PROCESS FOR REMOVING AND DETOXIFYING CADMIUM FROM SCRAP METAL INCLUDING MIXED WASTE

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PROCESS FOR REMOVING AND DETOXIFYING CADMIUM FROM SCRAP METAL INCLUDING MIXED WASTE. *

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Aiken, SC 29808

ABSTRACT

Cadmium-bearing scrap from nuclear applications, such as neutron shielding and reactor control and safety rods, must usually be handled as mixed waste since it is radioactive and the cadmium in it is both leachable and highly toxic. Removing the cadmium from this scrap, and converting it to a nonleachable and minimally radioactive form, would greatly simplify disposal or recycling. A process now under development will do this by shredding the scrap; leaching it with reagents which selectively dissolve out the cadmium; reprecipitating the cadmium as its highly insoluble sulfide; then fusing the sulfide into a glassy matrix to bring its leachability below EPA limits before disposal. Alternatively, the cadmium may be recovered for reuse. A particular advantage of the process is that all reagents (except the glass frit) can easily be recovered and reused in a nearly closed cycle, minimizing the risk of radioactive release. The process does not harm common metals such as aluminum, iron and stainless steel, and is also applicable to non-nuclear cadmium-bearing scrap such as nickel-cadmium batteries.

INTRODUCTION

Cadmium is a rare metal, roughly as plentiful as silver in Earth's crust. It is found chiefly as an impurity in zinc ores, although one primary cadmium mineral, greasone (cadmium sulfide, CdS) occurs in some hydrothermal ore bodies. As shown in Table 1, cadmium has physical and chemical properties intermediate between those of zinc and mercury, which share its column in the Periodic Table.

Cadmium's unusual properties have historically made it a valuable ingredient in metallurgy. Low-melting solders and fusible metals used in fire and steam safety have usually contained cadmium; a well-known example is "Wood's metal", an alloy containing one part each of tin and cadmium, two of lead and four of bismuth. Cadmium plating guards iron and steel against corrosion; it functions in this role much like zinc on galvanized iron, but is easier to apply and more effective on a weight-for-weight basis. Cadmium also helps form the contacts of electro-mechanical relays meant to handle high current. In general, any relay rated for ten amperes or more likely has cadmium-bearing contacts.

The ready oxidizability and reducibility of cadmium (as evidenced by its low reduction potential) makes it useful in energy storage, notably in rechargeable nickel-cadmium cells. Cadmium has also been used as an additive to improve the performance of lead-acid storage cells, especially in restoring old ones which have lost some of their capacity.

An additional property of cadmium is that its extremely long-lived radiisotope, cadmium-113 -- which makes up 12.2% of natural cadmium -- has an unusually high absorption cross-section for thermal neutrons. As a result, cadmium metal is widely used in nuclear reactor control and safety rods, housings and shielding assemblies for thermal-neutron sources and measuring equipment, and various other devices throughout the nuclear industry.

As a result of these multiple uses, cadmium is present to some degree in scrap metal from a wide variety of sources.

...BUT NOW, THE BAD NEWS.

Cadmium is easily absorbed by the human body from food or water, but is much less readily excreted and so becomes highly concentrated in some body tissues. Like mercury, cadmium is very toxic. Its primary effect is on the kidneys, but it can also affect the bones, liver and nervous system. Inhaling fumes of the metal or freshly-formed oxide can cause lung scarring, pneumonia, emphysema or even death.

As a result, cadmium is listed as a characteristic hazardous waste, with a T.C.L.P. limit of only one part per million. This means that, to be discardable as nonhazardous, any cadmium-bearing waste must be in such a form that, after leaching by simulated groundwater in a specified laboratory procedure, the water will contain less than one part per million of dissolved cadmium.

Like zinc and mercury, cadmium is almost inert to pure water but is readily attacked by some dissolved species, particularly those which can form stable, water-soluble complexes with the metal ion. Ammonium...
Cadmium compounds have a disproportionate effect because of the easy formation, stability and water-solubility of the cadmium tetrammine complex ion:

\[ \text{Cd}^{2+} + 4 \text{NH}_3 \rightarrow \text{Cd} (\text{NH}_3)_4^{2-} \]

This process is further accelerated if oxygen or another oxidizing agent is present.

