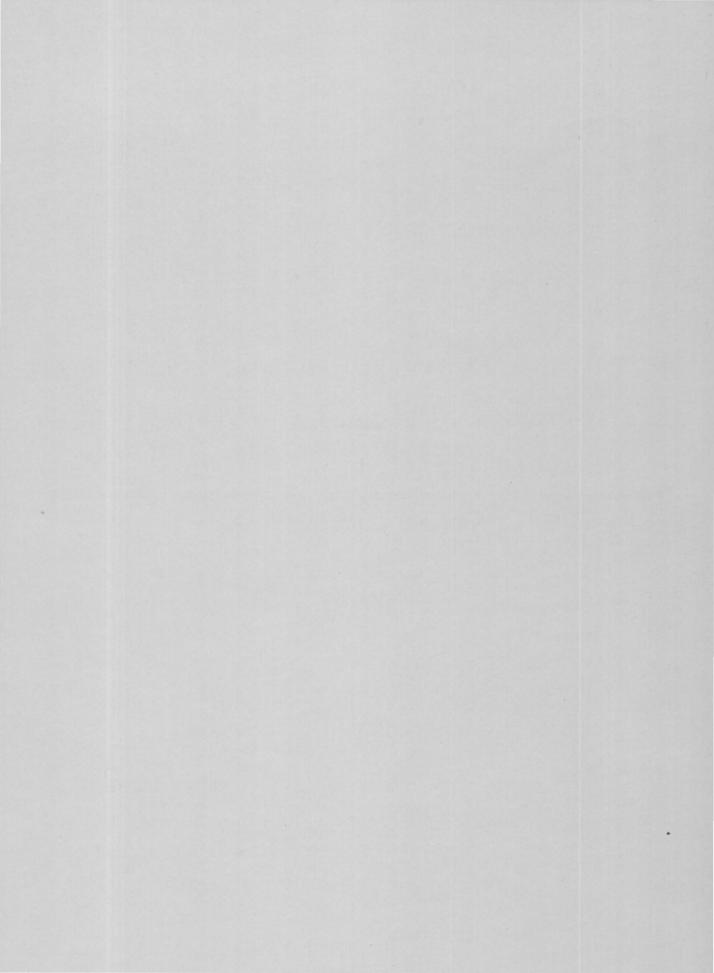GEOLOGICAL SURVEY CIRCULAR 784

Gold, Silver, and Other Resources in the Ash of Incinerated Sewage Sludge at Palo Alto, California --

A Preliminary Report

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By R. A. Gulbrandsen, Norma Rait, Donathan J. Krier,

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ABSTRACT

The ash of incinerated sewage sludge in Palo Alto, Calif., contains large contents of gold (30 parts per million) and silver (660 ppm). As much as 9000 metric tons of ash is piled in the city dump and comprises a gold and silver deposit that has a market value of about $2.5 million. Annual production of ash is about 1800 metric tons with a value of nearly $.5 million. The contents of copper (8000 ppm) and tin (1000 ppm) increase the value of the ash appreciably. Phosphorus makes up about 6.6 percent of the ash and has a potential value for fertilizer manufacture.

The principal source of the metals appears to be the large electronics industry that is located in the area. Part of the silver likely comes from the photographic industry.

No resources are being recovered presently from the ash of incinerated sewage sludge in the United States. The ash from the Palo Alto sewage sludge appears to offer an attractive opportunity for the profitable recovery of a number of mineral resources.

INTRODUCTION

Bizarre as it may seem, a gold and silver deposit is located in the city dump of Palo Alto, Calif. The deposit is composed of incinerated sewage sludge. The multiple hearth incinerator handles about 6500 metric tons (dry basis) of sludge annually and yields about 1800 metric tons of ash. As much as 9000 metric tons has been piled in the city dump. The temperature of incineration is about 760°C, and very little unburned material remains in the ash.

The apparent value of the deposit, based on a gold price of $175 per troy ounce and a silver price of $5.00 per troy ounce, is nearly $2.5 million, and the apparent value of the ash produced annually is almost $.5 million. Significant amounts of phosphate, copper, and tin increase the value of the ash appreciably.

