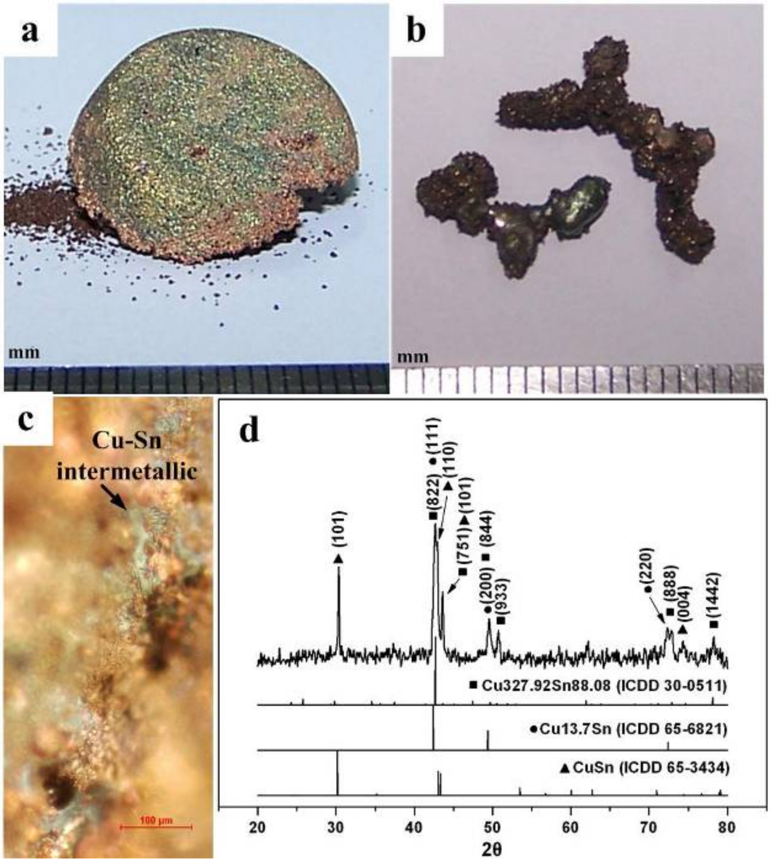

FIGURE S3. Cu-Sn intermetallic formed on the bottom of crucible (a), among Cu particles (b), its micrograph (c) and the corresponding XRD pattern (d) (41).

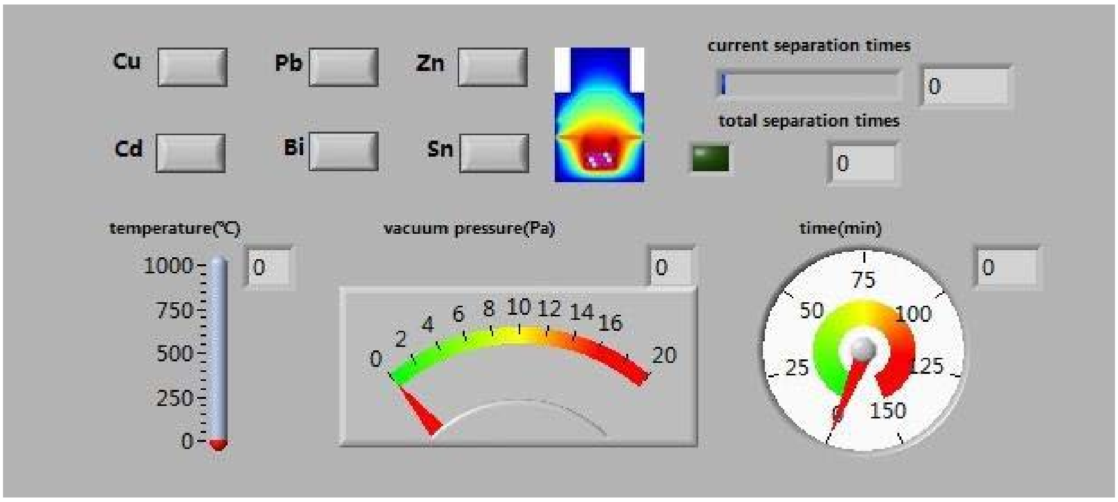

Figure S4 The designed front panel based on Labview (42)