Since both ammonium compounds and oxygen are naturally present in rain and in most groundwater, cadmium-bearing scrap which is buried or exposed to the weather will tend to release cadmium to the environment in the form of soluble tetrammine salts. Like the metal and its uncomplexed ions, cadmium tetrammine salts are highly toxic. Hence, most cadmium-bearing scrap requires special handling and disposal as toxic waste.

A special problem arises when waste is above the T.C.L.P. limit for a characteristic waste and is also radioactive. Such material is termed "mixed waste". Its disposal is extremely difficult because of the conflicting regulations governing toxic and radioactive wastes. Much nuclear scrap, such as used reactor control and safety rods, must be handled as mixed waste because it contains not only cadmium but also residual radioactive activity from neutron activation.

It should be noted that very little of this radioactivity is actually in the form of cadmium isotopes. Table 2 lists all stable cadmium isotopes, plus radioisotopes whose half-lives exceed ten minutes. Of these, only five are longer than a day. Cd-113 occurs naturally. Cd-109, 111m, 117 and 117m form by neutron activation of cadmium, silver or palladium, but are even more quickly burned out by further neutrons and thus do not accumulate much in the irradiated material.

The volatility of cadmium, combined with its toxicity, makes cadmium-bearing scrap difficult and often impractical to reprocess.

Nearly all scrap-metal reclamation schemes use heat to burn off grease, paint and other contaminants. Heat may also be applied to melt the metal into more compact, easily-handled forms such as ingots, or disperse it into granules for more efficient chemical processing. But when cadmium-bearing scrap is heated the cadmium vaporizes and burns, forming a smoke of fine oxide particles suspended in the air which can poison anyone who breathes it in. As a result, it is often preferable to discard cadmium-bearing scrap metal as waste -- or to store it indefinitely -- than to attempt to reprocess it.

Some simple method for removing cadmium from scrap metal -- preferably, without attacking any other metals present -- would permit easier waste disposal, safer recycling of used materials, and the reclassification of much "mixed" nuclear waste into separate fractions which could then be handled according to well-established and nonconflicting regulations. Preferably, such a process would turn the cadmium into a relatively stable, compact and water-insoluble form which either could be reused or, by meeting the T.C.L.P. limit, could be discarded as nonhazardous. The stabilized cadmium should be free of impurities, especially those from nuclear scrap which could be reasonably expected to carry significant levels of radioactivity.

No such method is presently known to be in use.

A CADMIUM EXTRACTOR.

Cadmium-bearing scrap metal can be freed from cadmium, and the cadmium rendered insoluble and hence nontoxic, by carrying out the following steps:

1. Shredding the scrap, or otherwise treating it, if necessary, so that all bodies of cadmium are exposed to the outside.

2. Leaching the shredded scrap with a hot, aqueous solution of an ammonium salt, plus an oxidizer.

3. Decanting the leach liquid and removing ammonium compounds and ammonia, leaving a concentrate of uncomplexed cadmium salts.

4. Redissolving if necessary, acidifying, and adding a soluble sulfide to reprecipitate the cadmium as nearly insoluble, thermally stable cadmium sulfide.

5. Removing excess soluble sulfide and any other water-soluble materials which may be present.

6. Drying the cadmium sulfide. If it is pure enough and an adequate market exists (as, in making photoconductive cells), the sulfide may be sold in this form. If not, it may be prepared for disposal as a nonhazardous substance by....

7. Fusing the cadmium sulfide with a suitable glass frit, in the absence of air, to form a solid mass. Only those few surface particles not enclosed by glass are then accessible to leaching. This should permit the T.C.L.P. limit to be met, and the sulfide to be discarded as nonhazardous waste.

