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Recovery of Precious Metals From Electronic Scrap

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RECOVERY OF PRECIOUS METALS FROM ELECTRONIC SCRAP

by

R. O. Dannenberg,¹ J. M. Maurice,² and G. M. Potter³

ABSTRACT

The Bureau of Mines investigations described in this report were undertaken to devise a process to economically recover precious metals and copper from low-grade, complex electronic scrap generated in large quantities by military and civilian electronic operations. Leaching with various media is applicable to certain selected items of electronic scrap but cannot be practically applied to complex mixtures of scrap.

A process comprising incineration, caustic leaching to remove aluminum, smelting with a siliceous slag, and electrolysis recovered 99.9-percent-pure copper metal and anode slimes assaying more than 7,000 ounces per ton of combined precious metals. Silver, gold, and copper recoveries were 93, 95, and 87 percent, respectively. Cost analysis indicated that an alternative process using direct smelting of the scrap to make assayable products for sale to a custom smelter would provide better overall financial returns.

INTRODUCTION

Electronic scrap represents a significant source of secondary precious metals. Table 1 shows the consumption of precious metals by the electrical industry in 1969. Ultimately, most of this electronic equipment becomes obsolete or damaged and is scrapped. Some of the scrapped items may be salvaged and reused as electronic components. The remainder represents a potential source of secondary precious and base metals.

Much of the higher grade scrap is processed for precious metal recovery; however, at present significant quantities of precious metals are being lost in scrap which is too low in precious metal content or too complex to warrant recovery. The Bureau of Mines undertook the development of a practical process to recover precious metals from complex low-grade scrap which presently is not being treated.

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TABLE 1. - Consumption of precious metals by the electrical industry in 1969

	Consumption by the electrical industry, troy ounces	Electrical consumption as proportion of total industrial consumption, percent
Silver.....	38,354,000	27.1
Gold.....	2,560,000	36.0
Palladium.....	430,258	56.8
Platinum.....	112,589	21.9
Rhodium.....	10,788	21.5
Iridium.....	2,154	15.1
Ruthenium.....	2,057	12.0
Osmium.....	5	.3

Sources: Hoyt, C. D. Gold. BuMines Minerals Yearbook 1969, v. 1-2, 1971, pp. 521-538.
Hoyt, C. D. Silver. BuMines Minerals Yearbook 1969, v. 1-2, 1971, pp. 997-1010.
Hoyt, C. D., and J. P. Ryan. Platinum-Group Metals. BuMines Minerals Yearbook 1969, v. 1-2, 1971, pp. 921-931.

This report presents the results of hydrometallurgical and pyrometallurgical investigations designed to screen various potential processes.

Description of Electronic Scrap

From a metallurgical standpoint, electronic scrap is a complex mixture of various metals attached to, covered with, or mixed with diverse types of plastics and ceramics. Precious metals occur as platings of various thicknesses, relay contact points, switch contacts, and wires, or in solders. As electronic circuits become more sophisticated, the proportion of precious metals in relation to other metals increases, as illustrated by table 2, which shows the composition of electronic components from an obsolete B-47 bomber and from more recent electronic equipment. Figure 1 shows a batch of typical scrap ready for treatment.

TABLE 2. - Comparison of electronic scrap compositions

	B-47 bomber scrap	Recently generated scrap
Copper.....weight-percent..	14.1	18.6
Aluminum plus magnesium.....do.....	42.7	34.4
Iron.....do.....	22.7	26.2
Other (plastics, ceramics, other metals).....do.....	18.5	19.8
Silver.....troy ounces per ton..	58.6	57.8
Gold.....do.....	0.5	7.1
Palladium.....do.....	1.1	1.0
Platinum.....do.....	0.001	0.03
Rhodium.....do.....	-	0.13



FIGURE 1. - Typical Military Electronic Scrap.

Review of Presently Used Processes

Most of the precious metals presently being recovered from scrap are derived from selected items high in precious metal value and free from complicating contaminations such as aluminum chassis. Items must be plastic-free or incinerated to remove plastics.

Thin exposed platings of gold or silver are successfully recovered by cyanidation, sometimes accelerated with electrolysis. Proprietary cyanide-based, organic compounds⁴ are available that dissolve gold and silver much faster than ordinary cyanide solutions.

In at least one installation, gold plating is removed from copper or brass objects by reverse electrolysis in strong sulfuric acid. In this

⁴Springer, R. Method of Dissolving Metals and Composition Therefore. U.S. Pat. 2,649,361, Aug. 10, 1953.

process, the gold dissolves at the anode but immediately reprecipitates as it leaves the anode and falls to the bottom of the cell as a sludge. Nitric acid and/or aqua regia leaching followed by treatment with sodium chloride or ferrous sulfate to precipitate the silver or gold, respectively, is used in some cases where the ratio of precious metals to acid-soluble base metals is high.

Hand stripping to separate aluminum and components high in value as electronic items, followed by smelting to form assayable products for sale to a custom smelter, is the most widely used procedure to treat complex scrap. The cost of hand stripping is high and is usually justified only if the scrap contains items which are resalable for their electronic value.

Chemical treatment is generally applicable only to gold, silver, and palladium-bearing scrap. Other platinum-group metals dissolve too slowly in chemical reagents unless they are very finely divided. All presently used commercial processes for the recovery of platinum-group metals depend upon concentration by hand-sorting or smelting-electrolysis, usually followed by dissolution of the precious-metal-rich fraction in molten lead. Dissolution of the lead in dilute nitric acid dissolves some of the precious metals but leaves most of the less soluble ones in the form of a finely divided residue from which they can be selectively dissolved.⁵

EXPERIMENTAL INVESTIGATIONS

Leaching

Several potential leaching agents were examined to evaluate the feasibility of a wet process for treating scrap. Leaching agents examined included ammonium carbonate, nitric acid, aqua regia, sodium cyanide, and copper sulfate. Although some of the agents were effective in treating selected items--such as nitric acid for silver-bearing items, aqua regia for gold-bearing items, and cyanide for thin exposed plating of silver or gold--none of the reagents was applicable to complex scrap bearing both silver and gold as well as the less soluble platinum-group metals. Copper sulfate effectively eliminated aluminum and iron as a presmelting step; however, reagent requirements were excessive. For example, 1 ton of typical scrap requires 7,594 pounds of copper sulfate and concurrently produces 3,035 pounds of cement copper.