The sewage system serves the cities of Mountain View, Los Altos, Los Altos Hills, Stanford, and East Palo Alto, in addition to Palo Alto itself. The principal source of the metals appears to be the large electronics industry that is located in the area served by the sewage system, although the photographic industry may contribute a significant part of the silver.

The remarkably large gold and silver contents of the ash were indicated first by semiquantitative spectrographic analyses made as part of a study of the ash as a potential source of phosphate for fertilizer. The spectrographic analyses were subsequently confirmed by neutron activation analysis for gold and atomic absorption analysis for silver.

Analytical data of two samples that were collected 5 months apart at the incinerator are presented here. The close similarity in composition of the samples with one another as well as with another sample that is reported by Gabler and Neylan (1977) indicates that the ash is remarkably homogeneous. Since the press release by the U.S. Geological Survey, in March, 1977, of the gold and silver contents of the ash, the Palo Alto City staff reports (oral commun., May 23, 1978) that subsequent determinations of the amounts of gold and silver in ash from the incinerator have not changed significantly.

In addition to the analytical data, this report treats some features of the ash that bear on recovery methods for some of the elements, particularly phosphorus. This study is not intended to be thorough or comprehensive in scope.

PHYSICAL CHARACTERISTICS AND MINERAL COMPOSITION

The reddish-brown fine-grained ash is similar in general appearance to natural material. More than 80 percent of the ash is smaller than .061 mm in grain size (silt and clay). Size fractions are presented in the following table (sample taken in October 1975).

Grain size (mm)	Percent of total sample
>0.833	1.3
.495-.833	1.5
.149-.495	6.2
.061-.149	9.4
<.061	81.6

Microscopic examination shows that the ash differs markedly from natural materials in containing bits of aluminum foil, wire, common glass, and animal bone. X-ray diffraction reveals the presence of another anomalous component, silicon, which is an important semiconductor used by the electronics industry.

The minerals, compounds, and native elements in the ash that have been identified are listed in table 1. Most are minerals, that is, naturally occurring chemical compounds and native elements, and many of them, particularly quartz, plagioclase, potassium feldspar, amphibole, and pyroxene, are likely derived from the sand, soil, and dust of the area. Other minerals, such as corundum and garnet, have been used by man as abrasives and then discarded. Possibly some part of all of the minerals have been used in some way. The only identified minerals in the ash that do not occur naturally are aluminum, silicon, and silicon carbide. Some of the minerals are synthetic, at least in part; cristobalite, for example, is commonly formed in ceramics. Much of the hematite and probably all of the whitlockite are developed during the incineration of the sludge.

The number of identified constituents in the ash is unusually large in comparison

with natural sediment, and, because of the heterogeneous origin of sewage, many more are undoubtedly present. Quartz, cristobalite, whitlockite, and apatite are the major components, and many others occur in significant amounts.

Table 1.--*Identified minerals, compounds, and native elements in Palo Alto ash*

Elements:
  Iron
  Aluminum
  Gold
  Silicon

Oxides:
  Hematite (ferric oxide)
  Corundum (aluminum oxide)
  Rutile (titanium oxide)
  Quartz (silicon oxide)
  Cristobalite (silicon oxide)

Silicates:
  Plagioclase   (sodium calcium aluminum silicate)
  Potassium feldspar (potassium aluminum silicate)
  Amphibole   (many compositional variables)
  Pyroxene   (many compositional variables
  Muscovite   (potassium aluminum hydroxyl silicate)
  Talc   (magnesium hydroxyl silicate)
  Garnet   (many compositional variables)
  Zircon   (zirconium silicate)

Phosphates:
  Whitlockite   (calcium magnesium carbonate(?) phosphate)
  Carbonate hydroxyl apatite (calcium hydroxyl carbonate phosphate)

Carbonate:
  Calcite   (calcium carbonate)