The following paragraphs outline one possible

<table>
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<tr>
<th>Atomic Weight</th>
<th>Half-Life</th>
<th>Percentage of Natural Abundance</th>
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<tr>
<td>104</td>
<td>58 minutes</td>
<td>0</td>
</tr>
<tr>
<td>105</td>
<td>56 minutes</td>
<td>0</td>
</tr>
<tr>
<td>106</td>
<td>(stable)</td>
<td>1.25%</td>
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<tr>
<td>107</td>
<td>6.5 hours</td>
<td>0.89%</td>
</tr>
<tr>
<td>108</td>
<td>(stable)</td>
<td>12.5%</td>
</tr>
<tr>
<td>109</td>
<td>462 days</td>
<td>12.8%</td>
</tr>
<tr>
<td>110</td>
<td>(stable)</td>
<td>0.89%</td>
</tr>
<tr>
<td>111</td>
<td>(stable)</td>
<td>12.8%</td>
</tr>
<tr>
<td>111m</td>
<td>48 minutes</td>
<td>24.3%</td>
</tr>
<tr>
<td>112</td>
<td>(stable)</td>
<td>24.3%</td>
</tr>
<tr>
<td>113</td>
<td>9x10^12 years</td>
<td>12.2%</td>
</tr>
<tr>
<td>113m</td>
<td>14.1 years</td>
<td>0</td>
</tr>
<tr>
<td>114</td>
<td>(stable)</td>
<td>28.7%</td>
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<tr>
<td>115</td>
<td>2.23 days</td>
<td>0</td>
</tr>
<tr>
<td>115m</td>
<td>44.6 days</td>
<td>0</td>
</tr>
<tr>
<td>116</td>
<td>(stable)</td>
<td>7.5%</td>
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<tr>
<td>117</td>
<td>2.5 hours</td>
<td>0</td>
</tr>
<tr>
<td>117m</td>
<td>3.4 hours</td>
<td>0</td>
</tr>
<tr>
<td>118</td>
<td>50 minutes</td>
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</tr>
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</table>
While tetrammine cadmium carbonate is quite water-soluble, cadmium carbonate uncomplexed by ammonia is much the opposite: it dissolves in neutral, room-temperature water to the extent of only 0.002 parts per billion. In acids, however, the carbonate breaks down to form other, often soluble salts. It is also redissolved by water containing ammonia, reforming the tetrammine complex. At 332 degrees Celsius it dissociates, releasing carbon dioxide and leaving behind solid, brown cadmium oxide.

Unlike ammonium nitrate, aqueous ammonia and ammonium "carbonate" have no oxidizing power of their own. A supplementary oxidant may be added, however: either as water-dissolved hydrogen peroxide, or as elemental oxygen dissolved under pressure in the leaching solution. To permit work at ambient pressure, the hydrogen-peroxide approach has been used exclusively in the pilot tests.

In a typical test, a stock leachant is first made by letting commercial 3% hydrogen peroxide stand over solid ammonium "carbonate" until saturated, then decanting. An equal volume of 29% aqueous ammonia may then be added. Leaching so far has been conducted only at room temperature, about 25 degrees Celsius, with occasional stirring.

Cadmium-plated steel screws, shredded cadmium sheet, and chemically-pure "mossy" cadmium have all been leached successfully. Weak effervescence slowly appears and lasts for about thirty minutes. The leach liquid is initially clear, but on standing or heating a white precipitate appears as a surface crust and a coating on the sides and bottom of the beaker. This material is water-insoluble but readily redissolved by strong acids, with effervescence, showing that it is uncomplexed cadmium carbonate.

During the leaching process, the cadmium typically takes on a whitish, matte finish. Solid cadmium loses weight equivalent to 5% to 10% of the peroxide's oxidizing capacity, with the higher losses occurring in leachant containing aqueous ammonia. With plated goods most or all of the cadmium is removed, leaving bare steel. Carbon-steel surfaces may become lightly rusted if left long in the leachant, but the rust, made up of gelatinous ferric hydroxide, is easily rinsed away.