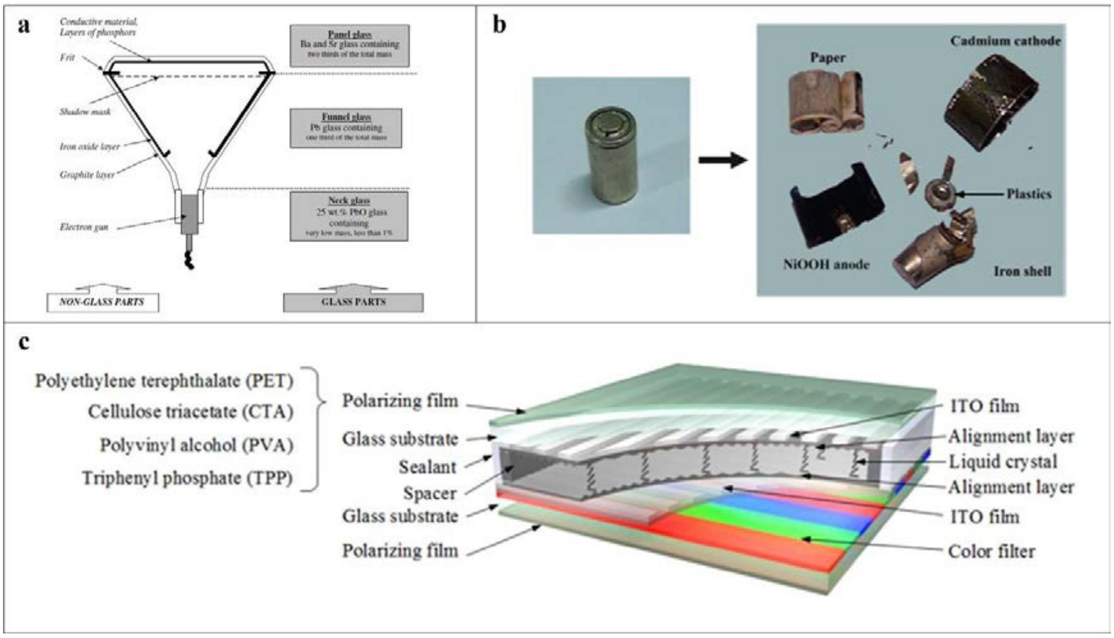

Figure S5 Schematic diagrams of several kinds of e-wastes

a Schematic diagram of the CRT components (46), b Schematic diagram of a dismantled waste Ni-Cd battery (53), c Schematic diagram of the LCD panel (78).

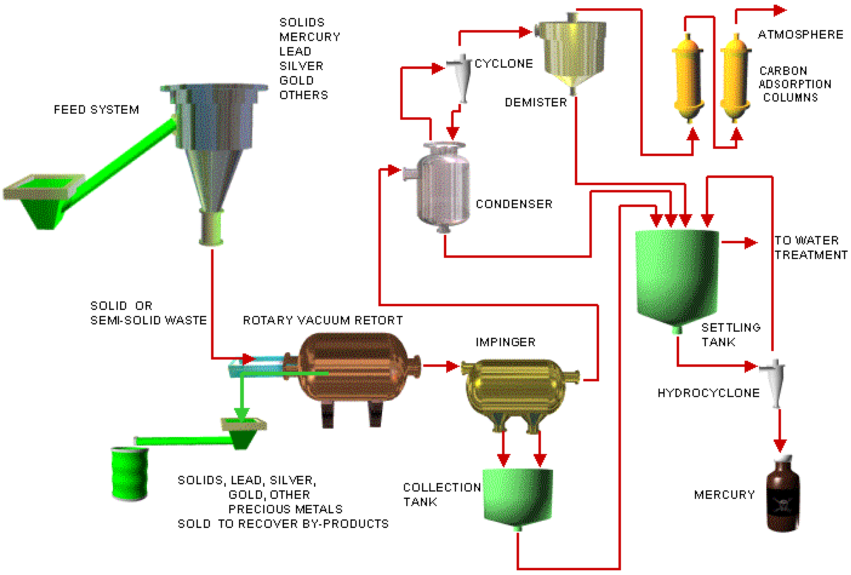

Figure S6. Flow diagram of the SepraDyne separation process (70)

Table S1 The comparison of different methods for e-wastes recycling

	methods	materials recycled	advantages	disadvantages
Hydrometallurgical recycling	adsorption, leaching, cementation, solvent extraction, ion exchange, etc.	mainly Cu, Au, Ag, Pd	low costs, operational flexibility, high selectivity, high metal purity	high solvent consumption, leaching solution needs to be further treated
Pyrometallurgical recycling	incineration, smelting, drossing, sintering, melting, etc.	mainly precious metals	no requirements for the compositions of wastes	high costs, gas/dust needs to be further treated, possible formation of dioxins
Biological recycling	bioleaching, biosorption, etc.	mainly Cu, Au	low costs, easier operability, better environmental property	low recovery efficiency, time consuming, difficult to select the biomass with high adsorption capacities
Mechanical physical recycling	screening, magnetic separation, eddy current separation, electrostatic separation, jigging, etc.	Fe, Al, glasses, plastics	better environmental property, easier operability, low costs	loss of valuable metals due to the insufficient liberation, generate noises and dusts
VMS	vacuum evaporation, vacuum carbon reduction, vacuum pyrolysis, etc.	mainly Cd, Pb, Hg, Zn, also toxic organics	no waste gas nor liquid, high metal purity, high recovery efficiency	high costs, require sufficient pretreatments

Table S2 Applications of VMS on e-wastes recycling.