Carbide:
  silicon carbide

CHEMICAL COMPOSITION

Data that we have obtained on the chemical composition of ash from Palo Alto are presented in table 2. Other constituents that have not been determined but that are known qualitatively to be present are carbon as inorganic carbonate, carbon of unburned organic material, and sulfur as sulfate. Also included in the table is a measure of concentration of the elements relative to their respective abundances in the continental crust of the earth, called the concentration factor (C.F.). Table 3, compares the average composition of the ash that we determined with an analysis of the ash made by Gabler and Neylan (1977) of the U.S. Bureau of Mines as well as with a summary of their analyses of incinerated sludge ashes of other United States cities. The analyses of the Palo Alto ash compare well for most constituents. The large difference between the tin determinations deserves attention, however, because of the appreciable apparent value of the tin in the ash. Since our determination of tin was only semiquantitative, we accept the quantitative determination, 1000 ppm, of Gabler and Neylan as the better one. Comparison of the 14 rare elements common to both the average composition of Palo Alto ash and the average composition of ash from 13 plants in other U.S. cities shows that the concentrations of 10 of the elements are greater in the Palo Alto ash and that 8 of these 10 occur in amounts more than twice as large as those in the ash of other cities.

Gold was not detected in the ash of other cities, and compared to the Palo Alto ash, silver is present in much smaller

Table 2.—*Chemical composition of Palo Alto ash*

[Sample 1 is bulk sample of October, 1975; sample 1A is the grain-size fraction of sample 1 that is less than .053 mm; sample 1B is the acid-insoluble (HCl:H20-1:3) of sample 1A; sample 2 is bulk sample of March 1976. Footnotes: 1, semiquantitative spectrographic analysis by N. Rait; 2, instrumental neutron-activation analysis (INAA) by P. A. Baedecker; 3, atomic absorption spectrophotometric (AAS) analysis by Anne Childress; 4, average of INAA and AAS; 5, X-ray spectrographic analysis by R. A. Gulbrandsen; 6, spectrophotometric analysis by R. A. Gulbrandsen; 7, continental crust (Taylor, 1964); 8, Concentration factor (C.F.) = average ash/continental crust].

Element	Sample No.				Average of 1 and 2	Crustal abundance[7]	C.F.[8]
	1	1A	1B	2			
		Percent by weight					
Si[1]	21.0	17.0	--	23.0	22.0	28.15	0.8
Al[1]	5.4	4.4	6.4	4.8	5.1	8.23	.6
Fe[2]	4.8	5.4	3.2	4.1	4.4	5.63	.8
Mg[1]	1.9	1.7	.9	1.8	1.8	2.33	.8
Ca[5]	8.6	8.7	.4	7.0	7.8	4.15	1.9
Na[1]	1.1	1.3	.9	1.1	1.1	2.36	.5
K[1]	.5	.5	.6	.4	.4	2.09	.2
Ti[1]	.3	.3	.6	.3	.3	.57	.5
P[6]	6.2	7.4	.3	7.1	6.6	.105	63
		Parts per million					
Ag[4]	680	760	710	635	660	0.07	9400
Au[2]	28	34	64	32	30	.004	7500
B[1]	89	59	51	74	82	10	8.2
Ba[2]	2600	2750	1850	2500	2550	425	6
Be[1]	5	5	8	13	9	2.8	3.2
Cd[4]	68	80	--	99	84	.2	420
Ce[2]	170	200	62	180	175	60	2.9
Co[2]	360	425	170	230	295	25	12
Cr[2]	1450	1700	2150	1200	1300	100	13
Cs[2]	18	22	22	12	15	3	5
Cu[3]	7400	8200	6400	8600	8000	55	145
Ga[1]	98	100	84	290	190	15	13
Hf[2]	5	6	11	7	6	3	2
La[2]	67	81	35	65	66	30	2.2
Mn[1]	680	650	270	580	630	950	.7
Mo[1]	23	14	7	27	25	1.5	16
Nb[1]	17	17	--	23	20	20	1
Nd[2]	50	55	18	44	47	28	1.7
Ni[3]	1700	2200	1400	1100	1400	75	19
Pb[3]	1800	2300	770	2000	1900	12.5	150
Pd[1]	5	5	11	4	4	.01	400
Sb[2]	14	18	14	24	19	.2	95
Sc[2]	4	4	4	3	4	22	.2
Sm[2]	4	4	2	3	4	6	.7
Sn[1]	3100	3600	3500	3000	3050	2	1500
Sr[1]	430	400	61	480	455	375	1.2
Ta[2]	8	9	17	6	7	2	3.5
Th[2]	6	7	7	4	5	9.6	.5
U[2]	11	12	2	14	12	2.7	4.4
V[1]	41	33	33	43	42	135	.3
Y[1]	8	7	6	8	8	33	.2
Yb[1]	.8	.6	.7	.7	.8	3	.3
Zn[4]	3700	4500	3100	4000	3850	70	55
Zr[1]	270	240	580	340	305	165	1.8