Figure 1 (next page) reproduces a scanning electron microprobe spectrum of as-plated metal. Figure 2 gives a corresponding spectrum for a surface essentially stripped of cadmium, and Figure 3, for the white material formed on leachant evaporation. Note the strong cadmium peaks in Figures 1 and 3, and their near-absence in Figure 2.

A likely reason for the poor oxidation yield from peroxide is that cadmium salts, like those of most other transition metals, catalyze peroxide decomposition; most of the peroxide's oxidizing capacity is lost as oxygen bubbles. Hence, an industrial version of the process would preferably use elemental oxygen at elevated pressure instead. An all-gaseous approach might be taken: simply bubbling oxygen, ammonia and carbon dioxide through the scrap metal and leach
Figure 1. Scanning electron microprobe spectrum of cadmium-plated steel screw head. One horizontal spectrum division = 1 KEV.

Figure 2. Spectrum of steel surface stripped of cadmium by ammonium carbonate/peroxide.

Figure 3. Spectrum of cadmium carbonate precipitated from evaporating, used leachant.

Figure 4. A Glass Soxhlet Extractor.

Figure 5. Soxhlet Apparatus for Industrial-Scale Cadmium Extraction from Scrap Metal.

Liquid, and returning unabsorbed gas in a closed loop to be bubbled again and again. This bubble action would also provide needed agitation.

Separation efficiency could be enhanced by adapting the principle of the Soxhlet extractor, shown in Figure 4. This device is commonly used in biochemical preparation, such as isolating alkaloids from plant material. A solvent boils in the lower flask; its vapors are recondensed at the top and flow down into the central extraction chamber, where the source material is held in a porous thimble. When the liquid level nears the top of the extraction chamber, a siphon tube "flushes" the recondensed liquid back into the lower flask and the action begins anew. As a result, the source material is repeatedly exposed to fresh solvent, while the extracted material is concentrated in the lower flask. (Figure 4 was reproduced from the American Scientific Products General Catalog, 1987-88, page 781.)

Figure 5 shows a modification of the basic Soxhlet design, meant for industrial-scale cadmium extraction. A small-scale prototype is now under construction.

Scrap to be treated is placed in the extraction chamber (1) where it rests on a porous plate (2) which takes the place of the extraction thimble. Carbon dioxide, ammonia and oxygen are injected just below the plate. Water in the lower chamber (3) is boiled, the steam rises (4), mixes with the gases, then is recondensed (5) and falls into the extraction chamber to surround the scrap. Uncondensed gases are recirculated by a pump (6) and bubble up again through the liquid and scrap.

When the extraction chamber has become filled with liquid, the siphon tube (7) spils over and quickly "flushes" the liquid back into the lower chamber. The liquid carries with it any leached-out cadmium. A diverter valve (8) at the base of the extraction chamber allows sampling of the liquid at any time for analysis. Cadmium is readily detected by precipitation as the white uncomplexed carbonate or the yellow sulfide, by atomic-absorption spectrophotometry, or otherwise.

After a number of "flush cycles", all leachable cadmium has been removed from the scrap and none is detectable in the leachant. At this point, the diverter valve is opened and the recondensed liquid begins to be drained away (9). This liquid holds dissolved reagent gases and may be reused.
Continued heating both concentrates the liquid remaining in the lower chamber (10), holding the extracted cadmium, and drives off the dissolved gases and complexing ammonia. The result is a "mush" of water and uncomplexed, solid cadmium carbonate. When this is sufficiently concentrated, heating stops, an acid is added to redissolve the carbonate, and the resulting solution is drained off (11).

With the cadmium removed, the remaining metal scrap can be either reprocessed and reused, or discarded as essentially nontoxic. While radioactivity may remain in some nuclear scrap, the material -- unless it also contains lead, mercury or another listed toxin -- will no longer be mixed waste.

At this point, the drained-off solution consists only of water, dissolved metal salts, and a small amount of residual acid. The salts may not be of cadmium alone, since this leachant will also remove from the scrap (or its exposed surfaces) any other transition metals which form water-soluble ammine complexes. This is true of copper, zinc, nickel, chromium, cobalt, iridium, platinum, palladium and silver. Colloidal ferric hydroxide, derived from rusted carbon steel, may also be present.