Incineration

Electronic scrap contains significant quantities of plastics and organic liquids which must be eliminated to prepare feed for smelting. Incineration may be accomplished by heating the scrap to 400° to 500° C in a gas-fired furnace. Excessive temperatures should be avoided to prevent fusion of the aluminum. In most instances, an adequate afterburner and possibly a gas filtration unit or wet scrubber must be installed to meet antipollution regulations.

⁵Hampel, C. A. Rare Metals Handbook. Reinhold Pub. Co., London, 2d ed., 1961, pp. 304-355.

Whiteley, J. O., and C. Dietz. Refining and Melting Some Platinum Metals. AIME Tech. Pub. 84, 1928, pp. 635-643.

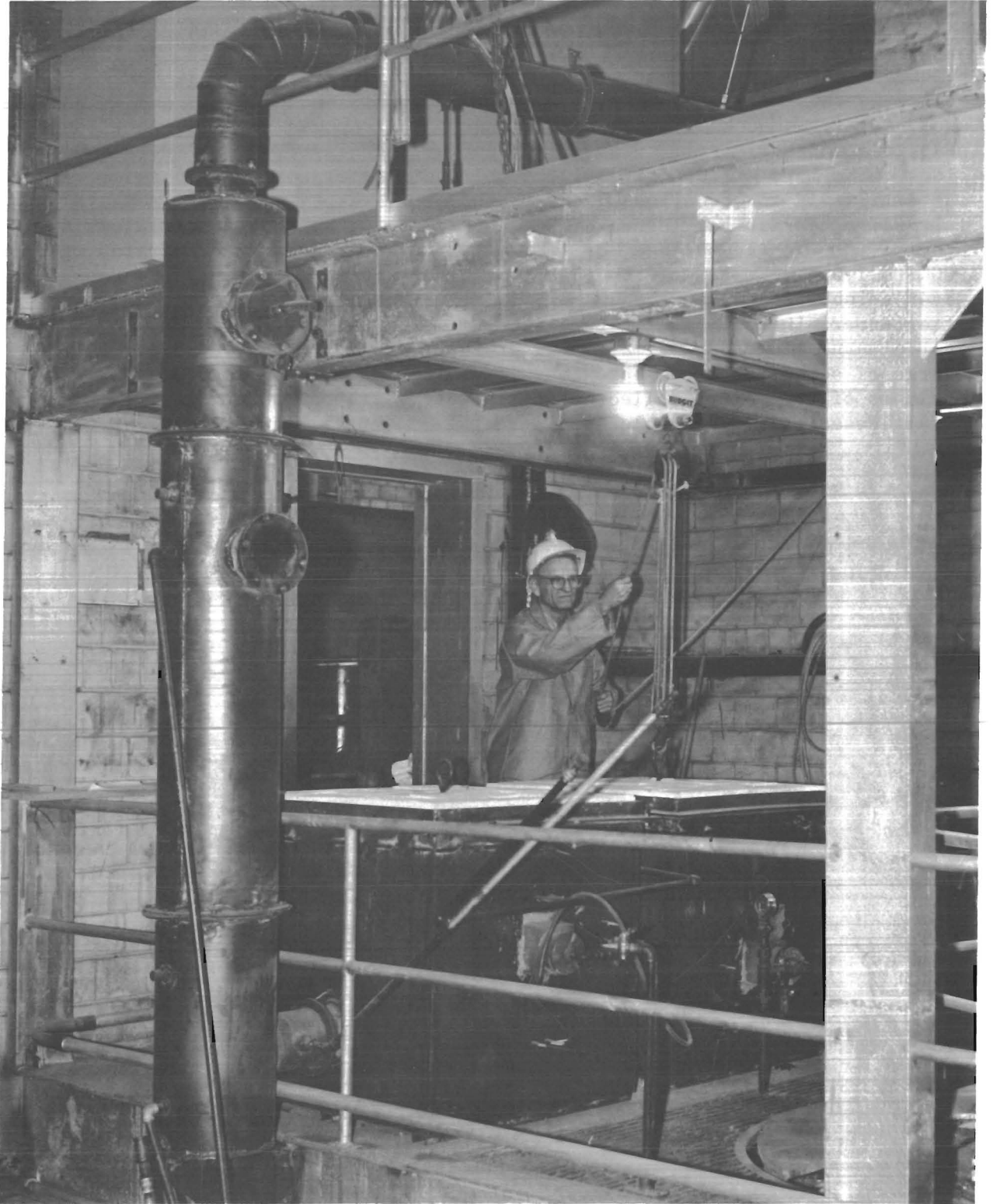


FIGURE 2. - Electronic Scrap Incinerator, Afterburner, and Water Scrubber.

Figure 2 shows the incinerator used in the experimental work, a 3- by 3- by 3-foot steel shell lined with firebrick. Heat is supplied with one atmospheric-type gas burner. The maximum quantity of scrap that can be incinerated in this unit is about 50 pounds per batch. Because only one burner was used, a large amount of free space around the scrap was required to allow the heat to penetrate to all sides. A larger unit equipped with burners on all sides could more efficiently utilize the incinerator space. The afterburner was similar in construction to the incinerator except for the presence of internal firebrick baffles to direct the fumes through the burner flame and provide more heated surface for burning. The afterburner was operated at 900° to 1,000° C. Fumes from the afterburner were passed through a packed water scrubber and then through a blower. Figure 3 shows fumes without the afterburner in use, and figure 4 shows fumes from the afterburner. The plume in the burned fumes is primarily water vapor from the scrubber. A 50-pound charge of scrap required approximately one-half hour to burn completely. Analysis of the solids collected in the water scrubber showed that precious metal losses were negligible in all tests.