amounts. The only other city that is known to have a significant amount of gold in its sewage is Sunnyvale, which is located a few miles south of Palo Alto and which has a large electronics industry like that of Palo Alto. An analysis of this sewage by K. E. McAbee (San Jose Mercury, 1977; oral commun., 1977) shows a gold content of 0.1-0.2 troy ounce per ton of wet sludge. This content of gold in wet sludge would be concentrated a number of times if it were incinerated, and the ash would likely

contain about the same amount of gold as the ash of Palo Alto's incinerated sludge. Silver in the wet sludge was reported to be about 0.5 troy ounce per ton, an amount that would be much less than that of Palo Alto's ash even after incineration.

Phosphorus is a major constituent of the ash, averaging 6.6 percent by our analysis, and is about double the average amount for other U.S. cities (table 3). Analyses of Toronto, Ontario, ash have an average of 5.1 percent phosphorus (Diosady, 1975, p. 11). The reason for the high amount in the Palo Alto ash is not known.

Table 3.--*Chemical composition of ash of incinerated sewage sludge from Palo Alto and other U.S. cities*

Element	Palo Alto		Other U.S. cities[1]	
	This Paper	Gabler and Neylan, 1977	(Gabler and Neylan, 1977)	
			Average	Range
	Percent by weight			
Si -------	22.0	21.0	20.0	9.3-42
Al -------	5.1	4.8	4.0	1.2- 7.0
Fe -------	4.4	4.3	6.1	1.6-15
Mg -------	1.8	1.8	2.0	.3-10
Ca -------	7.8	9.3	14.0	.8-30
Na -------	1.1	1.5	1.4	.06-2.3
K -------	.4	1.2	.8	.13-1.4
Ti -------	.3	.5	.6	.2-1.4
P -------	6.6	5.6	3.1	1.2-5.7
LOI[2] -----	--	3.0	3.8	.2-16
	Parts per million			
Ag -------	660	575	110	24-280
Au -------	30	30	--	--
B -------	82	--	--	--
Ba -------	2550	8400	5700	1200-8700
Be -------	9	--	--	--
Bi -------	--	120	83	39-150
Cd -------	84	59	25	6-96
Ce -------	175	--	--	--
Co -------	295	290	31	11-57
Cr -------	1300	1500	1200	52-3600
Cs -------	15	--	--	--
Cu -------	8000	7300	1200	210-2200
Ga -------	190	--	--	--
Hf -------	6	--	--	--
La -------	66	--	--	--
Li -------	--	10	24	7-66
Mn -------	630	600	1100	260-2400
Mo -------	25	--	--	--
Nb -------	20	--	--	--
Nd -------	47	--	--	--
Ni -------	1400	1500	360	19-1300
Pb -------	1900	1500	760	160-1800
Pd -------	4	9	--	--
Sb -------	19	--	--	--
Sc -------	4	--	--	--
Sm -------	4	--	--	--
Sn -------	3050	1000	330	110-1100
Sr -------	455	170	170	12-950
Ta -------	7	--	--	--
Th -------	5	--	--	--
U -------	12	--	--	--
V -------	42	--	--	--
Y -------	8	--	--	--
Yb -------	.8	--	--	--
Zn -------	3850	3800	3100	570-800
Zr -------	305	--	--	--

[1]Albany, N.Y.,: Atlanta, Ga.; Cleveland, Ohio; Detroit, Mich.; Laurel, Md; Minneapolis - St. Paul, Minn. (3 plants); Monterey, Calif.; St. Louis, Mo. (2 plants); San Mateo, Calif.; and Savannah, Ga.