Where valuable metals, or radioactive ones such as cobalt-60 or nickel-63, are present in addition to the cadmium, the solution may be further treated to remove or recover them. For example, since most of these metals are more noble than cadmium, they may be removed by selective electrodeposition.

Next, the solution is saturated with a soluble sulfide. This may be done either by bubbling in hydrogen sulfide gas, or by adding solid ammonium hydrosulfide or a water solution of it while maintaining a slightly acid pH. Sulfide precipitates the dissolved cadmium:

\[ \text{Cd}^{2+} + 2\text{S}^{2-} \rightarrow \text{CdS} \downarrow \]

The pilot studies have shown that the solution should be freed of all possible ammonia and oxidizing capability before sulfide is added. Sulfide is unable to decompose or precipitate tetrathamine cadmium. If an oxidizer such as hydrogen peroxide is still present, however, elemental sulfur may slowly precipitate and interfere with later separation steps.

Once precipitated, the cadmium sulfide may simply be filtered out. This is easier if the mixture is held near its boiling point for a while ("digested") before filtration, causing larger particles to grow at the expense of smaller ones. The cadmium-sulfide filter cake may be dried by heating it for a while at about 80 degrees Celsius. Uncombined sulfide can be recovered from the remaining liquid, the vapors released during digestion and those from drying, and reused.

The process just described has the economic and environmental advantage of using mainly volatile reagents: either gaseous, readily decomposed into gases by heat, or easily boiled off and recondensed. Only the scrap being treated, the cadmium-sulfide product, and perhaps the acid used to redissolve the precipitated carbonate, are nonvolatile. Hence, unconsumed reagents are easily separated from the treated scrap and sulfide waste for reuse.

This fact gives the described process a second, very significant advantage for use with radioactive scrap, in that no waste streams need be generated apart from the sulfide itself and thus there is little chance of radioactive material's escaping from the process. Even if excess gas is vented to the outside -- whether deliberately or as the result of an accident -- it is unlikely to carry radioactive contamination along.

**DECORATING WITH CADMIUM**

As noted above, cadmium sulfide occurs naturally in certain hydrothermal deposits. While this shows that it is soluble in very hot water under considerable pressure deep underground, the material has very low water solubility at room temperature: on the order of 1.3 parts per million.

Cadmium sulfide oxidizes in air if heated above 400 degrees Celsius, forming toxic fumes:

\[ 2\text{CdS} + 3\text{O}_2 \rightarrow \text{CdO} + \text{SO}_2 \]

Heated in the absence of oxygen, however, the material is stable up to 980 degrees Celsius, where it sublimes at normal pressure. At 100 atmospheres it remains solid up to 1750 degrees Celsius, then finally melts -- still without decomposing.

Cadmium sulfide is a semiconductor with an unusually wide band gap -- 2.42 electron volts, about twice that of silicon -- and as such it has many uses both in established technologies and in emerging ones. It has long been used to form low-leakage, responsive yet low-cost photocathode cells. Thin-film photo-voltaic cells, and light-emitting diodes and solid-state lasers producing blue-green light, have all been demonstrated in the laboratory.

If sufficiently pure, some of the "waste" cadmium sulfide may find a market for these uses. A larger market, however, likely exists in the paints-and-pigments arena.

Cadmium sulfide's band-gap energy corresponds to a light wavelength of 512 nanometers, within the blue-green range. Photons with shorter wavelengths (blue and violet) are strongly absorbed, while longer-wave photons are reflected. This gives the material a deep golden-yellow color, verging on orange. If zinc replaces some of the cadmium, the band gap widens and a paler shade of yellow appears. With selenium replacing some of the sulfur, the band gap narrows and darker orange, reds or even black may result.

Because these colors are vivid and unaffected by heat, light, air, moisture or common atmospheric pollutants, cadmium sulfide and its various modifications have long been popular with artists and artisans as pigments, collectively called "cadmium yellows". The vivid glow of Vincent Van Gogh's "Sunflowers on Yellow Background", for instance, comes from nearly pure cadmium sulfide in an oil-based paint.