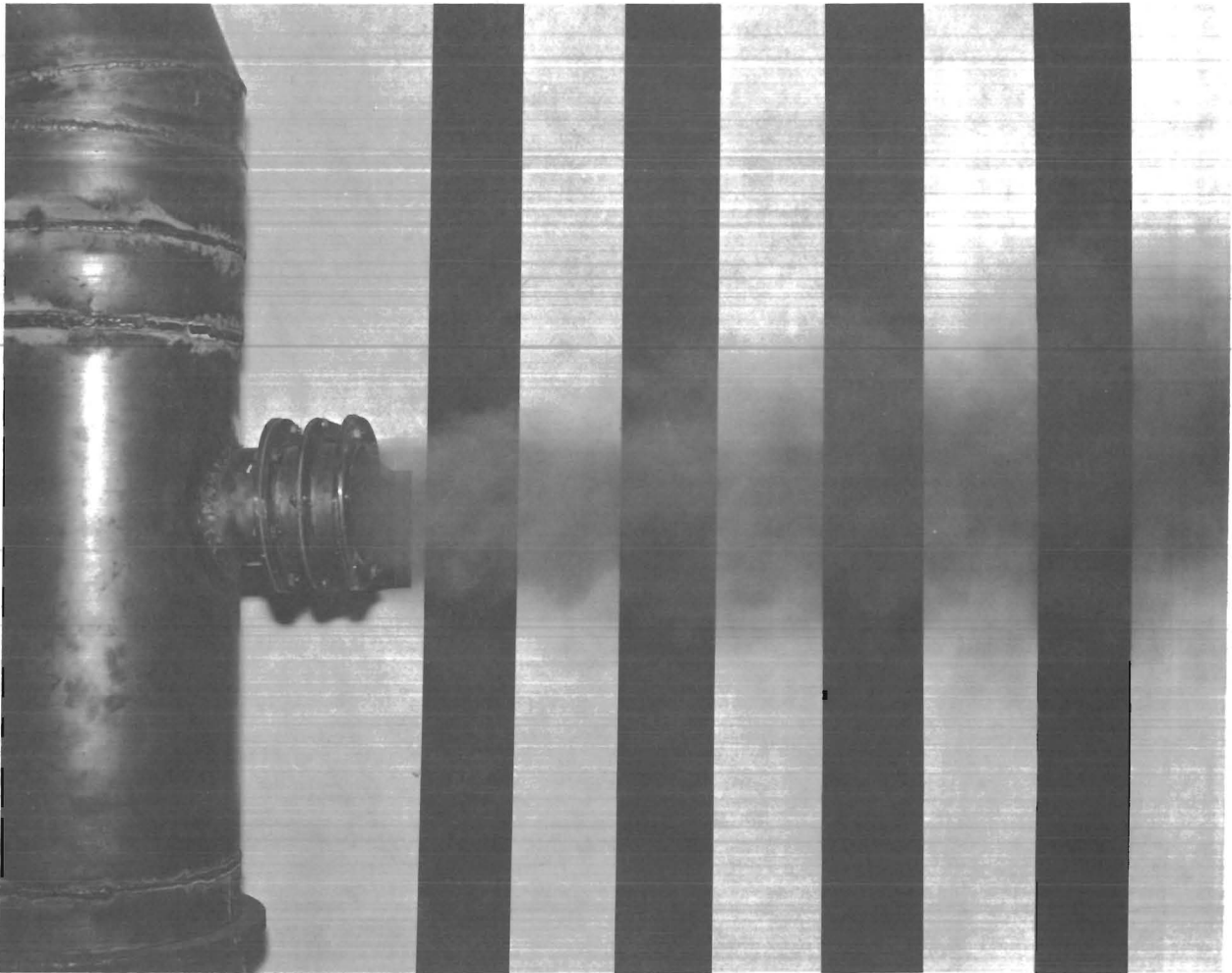


FIGURE 3. - Fumes From Electronic Scrap Incineration—No Afterburner.

Aluminum and Iron Elimination

Pyrometallurgical processes appeared to be the most practical approach for the treatment of complex scrap. These processes are complicated by the large quantity of aluminum and iron. Several aluminum and iron rejection schemes were investigated. The following sections describe the results of these investigations.

Sink-Float-Magnetic Separation

Tests were made to evaluate the feasibility of separating aluminum and iron from the remainder of the scrap by a sink-float-magnetic separation process. The scrap was first shredded to about 1 inch maximum dimension in the hammermill-type shredder shown in figure 5. Figure 6 shows a batch of the shredded scrap. After screening out the fine material, the shredded scrap was sink-float separated in a water-galena slurry at specific gravity 1.9; then the heavy fraction was separated in a 2.9 specific gravity slurry. The