[2]LOI is loss on ignition.

MINERAL RESOURCES

The concentration factors (C.F.) shown in table 2 provide one means of judging the economic potential of the elements in the Palo Alto ash. McKelvey (1960) shows that concentration factors of the elements in ore deposits range from about 3 to 10,000 and are, in general, inversely proportional to the respective abundances of the elements in the Earth's crust. Abundant elements, such as aluminum and iron have C.F.'s less than 10. Phosphorus, the eleventh most abundant element, has C.F.'s in commercial deposits from about 20 to 150; the C.F. in the Palo Alto ash is 63. Silver is the most highly concentrated element in the ash, with a C.F. of 9400, and is present in an amount that is similar in magnitude to the rich deposits of the Coeur D'Alene district in Idaho (Heyl and others, 1973, p. 594). Gold is the next highest, with a C.F. of 7500, and the amount of gold is about double the average grade that is mined currently in the world (Simons and Prinz, 1973, p. 274). Tin is highly concentrated with a C.F. of 500 (using the value of Gabler and Neylan, 1977), but not especially high in actual grade. Palladium has a C.F. of 400 and would likely be recovered with gold. The C.F. of copper is only 145, but the amount present is of common ore grade. Cadmium is highly concentrated, with a C.F. of 420, but the amount present in the ash is not of significant value. Lead, with a C.F. of 150, is also of only small value. Seven more elements—cobalt, chromium, gallium, molybdenum, nickel, antimony, and zinc—have factors greater than 10 but are present in amounts that are of low value. All of the elements that have concentration factors greater than 10 make the Palo Alto ash an unusual material in comparison with the natural materials of the Earth's crust. Average shale (Turekian and Wedepohl, 1961), for example, has only one rare element with a C.F. as high as 10 from the group of those reported in the ash. Compared to natural materials, the ash may even be unique in containing a suite of elements that are significantly concentrated but that are of diverse geochemical affinities.

RARE ELEMENTS

Methods of recovery of some of the rare elements from the ashes of incinerated sewage sludges have been studied by Diosady (1975), Oliver and Carey (1976), and Gabler and Neylan (1977). All of the studies contain many data on the solubility of the elements in various kinds of solvents. Gabler and Neylan are the only ones to work on the Palo Alto ash and on the extraction of gold and silver in particular. They

found in preliminary studies that a two-stage leach of the ash with boiling concentrated hydrochloric acid and a strong alkaline sodium cyanide solution was required to extract 77 percent of the gold and 40 percent of the silver. The only other extractive data on gold and silver in the Palo Alto ash are those that we obtained (sample 1B, table 2). They comprise the determinations made on the acid-insoluble part of sample 1A. Hydrochloric acid was used in a 1:3 ratio of concentrated HCl to H_2O at ambient temperature. The amount of gold, 64 ppm, indicates that essentially all of the gold is insoluble in the hydrochloric acid solution, and about half of the silver is not dissolved. We have observed gold in the metallic state as individual plates and variously shaped chunks and also incorporated in particles of fused or aggregated material. No other mode of occurrence has been recognized although Gabler and Neylan's data indicate that more than one exists. At least two modes of occurrence of silver are present, as our solubility data indicate as well as those of Gabler and Neylan's, but none has been identified. We found that the silver dissolved in the hydrochloric acid solution could be separated effectively by a small increase in the solution's pH. The addition of sodium hydroxide solution precipitated silver chloride, the mineral ceragyrite.