Vacuum technology	Combined measures	Participant reactant	Treated object	Operating parameters	Recovered materials	Residues	Appeared section	Literature
Vacuum evaporation	Dismantling, crushing, and electrostatic separating	-	WPCBs	1123 K under 0.1-1 Pa for 90 min	Pb, Cd	Cu-Sn alloy	3.1	37, 39, 41
Vacuum carbon reduction	Crushing	Carbon	CRT	1273 K under 1000 Pa for 4 h, 9% of carbon adding amount	Pb, K, Na	foam glass	3.2	47,48
Vacuum carbon reduction	Inert-gas injecting	Carbon	CRT	1273 K under 500–2000 Pa for 2–4 h,10% of carbon adding amount, 50–200 ml/min of the argon gas flow rate	nano-lead particles with 4–34nm	harmless glass powder	3.2	49
Vacuum evaporation	-	-	Grids of waste lead-acid battery	900 K under 5-7 Pa for 30 min	Sb, Sb_2O_3 and Pb bullion	-	3.3	51
Vacuum reduction	Treated with Na_2CO_3 solution	Carbon	Pastes of waste lead-acid battery	1000 K under 2-4 kPa for 90 min	Pb	-	3.3	51
Vacuum pyrolysis	-	-	Plastics of waste lead-acid battery	923 K under 50-80 Pa for 30 min	Pyrolysis oil, gas	-	3.3	51
Vacuum distillation	-	-	Ni-Cd batteries	1173 K under 100 Pa for 2h	Cd	Ni–20% Co alloy	3.4	56, 57
Vacuum distillation	-	Carbon	Ni-Cd batteries	1027 K under 1.33 Pa for 1.5 h, 1 % of	Cd	NiFe scrap	3.4	63

				carbon adding amount				
Vacuum evaporation	-	-	Zn-Mn batteries	573 K under 35-600 Pa for 4h	Hg	Slags of Fe, MnO_2, and ZnO	3.5	65
Vacuum evaporation	-	-	Mercury button cells	623 K-923 K under 100 Pa	Hg	not mention	3.5	67, 68
Vacuum evaporation	Magnetic separation	CaO	Zn-Mn dry batteries	1073-1123 K under 250 Pa for 60 min, 20% of CaO adding amount	Zn	manganese oxide	3.6	74
Vacuum evaporation	-	-	Alkaline manganese dry batteries	1200 K under 10Pa	Zn	Slags of MnO_2, ZnO and steel	3.6	76
Vacuum chlorinated separation	Grinding to less than 0.13 mm	NH_4Cl	LCDs	673 K under 0.09 MPa for 10 min, with 33% of NH_4Cl adding amount	Indium chloride	Glass powder	3.7	81
Vacuum carbon reduction	Grinding to less than 0.3 mm	Carbon	LCDs	1223 K under 1 Pa with 30 wt% carbon addition for 30 min	In	Glass powder	3.7	82
Vacuum CO reduction and evaporation	-	CO	ITO scraps	1023 K, with 70 vol% CO for 90 min	In-Sn alloy	-	3.7	83
	-	-	In-Sn alloy	1373 K under 1 Pa for 30 min	In	Sn	3.7	83
Vacuum pyrolysis	Centrifugal separation	-	WPCBs	873 K under1.5 kPa for 30 min	pyrolysis oils, gases, solders	metals, glass fibers, etc.	4.1	85, 86
Vacuum pyrolysis	Crushing, screening	-	WPCBs	825 K under 20 kPa for 120 min	pyrolysis oils, gases	Cu foil, glass fibers, carbon	4.1	88

Vacuum co-pyrolysis	-	Chinese fir sawdust	WPCBs	773 K under 10 kPa for 30 min	co-pyrolysis oils with more brominated compounds, gases	not mention	4.1	89
Vacuum evaporation	Dismantle	-	Pole transformers	473 K under <7Pa for 10 h	oil	component materials with PCB less than 0.05 mg/kg	4.2	92, 93
Vacuum evaporation	Dismantle	-	Capacitors and pressure-sensitive paper	668 –673 K under 6.0 to 6.5 kPa for 4 h	oil	component materials with PCB less than 0.1 mg/kg	4.2	96
Vacuum pyrolysis	-	-	LCDs	573 K under 50 Pa for 30 min	pyrolysis oils, gases	residues containing In	4.3	78
Vacuum pyrolysis	-	-	Metal-free electric cable waste	723 K under 20 kPa for 30 min	pyrolysis oils, gases	wax and carbon black	4.3	101

Table S3. Summary of cost basis information for the SepraDyne process (70)

Parameter	Design and Cost Basis
Plant Life	10 years
Operations	250 days/year, 5 days/week, 8 hrs/day
Throughput	1000 lbs/hr
Treatment Process	High vacuum rotary retort
Capital Costs	Processing equipment, air pollution control equipment, scale and forklift
Operating Cost	Laborers, oversight and management support and electricity
Disposal Costs	\$1000/M^3 for solids, \$ 0.10/gal for wastewater, \$ 25/gal for organics
Decommissioning Costs	Not included
Personal protection equipment	Purchase and disposal costs
Transportation	Shipping costs to disposal site

All the references cited in SI have been listed in the text, and they have the same numbers.