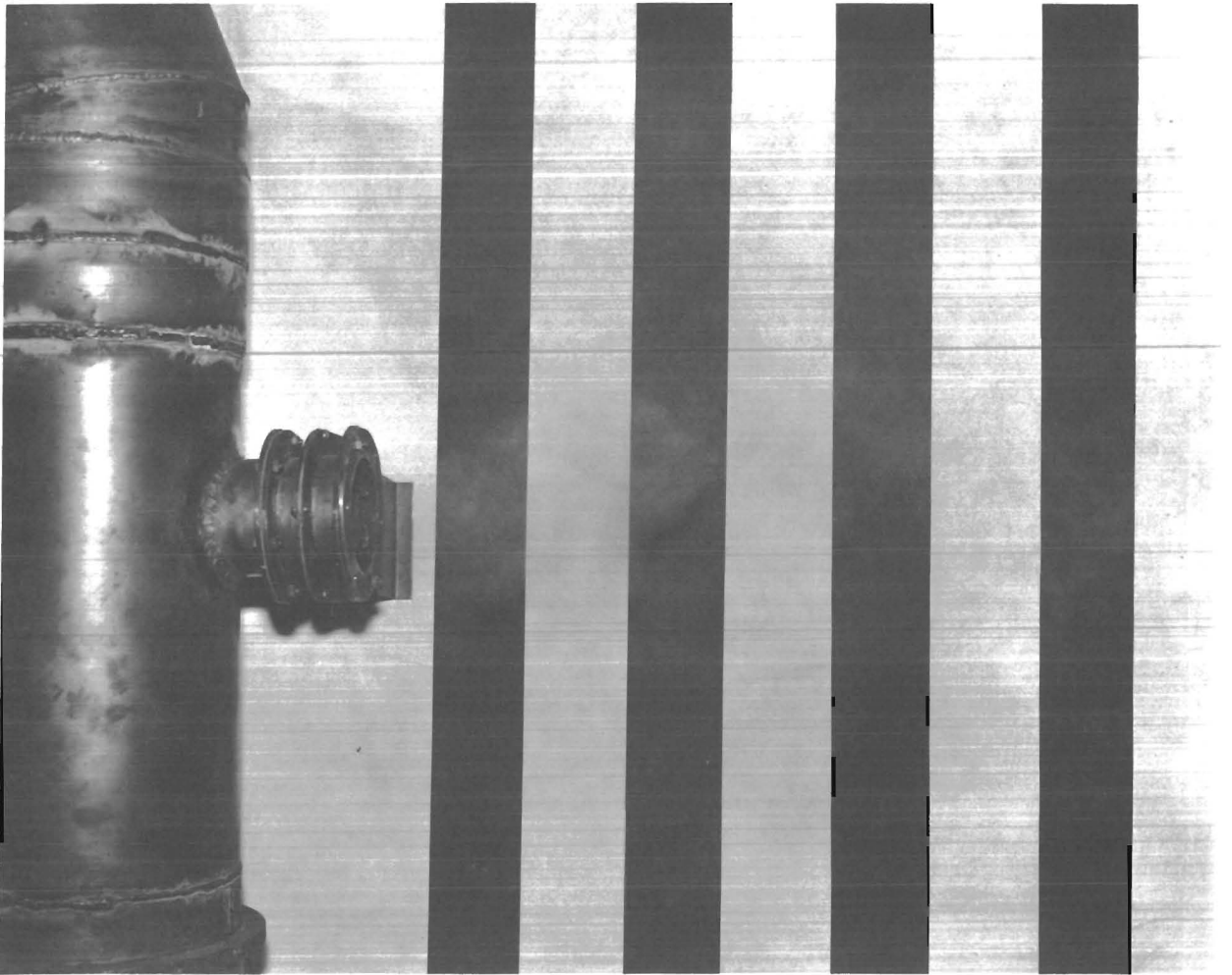


FIGURE 4. - Fumes From Electronic Scrap Incineration—With Afterburner.



FIGURE 5. - Hammermill Shredder.

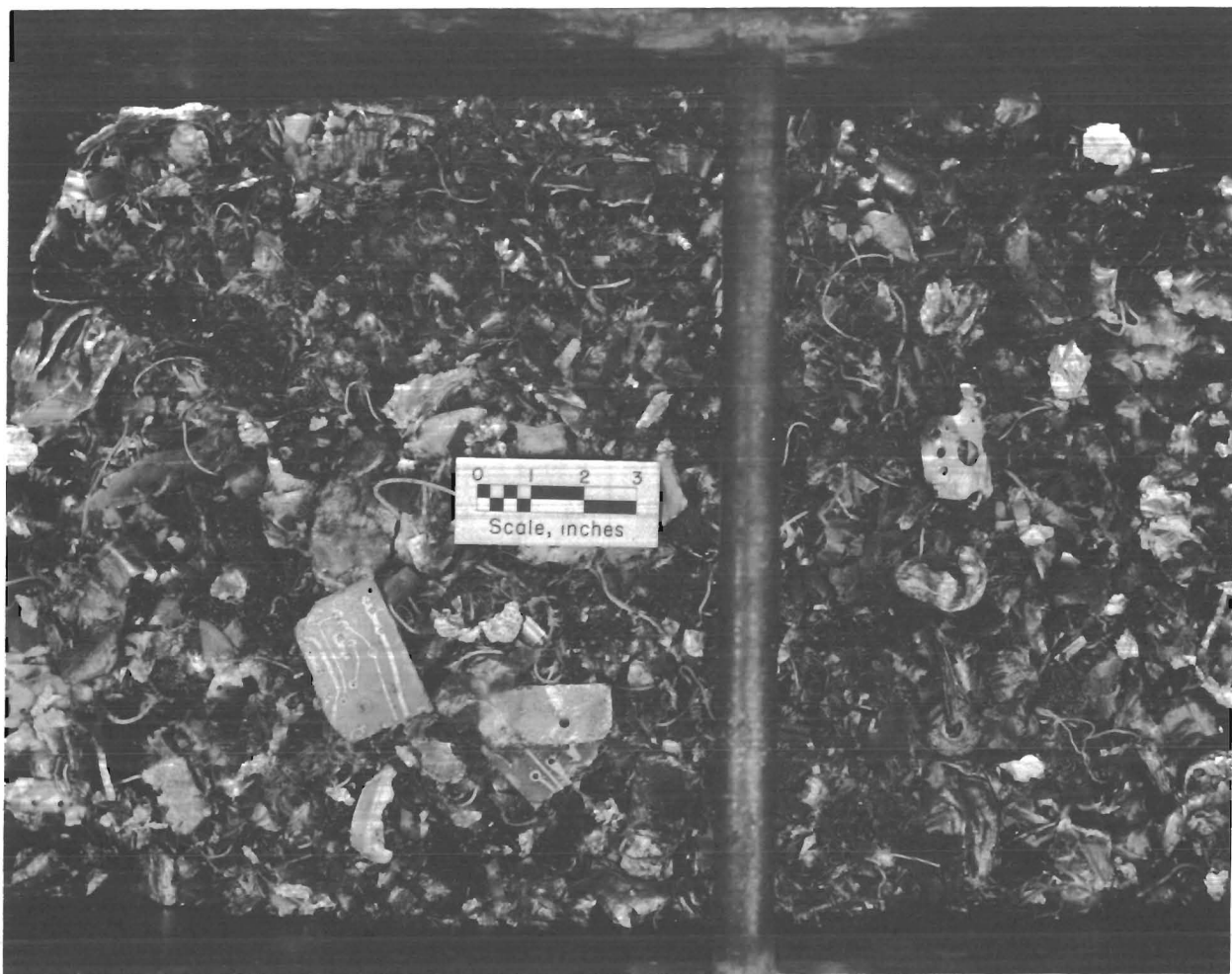


FIGURE 6. - Shredded Scrap.

fraction heavier than specific gravity 2.9 was separated magnetically. Table 3 shows the results of a typical test. Iron and aluminum rejection was satisfactory, but copper and precious metal content of the rejects was excessive.

Hand Sorting

A test was made to determine the feasibility of using hand sorting to produce a fraction rich in copper and precious metals. A batch of scrap was broken into minus 1-inch fragments with the hammermill. The shredded material was spread out on a bench, and all pieces of aluminum and iron that could be easily recognized and handled were hand-picked in a timed test. The rate of sorting was 81 pounds per man-hour. Table 4 shows the composition of the fractions and the metal distribution.