The recovery of rare elements in the Palo Alto ash is complicated by the number of elements that are present in significant amounts, as well as by the lack of knowledge about the elements' modes of occurrence. The ash is a new kind of ore for which efficient extractive methods for the greatest number of elements possible have yet to be developed.

PHOSPHORUS

The phosphorus content of worldwide commercial phosphate deposits ranges from about 2.2 to 16 percent. A proposed mine by U.S. Gypsum at Pine Mountain, Ventura Co., California, would have ore with an average grade of 3.7 percent phosphorus (Evans, 1976, p. 275) and would be the only phosphate mine in California that is mined for phosphate products (some phosphatic rock is mined for use as a soil conditioner).

Nearly all of the phosphorus mined in the United States occurs as carbonate fluorapatite, a phosphate mineral that is formed in the marine environment. About 83 percent of U.S. consumption is for fertilizer and animal feed supplement, about 9 percent for detergents, and the remainder is used in a large number of other products (Stowasser, 1977, p. 6).

Fertilizer manufacture employs two basic processes. In the first, the water-insoluble apatite that is mined is converted into soluble monocalcium phosphate by sulfuric acid. Gypsum is also formed in the reaction. The product is ordinary superphosphate, a fertilizer that is declining in popularity.

In the second process, sufficiently more sulfuric acid than that required in the superphosphate process is added in order to dissolve all of the phosphate compounds and yield phosphoric acid and gypsum. The gypsum and other insoluble residues are removed by filtration, leaving a phosphoric acid product. This method of processing is popular because many kinds of fertilizers can be made from phosphoric acid. There are three general types:
1. Triple superphosphate. A solid fertilizer made by the reaction of phosphoric acid with apatite ore. It contains up to three times as much available P_2O_5 as ordinary superphosphate.
2. Mono- and diammonium phosphates. Solid fertilizers that can be mixed with potassium salts to make all grades of three-component (nitrogen-phosphorus-potassium) fertilizers.
3. Liquid fertilizers that contain phosphate and other element nutrients.

Phosphorus compounds that have been identified in the Palo Alto ash are the minerals carbonate hydroxyl apatite and whitlockite. Both are principally calcium phosphates like the apatite of most commercial ore deposits and are similarly soluble in acid solutions. The amount of calcium in the ash, however, is insufficient to account for all of the phosphorus in these compounds. The presence of a small amount of calcium carbonate (calcite) further accentuates the calcium deficiency. It seems most likely that iron, and possibly aluminum, are combined with the excess phosphate. A rough calculation indicates that about 35-40 percent of the ash is composed of phosphate compounds.

The amounts of constituents of the ash that are dissolved in the hydrochloric acid solution along with those of phosphate compounds are shown in table 4. Sample 1B is the acid-insoluble part, 53 percent, of 1A. The amount of an element that is dissolved, therefore, equals the total (in 1A) minus the amount that remains in the acid-insoluble part (percent in 1B multiplied by .53, the proportion of the total 1A that is acid insoluble). The amount of phosphorus dissolved, for example, is:
P (dissolved)=P (total)-P (acid insoluble),
7.2 percent=7.4 percent-.2 percent (.3x.53).
Nearly all the phosphorus, calcium, strontium, and uranium are dissolved (table 4).

Table 4.--*Amounts of elements dissolved in HCL*

[Samples 1A and 1B from table 2. Part in A.I. is
amount that remains in acid-insoluble part of 1A
(percent in 1B multiplied by .53, the proportion of
total in 1A that is acid insoluble). Part dissolved is
total in 1A minus part of 1A that is acid insoluble.
Percent dissolved is part of 1A dissolved relative to
total in 1A.]