If a cadmium yellow is mixed with a suitable frit (powdered glass) and then heated under an inert gas,
it is first wetted by the hot molten glass and then, around 1500 degrees Celsius, wholly dissolves in it. On slow cooling, the material reprecipitates to form a vast number of tiny hexagonal crystals which remain suspended in the glass. Although almost any silicate composition will dissolve and hold the cadmium, lead-bearing frits have traditionally been used since they are low-melting and yield the most vivid colors.

Because the cadmium sulfide is strongly wetted by the glass matrix, fused surfaces expose little or none of it. Once encased by glass, the sulfide is protected from chemical attack or dissolution. Subsequent remelting of the glass may therefore be carried out in air without noticeable effect on the crystals.

Glasses pigmented with cadmium yellows may be formed directly into decorative objects, but more commonly are reground to make vitreous enamels. Supplied as a powder, such an enamel is melted and fused onto metal in a thin, continuous layer for decoration and protection from corrosion.

Lead-based, cadmium-pigmented enamels were widely used on metal goods, jewelry and cookware up to about the mid-1970's. They have since been replaced by lead-free equivalents. Microprobe spectra of representative lead-bearing and lead-free enamels, Thompson Enamels #459 and #3820 respectively, are shown in Figures 6 and 7. While the exact formulas are proprietary, comparison of peak heights suggests cadmium-sulfide loadings of about 5% by weight in each enamel.

Cadmium leaching from properly-fired vitreous enamels at ordinary temperatures seems to be almost nil. Some attack will occur on fractured surfaces where cadmium-sulfide crystals are exposed, but should present little hazard because the amount of cadmium involved is very slight. Properly made and properly fired, lead-free enamel may therefore be used safely on consumer goods, including cookware, without significant cadmium release or poisoning risk.

...BUT WILL IT WORK AS A WASTE FORM?

Cadmium sulfide produced by the described process should be tested both for purity and, in the case of nuclear scrap, for radioactivity. If it is found to be nonradioactive and sufficiently pure, it may be feasible to offer the material for sale on the open market. If not, fusion into a glassy matrix will ready it for safe disposal in a compact form as a nonhazardous or, at worst, as a radioactive but nontoxic material.

Although process details are often trade secrets, the technology for making cadmium-pigmented enamels is well worked out, and at least the basics of it are in the open literature. In a waste-treatment application, of course, more care will need to be paid to the control of incoming and outgoing material streams, and less to the color and day-to-day consistency of the product, than in the manufacture of bulk cadmium sulfide or decorative enamel.

T.C.L.P. tests have been conducted on Thompson

---

**Figure 6.** Scanning electron microprobe spectrum of Thompson #459, a lead-bearing enamel colored by about 5% cadmium sulfide. One horizontal spectrum division = 1 KEV.

**Figure 7.** Spectrum of Thompson #3820, a lead-free enamel colored by cadmium sulfide and other pigments.

| Table 3. Results of T.C.L.P. Testing on Commercial Cadmium-Pigmented Vitreous Enamels: Thompson Enamels #459 and #3820. |
|-----------------|-----------------|-----------------|
|                  | Limit Found in #459 | Found in #3820  |
| Lead            | 5                | 6.56            | <0.14           |
| Cadmium         | 1.210            | 4.09 (l)        |

Concentrations are in milligrams per liter of leach solution (ppm). Limits are the maximum T.C.L.P. leachables permitted for nonhazardous waste.

While it seems likely that a lead-free formulation can be developed which has cadmium leachability low enough to meet the E.P.A. limit, more work is clearly needed. Arrangements are now being made to use a controlled-atmosphere furnace in attempts to develop a low-cadmium-leachability formulation.
WHAT IS CADMIUM...AND WHY IS IT A CONCERN?