TABLE 3. - Results of sink-float-magnetic separation test

Product	Weight-percent	Assay						Distribution, percent					
		Percent			Troy oz/ton			Cu	Fe	Al	Ag	Au	Pd
		Cu	Fe	Al	Ag	Au	Pd						
Concentrate.	58.6	54.5	2.0	0.3	247	40.5	0.1	92.9	9.6	7.3	72.1	88.2	41.0
Aluminum reject.....	19.0	9.5	2.2	11.8	241	15.5	.15	5.3	3.5	92.7	22.8	10.9	19.9
Iron reject.	22.4	2.8	47.2	0	45.6	1.1	.25	1.8	86.9	0	5.1	.9	39.1
Head...	100.0	34.4	12.2	2.4	200.7	26.9	.14	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 4. - Results of hand-sorting test

Product	Weight-percent	Assay					Distribution, percent				
		Percent			Troy oz/ton		Cu	Fe	Al	Ag	Au
		Cu	Fe	Al	Ag	Au					
Copper and precious metal fraction.....	67.1	33.8	7.7	29.3	74	9.4	93.4	54.9	43.3	100	100
Aluminum and iron fraction.....	33.9	4.7	12.5	76.0	0	0	6.6	45.1	56.7	0	0
Head.....	100.0	24.3	9.4	45.4	49.7	6.3	100.0	100.0	100.0	100.0	100.0

The copper- and precious-metal-rich fraction contained more than 90 percent of the copper and precious metals, but still had nearly half of the aluminum and iron because small metallic particles could not be hand-sorted.

Sweating of Aluminum

Aluminum melts at a lower temperature than most other metals and can be separated as a molten liquid in a process commonly called "sweating." Recovery of aluminum from electronic scrap by sweating is complicated by the high solubility of precious metals in molten aluminum. Tests showed that as much as 60 percent of the precious metal content of complex scrap dissolves in the aluminum. Table 5 shows the assay of an ingot of aluminum sweated from electronic scrap by a commercial secondary metal smelter.

TABLE 5. - Analysis of sweated aluminum

Metal	Weight-percent	Troy oz/ton
Aluminum.....	69.7	-
Copper.....	20.0	-
Zinc.....	4.02	-
Silicon.....	2.59	-
Tin.....	1.19	-
Lead.....	1.07	-
Iron.....	.54	-
Nickel.....	.22	-
Manganese.....	.20	-
Magnesium.....	.13	-
Silver.....	-	190
Gold.....	-	11.7

Fused-salt electrolysis may be a feasible method for separating precious metals from aluminum.

Caustic Leaching

Aluminum may be eliminated by leaching the scrap in aqueous sodium hydroxide. A 5 normal sodium hydroxide solution will load to a concentration of approximately 100 grams of aluminum per liter in 6 hours at 80° to 85° C while leaching typical incinerated electronic scrap including aluminum chassis and housings. The loaded caustic may be either discarded or treated to recover a portion of the sodium hydroxide as discussed in subsequent sections. If the loaded sodium aluminate solution were discarded, sodium hydroxide requirements for leaching 1 ton of scrap containing 34.4 percent aluminum would be 1,370 pounds.

The leaching reaction develops a large amount of heat and liberates hydrogen; consequently, the leach vessel must be equipped with adequate cooling and ventilating facilities.

Regeneration of Caustic

A portion of the sodium hydroxide can be regenerated in a manner similar to that described by Peters and coworkers⁶ for a process to recover aluminum from clay. Figure 7 is a flowsheet of the process based on experimental work. Hot leach liquor containing from 90 to 100 grams of aluminum per liter is supersaturated with sodium aluminate. Seeding the supersaturated solution with previously crystallized aluminum trihydrate causes over one-half of the dissolved aluminum to hydrolyze according to the following reaction:

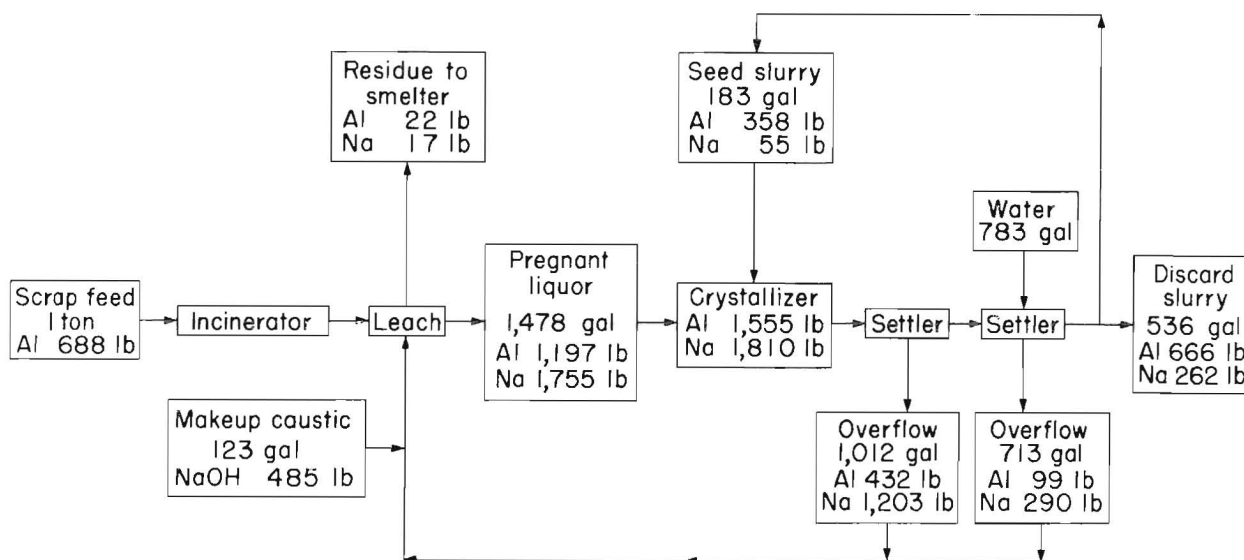


FIGURE 7. Caustic Leaching and Caustic Regeneration Flowsheet.

⁶Peters, F. A., P. W. Johnson, and R. C. Kirby. Methods for Producing Alumina From Clay. An Evaluation of Five Hydrochloric Acid Processes. BuMines Rept. of Inv. 6133, 1962, 67 pp.

Approximately 72 hours is required to attain optimum crystallization. The aluminum trihydrate may be removed by settling and the regenerated sodium hydroxide reused. Experimental work showed that caustic makeup requirements averaged 485 pounds per ton of scrap treated.

Table 6 shows the assay of a typical batch of aluminum trihydrate after calcination. The copper, silver, and gold in the oxide is equivalent to 0.2, 0.8, and 0.2 percent of that in a head assaying 18.6 percent copper, 57.8 troy ounces silver, and 7.1 troy ounces gold per ton, respectively.