Element	Sample 1A	Sample 1B	Part in A.I.	Part dissolved	Percent dissolved
			Percent by weight		
Si	17	--	--	--	--
Al ----	4.4	6.4	3.4	1.0	23
Fe ----	5.4	3.2	1.7	3.7	68.5
Mg ----	1.7	0.9	.5	1.2	71
Ca ----	8.7	0.4	.2	8.5	98
Na ----	1.3	0.9	.5	.8	62
K ----	.5	0.6	.3	.2	40
Ti ----	.3	0.6	.3	0	0
P ----	7.4	0.3	.2	7.2	97
			Parts per million		
Ag ----	760	710	380	380	50
Au ----	34	64	34	0	0
B ----	59	51	27	32	54
Ba ----	2750	1850	980	1770	64
Be ----	5	8	4	1	20
Cd ----	80	--	--	--	--
Ce ----	200	62	33	167	93.5
Co ----	435	170	90	345	79
Cr ----	1700	2150	1100	600	35
Cs ---	22	22	12	10	45
Cu ----	8200	6400	3400	4800	59
Ga ----	100	84	44.5	55.5	55.5
Hf ----	6	11	6	0	0
La ----	81	35	19	62	77
Mn ----	650	270	140	510	78
Mo ----	14	7	4	10	71
Nb ----	17	--	--	--	--
Nd ----	55	18	9.5	45.5	83
Ni ----	2200	1500	795	1405	64
Pb ----	2300	770	410	1890	82
Pd ----	5	11	6	0	0
Sb ----	18	14	7	11	61
Sc ----	4	4	2	2	50
Sm ----	4	2	1	3	75
Sn ----	3600	3500	1900	1700	47
Sr ----	400	61	32	368	92
Ta ----	9	17	9	0	0
Th ----	7	7	4	3	43
U ----	12	2	1	11	92
V ----	33	33	17.5	15.5	47
Y ----	7	6	3	4	57
Yb ----	.6	.7	.4	.2	33
Zn ----	4500	3100	1600	2900	64
Zr ----	240	580	310	0	0

Strontium and uranium probably occur in the
calcium phosphate compounds as they do in
natural phosphate deposits. Nearly
insoluble elements are gold, titanium,
hafnium, palladium, and zirconium. The more
abundant rare elements in the ash are
dissolved in significant amounts: silver,
50 percent; barium, 64 percent; chromium, 35
percent; copper, 59 percent; nickel, 64
percent; lead, 82 percent; tin, 47 percent;
and zinc, 64 percent.

It seems likely from these data that
any process for making fertilizer from the
ash will have to include a means of
separating undesirable elements from the
fertilizer product. The amount of dissolved
lead, for example, is especially large and
potentially hazardous to health if it enters
the food chain in fertilizer.

Treatment of the ashes that were
studied by Diosady (1975) and Oliver and
Carey (1976) includes the recovery of a
number of rare elements as well a high-quality
phosphate fertilizer product. In general,
the principal procedures include the solu-
tion of rare elements and phosphate in hot
sulfuric acid solutions; separation of the
rare elements by ion exchange and sulfide
precipitation, or electrolysis; and the
recovery of the phosphorus as phosphoric
acid or ammonium phosphate.

Phosphorus was found to be the resource
of greatest value in the ashes investigated
by Diosady (1975) and Oliver and Carey
(1976), and Diosady concluded that only the
recovery of phosphorus seemed economically
possible. The recovery system for phos-
phorus and some other elements that was
proposed by Oliver and Carey was considered
likely to be economically feasible only for
very large sewage plants.

CONCLUSION

Recycling of mineral resources is of
increasing importance as the primary
deposits become depleted or more costly to
develop, as environmental concerns restrict
or prohibit the development of new deposits,
and as the nation strives to maintain or
gain independence from foreign sources for
some resources.

No resources are recovered presently
from ash of incinerated sewage sludge in the
United States, although a potential is
recognized, some research into recovery
processes has been done, and additional work
is underway. Part of the impetus for the
recovery of element resources arises from
the need to ensure that the ash is safe for
disposal in the environment. It is the
large number of potential resources in ash
that poses difficult recovery problems as
well as offering opportunities for
recycling.

The Palo Alto ash is especially rich in
resources. The remarkably large amounts of
gold, silver, phosphorus, tin, and copper,
in particular, present an unusual oppor-
tunity for pioneer work in profitable
recycling, which could lead also to the
development of processes for the recovery of
other element and mineral constituents in
the ash.

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