Cadmium is a rare metal, roughly as plentiful as silver in Earth's crust, and found chiefly as an impurity in zinc ores. Its physical and chemical properties lie intermediate between those of zinc and mercury, which share its column in the Periodic Table. These unusual properties make cadmium metal valuable for use in solders and other low-melting alloys, in plating to guard steel against corrosion, and in electrical contacts for switching high currents. Cadmium compounds are widely used as pigments, in photocells and in rechargeable batteries.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Specimen</th>
<th>Specimen</th>
<th>Specimen</th>
<th>Specimen</th>
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<td>4.25 X 5.5</td>
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Wood's plated relay metal screws contacts PC cell Nicad battery

Cadmium-113 readily absorbs thermal neutrons. Because of this, cadmium is widely used in the nuclear industry: in reactor control and safety rods, housings and shields for thermal-neutron sources and measuring equipment.

But the human body readily absorbs cadmium...and cadmium, like mercury, can be very toxic: damaging the bones, lungs, liver, kidneys and nervous system. As a result, the E.P.A has ruled that any discarded material from which water could leach more than one part per million of cadmium must be handled as toxic waste.

By law, toxic and radioactive wastes must be handled differently. Thus, where cadmium-containing scrap from the nuclear industry is also radioactive, there is presently no legal means for its disposal. This is "MIXED WASTE".
Cadmium toxicity: target organs

Brain and nervous system
Lungs
Liver
Kidneys
Bones
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HOW DOES THE NEW PROCESS TREAT CADMIUM-CONTAINING SCRAP TO RENDER IT HARMLESS?

The process described here consists of two main parts: first treating scrap with reagents which selectively dissolve out cadmium, then converting the cadmium into a nonleachable and thus nontoxic form.

The prototype apparatus at left shows how scrap may be freed of cadmium. Scrap is shredded to expose all cadmium at the surface, then placed in the central chamber, filled with an aqueous solution of oxygen, ammonia and carbon dioxide. Bubbled through the solution, these gases both agitate and refresh it.

This leaching solution is cheap, safe to handle and low in toxicity. It does not attack aluminum or stainless steel, and has little effect on other metals. It quickly converts cadmium and its compounds, however, into the very soluble cadmium tetrammine complex.

Used leachant is periodically flushed into the lower chamber, where the tetrammine complex is broken apart by heat and cadmium precipitates out as the insoluble carbonate. Water and gases are returned to the central chamber for reuse. As a result, this phase of the process generates no waste streams.

![Specimen goes here](4.25 X 5.5)

Plated screws

![Specimen goes here](4.25 X 5.5)

De-plated screws

After separation, the cadmium carbonate is dissolved in acid and reprecipitated as cadmium sulfide. Though more soluble in neutral water than the carbonate, cadmium sulfide is also much more stable at high temperatures.

Mixed with a glass frit and heated to about 1500 C in the absence of air, the sulfide dissolves in the melt. On slow cooling, a suspension of microscopic cadmium sulfide crystals forms within the glass matrix.

Since the sulfide is now completely enclosed by glass, its chemical reactivity and leachability are much reduced. Properly made, the cadmium-bearing glass can be discarded as nonhazardous or, at worst, as radioactive but nontoxic waste.

![Specimen goes here](4.25 X 5.5)

Yellow glass

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<th>Property</th>
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<th>CdS</th>
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<td>144.5</td>
</tr>
<tr>
<td>Color</td>
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<tr>
<td>Density (g/cc)</td>
<td>4.26</td>
<td>4.82</td>
</tr>
<tr>
<td>Water solubility, pH=7, 20 C (ppm)</td>
<td>.028</td>
<td>1.3</td>
</tr>
<tr>
<td>Soluble in...</td>
<td>Acids,</td>
<td>Slightly</td>
</tr>
<tr>
<td></td>
<td>KCN,</td>
<td>in acids,</td>
</tr>
<tr>
<td></td>
<td>NH₄ salts</td>
<td>NH₄OH.</td>
</tr>
<tr>
<td>Behavior when heated</td>
<td>Dissociates at 980 C; melts at 1750 C.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>332 C to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CdO + CO₂</td>
<td>(100 atm. pressure)</td>
</tr>
</tbody>
</table>

CdCO₃

CdS