TABLE 6. - Composition of calcined
aluminum trihydrate

Component	Weight- percent	Troy oz/ton
Al ₂ O ₃	86.0	-
Sodium.....	4.1	-
Silicon.....	1.0	-
Magnesium.....	.19	-
Zinc.....	.12	-
Copper.....	.06	-
Tin.....	.05	-
Iron.....	.02	-
Lead.....	.01	-
Silver.....	-	0.64
Gold.....	-	.02

Smelting

Smelting of scrap, with or without aluminum, may be done to prepare homogeneous assayable products for subsequent sale to a custom smelter or to prepare products amenable to further inplant refining. A previous paper described the results of smelting tests on high- and low-aluminum scrap using an electric arc furnace.⁷ This paper describes the results of smelting tests using a 500-pound gas-fired furnace. The results were metallurgically similar to those obtained in an electric arc furnace.

The maximum charge for this furnace consisted of the incinerated and caustic-leached residue from 100 pounds of scrap together with approximately 100 pounds of slag. The maximum temperature attainable was about 1,425° C.

Smelting Aluminum-Bearing Scrap To Form Assayable Products

Electronic scrap can be mixed with copper concentrates fed to an industrial reverberatory furnace. The proportion of electronic scrap in relation to the total weight of copper concentrates would be so small that impurities would have a negligible effect on furnace operation; however, custom smelters

⁷Dannenberg, R. O., and G. M. Potter. Smelting of Military Electronic Scrap. Proc. 2d Mineral Waste Utilization Symposium, BuMines and IIT Research Institute, Chicago, Ill., Mar. 18-19, 1970, pp. 113-117.

are reluctant to purchase raw materials without knowing their composition, and accurate analysis of large quantities of complex scrap is impossible. By melting the metals in the scrap to form a homogeneous fluid mixture together with a slag composed of plastic remnants and oxidized metals, the scrap is reduced to assayable fractions.

A test was made using 50 pounds of recycled calcium borosilicate slag and incinerated residue from 50 pounds of assorted scrap. The slag was melted, and the incinerated scrap was added slowly. Periodically, large pieces of unmelted iron were removed manually. Table 7 shows the composition of feed materials and products together with the distribution of the major metals. Subsequent tests showed that the borax could be eliminated from the slag without significantly affecting results.

The fused mixture poured relatively well; however, it was necessary to periodically scrape an unfused dross of ashes and alumina from the surface. This dross was subsequently added to the ground slag for assay. The calculated head assay based on slag and metal collected compared favorably with the composition of typical scrap shown in table 2, indicating that this smelting procedure is suitable for the preparation of assayable products. Copper and precious metal losses in the unoxidized iron were high. To decrease these losses, it might be preferable to use a shredding-magnetic separation step prior to smelting. Test results in table 3 show that magnetic separation of shredded, unincinerated scrap loses less than 2 percent of the copper and gold, approximately 5 percent of the silver, and about 40 percent of the palladium. Hand separation of relays from the shredded scrap would reduce palladium losses.

Smelting To Separate Metals

Aluminum-depleted scrap can be smelted to form either assayable products for sale, as described in the previous section, or products amenable to further inplant treatment, as discussed in the following sections.

Larger Scale Smelting Investigations

Three hundred pounds of assorted scrap was incinerated and caustic-leached to provide aluminum-depleted smelter feed. The leached scrap was separated into three equal portions.

A slag mixture composed of 32.8 pounds of calcium oxide, 35.0 pounds of silica, and 12.5 pounds of borax glass was melted at 1,350° to 1,400° C, and one of the portions of scrap was added slowly. Air was blown through the molten mixture for 2 hours to oxidize a portion of the iron so that subsequent reuse of the slag would result in a fluid calcium-ferrous silicate slag, thus obviating the need for additional borax. At the end of the 2-hour blowing period, unoxidized pieces of iron were removed and the melt was poured into molds. In subsequent smelts on the remaining portions of scrap residue, enough old slag was discarded so that the slag would contain 10 percent iron after addition of sufficient makeup calcium oxide and silica to make 90 pounds of slag. The copper bullion and slag from each test were sampled and analyzed.

Unoxidized iron was dissolved to obtain an estimate of the copper and precious metal losses. Table 8 shows the average assay of products, the calculated head assay, and the distribution of metals between the various products. In addition to the metals shown in table 8, the bullion contained, in weight-percent, 1.65 nickel, 2.2 lead, 1.6 tin, 1.9 zinc, and 0.12 antimony.

TABLE 7. - Smelting electronic scrap high in aluminum

Component	Weight, lb	Assay								Distribution, percent ¹					
		Percent							Troy oz/ton		Cu	Fe	Al	Ag	Au
		CaO	SiO ₂	Na ₂ B ₄ O ₇	Cu	Fe	Al	Ag	Au						
Slag feed...	50	34.9	39.5	13.5	0.3	6.7	2.2	1.04	0.06	-	-	-	-	-	
Scrap feed..	² 50	-	-	-	19.1	37.2	34.0	74.2	3.4	-	-	-	-	-	
Slag out....	81	21.6	28.4	8.4	7.1	10.1	17.4	29.9	1.9	58.8	26.0	76.4	63.9	89.6	
Metal out...	9.6	-	-	-	30.1	18.2	31.5	120.0	.8	30.3	9.4	17.8	31.0	4.6	
Unoxidized iron.....	14	-	-	-	7.4	85.7	7.1	13.6	.7	10.9	64.6	5.8	5.1	5.8	

¹Based on metals in with scrap feed.

²Unincinerated weight.

TABLE 8. - Average results of smelting tests on low-aluminum scrap

Component	Weight, lb ¹	Assay						Distribution, percent					
		Percent			Troy oz/ton			Cu	Fe	Al	Ag	Au	Pd
		Cu	Fe	Al	Ag	Au	Pd						
Metal.....	20.9	84.6	3.7	0.2	332.7	26.0	7.8	86.8	2.3	0.7	93.7	95.0	95.8
Slag.....	122	.5	7.3	5.2	.7	.06	.05	3.0	26.4	99.3	1.1	1.3	3.6
Unoxidized iron	26.2	7.9	91.5	0	14.6	.8	.04	10.2	71.3	0	5.2	3.7	.6
Head ¹	100	20.4	33.7	6.4	74.2	5.7	1.7	100.0	100.0	100.0	100.0	100.0	100.0

¹Based on 100 pounds, unincinerated, unleached head.

Electrolysis of Bullion

Copper bullion similar to that produced in the smelting test was refined electrolytically. Operating conditions were similar to those used in standard electrolytic copper refining practice except that a small alternating current was superimposed on the direct electrolytic current to prevent passivation due to the buildup of precious metal sludge on the anode surfaces. The copper sulfate electrolyte contained 46 grams copper, 200 grams free sulfuric acid, 0.4 gram sodium chloride, and 0.04 gram glue per liter. Operating temperature was 55° C, and cathode current density was 15 amp direct current and 1.5 amp alternating current per square foot. Iron concentration in the electrolyte was maintained at approximately 10 grams per liter by bleeding off old electrolyte and replacing with fresh. The composite electrolyte removed from the cell assayed 43.4 grams copper, 10.9 grams iron, 5.8 grams nickel, 0.9 gram tin, 0.2 gram zinc, 0.016 gram silver, and 0.0039 gram gold per liter together with small amounts of antimony, bismuth, calcium, cobalt, gallium, indium, lead, magnesium, and silicon. No attempt was made to recover the dissolved metals and reclaim the acid; however, a system similar to that described by Butts⁸ should be suitable. Makeup copper sulfate equivalent to the quantity of other metals dissolved would be required. Table 9 shows the assays of the anode used and cathode and anode slimes produced in the test. Table 10 shows the spectrographic analysis of the anode, cathode, and slimes.

The precious-metal-rich anode slimes are similar to those produced in nickel or copper refineries and should respond to treatment used in these refineries.⁹ Alternatively,

⁸Butts, A. Copper. Reinhold Pub. Co., New York, 1954, pp. 204-211, 265-289.

⁹First work cited in footnote 5 and work cited in footnote 8.

the slime could be sold to a commercial refinery for incorporation with its recovery system.

TABLE 9. - Results of electrolytic refining test

	Weight, grams	Assay								
		Percent				Troy oz/ton				
		Cu	Fe	Ni	Other	Ag	Au	Pd	Rh	Pt
Anode.....	¹ 3,899	85.0	6.5	2.8	4.5	283	35.5	5.0	0.7	0.15
Cathode.....	3,312	99.9	.002	.001	<.1	2.0	<.01	<.01	<.01	<.01
Slimes.....	161	3.3	.1	.04	69.9	6,800	857	122	15.6	3.6

¹Derived from 20.4 kilograms of scrap.

TABLE 10. - Spectrographic analysis of electrolytic feed and products

Weight- percent	Anode	Cathode	Anode slimes
>10	Cu.....	Cu.....	Ag, Pb, Sn.
1 - 10	Ag, Fe, Ni, Pb, Sn..	-	Au, Cu, Sb.
.1 - 1	Sb, Zn.....	-	As, Bi, Fe, Pd, Si.
.01 - .1	Au, Bi, Co, Pd.....	Ag, Sn.....	Al, Ca, Ge, Mg, Mo, Ni, Pt.
.001- .01	-	-	Cr, In, Mn, Ti.

PROCESS ECONOMICS

A cost evaluation was made on three processes described in previous sections; namely--

Process 1.--Incineration followed by direct smelting to prepare assayable slag and bullion for sale to a custom smelter.

Process 2.--Incineration, caustic leaching with discard of the sodium aluminate liquor, smelting, and electrolysis to form pure copper and a precious metal sludge to be sold to a precious metal refinery.

Process 3.--Same as process 2 but with recovery of part of the caustic by sodium aluminate hydrolysis.

The evaluation is based on (1) a capacity of 5 tons of electronic scrap per day, (2) an 8-hour day with a 5-day week (250-day year), (3) an assumed cost of \$90 per ton for the scrap, (4) 1971 prices for equipment, (5) a labor rate of \$3.90 per hour, and (6) 12.5 years' depreciation.

With the exception of copper, the value of the metal in the products that can be recovered during a year's operation is the same for all three processes and is shown in table 11. The average value of metals in a ton of scrap is about \$543 for the smelting process and \$594 for the two leaching processes.

TABLE 11. - Content and value of copper and precious metals produced annually

Metal	Production		Assumed selling price	Value	
	Pounds	Troy ounces		Total	Per ton of scrap
Copper.....	454,000	-	{ \$0.52 per lb ¹ .38 per lb ²	\$236,080.00 172,520.60	\$188.86 138.02
Gold.....	-	8,800	38.27 per oz	336,776.00	269.42
Silver.....	-	72,000	1.33 per oz	95,760.00	76.61
Palladium.....	-	1,225	33.67 per oz	41,245.75	33.00
Platinum.....	-	37.5	109.20 per oz	4,095.00	3.27
Rhodium.....	-	162.5	177.45 per oz	28,843.75	23.08

¹ Cathodes are assumed to be worth the full market value.
² Estimated value for copper in impure metal and slag sold to smelter.

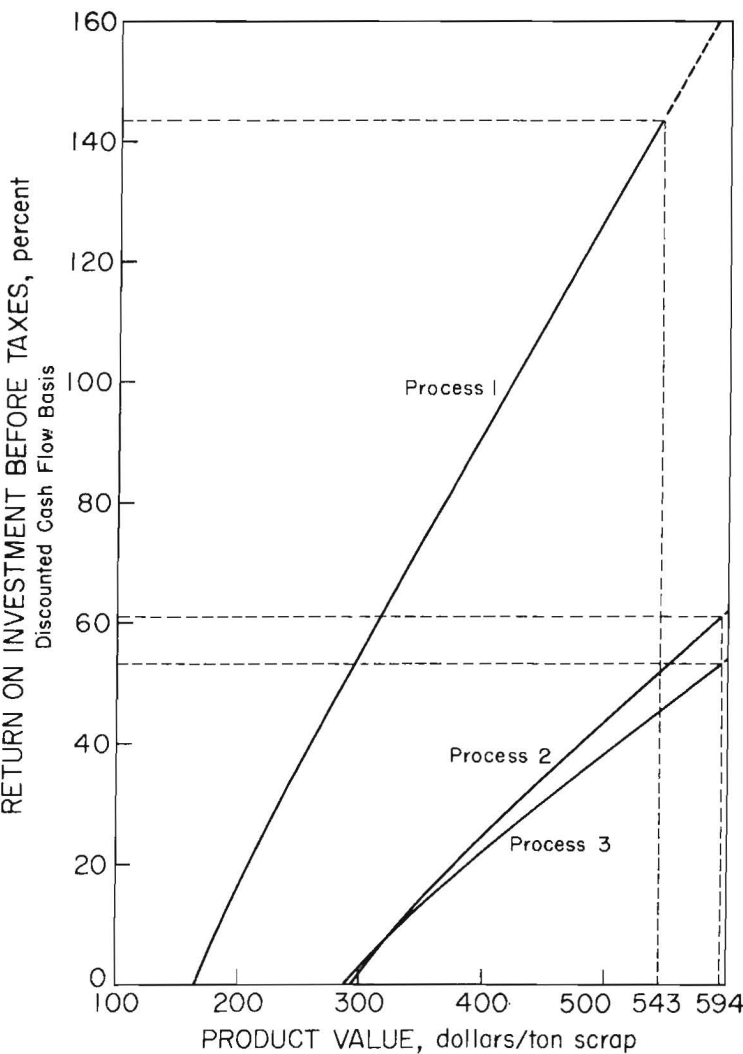


FIGURE 8. - Rate of Return on Investment for Processing Electronic Scrap.

Table 12 shows a summary of annual operating costs, operating personnel requirements, and unit production costs for the three processes. Table 13 shows details of the annual operating costs. Although all three processes can be operated economically, the annual operating costs and capital investment are significantly higher for the caustic leach processes than for direct smelting to form assayable products.

Additional data on the economics and relative profitability of the three processes can be obtained from figure 8. At the break-even point, with a zero return on investment, process 1 requires the least revenue for the products and is the most economical; this is followed by process 3. For product value above \$325 per ton of scrap, process 2 yields a higher return on investment than process 3. Return from processes 2 and 3 never approaches that from process 1. At the assumed current product value per ton of scrap, \$543 for process 1 and

\$593 for processes 2 and 3, the rates of return on investment are 143 percent for process 1, 60 percent for process 2, and 53 percent for process 3. While all three processes would be profitable for a wide range of product value, process 1 would have a definite economic advantage.

TABLE 12. - Summary of costs for processing electronic scrap

Operation	Process 1			Process 2		
	Capital cost	Annual operating cost	Unit production cost, per ton of scrap	Capital cost	Annual operating cost	Unit production cost, per ton of scrap
Fixed capital:						
Incineration.....	\$129,500	\$160,300	\$128.24	\$129,500	\$152,400	\$121.92
Leaching.....	-	-	-	142,100	108,800	87.04
Smelting.....	106,100	46,700	37.36	94,000	40,400	32.32
Electrorefining....	-	-	-	120,600	66,400	53.12
Facilities.....	23,600	-	-	48,600	-	-
Utilities.....	27,800	-	-	58,200	-	-
Total.....	287,000	-	-	593,000	-	-
Working capital.....	60,000	-	-	105,000	-	-
Total.....	347,000	207,000	165.60	698,000	368,000	294.40
	Process 3					
	Capital cost	Annual operating cost	Unit production cost, per ton of scrap			
Fixed capital:						
Incineration.....	\$129,500	\$152,500	\$122.00			
Leaching.....	254,000	102,500	82.00			
Smelting.....	94,000	40,400	32.32			
Electrorefining....	120,600	66,700	53.36			
Facilities.....	59,800	-	-			
Utilities.....	72,100	-	-			
Total.....	730,000	-	-			
Working capital.....	98,000	-	-			
Total.....	828,000	362,000	289.60			

TABLE 13. - Annual operating cost for electronic scrap processing

Item	Process 1			Process 2			Process 3		
	Annual consumption	Unit cost	Total cost	Annual consumption	Unit cost	Total cost	Annual consumption	Unit cost	Total cost
Direct cost:									
Materials:									
Electronic scrap.	1,250 tons	\$90.00	\$112,500	1,250 tons	\$90.00	\$112,500	1,250 tons	\$90.00	\$112,500
50 pct NaOH.....	-	-	-	1,715.3 tons	36.80	63,100	606.1 tons	36.80	22,300
Limestone.....	890 tons	3.00	2,670	394.1 tons	3.00	1,200	394.1 tons	3.00	1,200
Silica.....	560 tons	4.00	2,240	338.1 tons	4.00	1,400	338.1 tons	4.00	1,400
Copper sulfate....	-	-	-	50.0 tons	455.00	22,800	50.0 tons	455.00	22,800
Sulfuric acid....	-	-	-	20.0 tons	35.00	700	20.0 tons	35.00	700
Total.....	-	-	117,410	-	-	201,700	-	-	160,900
Utilities:									
Electricity.....	14.44 Mwhr	20.00	300	102.29 Mwhr	20.00	2,000	480.14 Mwhr	20.00	9,600
Natural gas.....	5,842 Mcf	.45	2,600	5,903.5 Mcf	.45	2,700	5,903.5 Mcf	.45	2,700
Total.....	-	-	2,900	-	-	4,700	-	-	12,300
Direct labor:									
Labor.....	-	-	16,200	-	-	24,400	-	-	24,400
Supervision.....	-	-	2,400	-	-	3,600	-	-	3,600
Total.....	-	-	18,600	-	-	28,000	-	-	28,000
Plant maintenance:									
Labor.....	-	-	6,900	-	-	14,300	-	-	17,500
Supervision.....	-	-	1,400	-	-	2,900	-	-	3,600
Materials.....	-	-	6,900	-	-	14,300	-	-	17,500
Total.....	-	-	15,200	-	-	31,500	-	-	38,600
Payroll overhead...	-	-	6,800	-	-	11,300	-	-	12,300
Operating supplies.	-	-	3,100	-	-	6,200	-	-	7,700
Total direct cost	-	-	164,000	-	-	283,400	-	-	259,800
Indirect cost (administration and overhead).....	-	-	14,800	-	-	26,300	-	-	29,700
Fixed cost:									
Taxes and insurance	-	-	5,200	-	-	10,900	-	-	14,100
Depreciation.....	-	-	23,000	-	-	47,400	-	-	58,400
Total fixed cost.	-	-	28,200	-	-	58,300	-	-	72,500
Total annual operating cost	-	-	207,000	-	-	368,000	-	-	362,000

CONCLUSIONS

Precious metals and copper may be recovered from complex electronic scrap by a process comprising caustic leaching, smelting, and electrolysis. Alternatively, assayable products may be prepared by direct smelting of the scrap.

Hydrometallurgical processes are not applicable to complex types of scrap; however, certain selected items are amenable to such treatment.

Evaluation of process costs indicates that direct smelting after incineration, followed by sale of the assayable products to a custom smelter, provides the most economic approach to the treatment of complex electronic scrap