The cleaning procedure involves flushing the channel (ten times the void volume) with a hypo-osmotic carrier phase to destroy the cells, then with a classical deproteinization agent (ten times the void volume) to desorb and destroy the cell and surfactant proteins adsorbed in the FFF separator. Finally the system is flushed again with the hypo-osmostic carrier phase.

Decontamination is performed by allowing a hypochloride solution (3–6°C) to flow through the whole FFF system. The volume used should be three to four times the void volume of the FFF device. Prior to injection the channel should be flushed with ethanol and rinsed with the sterile mobile phase. Decontamination and sterilization can be simultaneous if a 5°C hypochloride solution is used with a 70°C ethanol solution.

Cell Detection, Viability and Recovery

At the outlet of the channel it is necessary to obtain eluted material that retains its integrity, that is the diagnosis of the whole particle. Photometric devices operated in the light scattering mode can be used to follow elution. After fraction collection off-line analyses methods such as microscopy, granulometric or flow cytometry analyses are recommended. Cell specific staining is also possible. Cell viability can be diagnosed by means of specific tests, and recovery must also be clearly defined.

Conclusions

The choice of FFF separation techniques for purification of cell or cell organelle populations is influenced by their possible elution modes. Micron sized species eluted under the steric hyperlayer model can be separated using sedimentation techniques if their density differs from that of the carrier phase medium. This is also possible for ‘nonbuoyant’ sub-micron sized cell organelle species eluted according to the ‘Brownian’ elution mode.

If species are to be separated according to their size, FFF techniques that use a flow generated external field are preferred. If differences in surface characteristics are important, electrical-based FFF techniques should be chosen. For large sample volume preparations, SPLITT techniques are useful, whatever the external field. The major technical goal in cell separation is not the set-up of the separator, but the construction of a chain of knowledge. The separator is designed according to the sample characteristics as well as the mode of operation. Cleaning and sterilization procedures, and detection and viability procedures, are linked to the nature of the material to be purified. This ‘biotechnological’ process is of major importance for FFF separations in the life sciences.

See also: **II/Particle Size Separation:** Field Flow Fractionation: Electric Fields; Theory and Instrumentation of Field Flow Fractionation. **III/Colloids:** Field Flow Fractionation. **Polymers:** Field Flow Fractionation. **Proteins:** Field Flow Fractionation. **III/Catalyst studies: Chromatography: Isolation: Magnetic Techniques**.

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CHELATING ION EXCHANGE RESINS

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Introduction

The useful role of ion exchange is to separate a solution at a low initial concentration C_i into a small volume of concentrate and a much larger volume of depleted solution. In favourable cases the concentration C_e of the target species in the regeneration effluent approaches the regenerant concentration C_r. The concentration factor achieved is then given approximately by:

$$R \equiv C_e/C_i \approx C_r/C_i \qquad [1]$$

One usually wants to separate a single valuable species from the other constituents of the initial solution, and the ion exchanger must then be selective for the target species. (Separation can also be achieved by selective desorption, but selective adsorption is preferable because more of the available resin capacity is occupied by the target ion.) The affinity of a resin for a single ion M, under given conditions, can be represented by a distribution coefficient, defined by:

$$D \equiv \frac{\text{amount of } M \text{ on unit mass of resin}}{\text{amount of } M \text{ in unit volume of solution}} \qquad [2]$$

Selectivity between two ions can be expressed by a separation factor, defined by:

$$\alpha \equiv C_e^T \cdot C_d^U / C_d^T \cdot C_e^U \qquad [3]$$

where C^T represents the concentration of the target and C^U that of an unwanted species, while C_e refers to the regeneration effluent and C_d to the depleted solution.

Common strong acid resins show a small degree of selectivity between singly and doubly charged cations, and even within these categories. **Table 1** shows some selectivity values from the literature for a typical strong acid cation exchanger. These are rational equilibrium constants for the reaction:

$$n\mathrm{RSO_3Na} + M^{n+} \rightarrow (\mathrm{RSO_3^-})_n M^{n+} + n\,\mathrm{Na}^+ \qquad [4]$$

defined by:

$$K \equiv A_M \cdot a_{Na}^n / A_{Na}^n \cdot a_M \qquad [5]$$

where A_M is the activity (on the rational scale) of M^{n+} bound to the resin phase and a_M the activity (molal scale) of the salt MX_n in the solution phase. A_{Na} and a_{Na} are the activities of the analogous sodium species. The observed values are too small to allow one cation from a mixture to be selectively concentrated by a large factor.

Weak acid resins tend to be more selective than strong acid. Table 1 also lists some selectivity coefficients (not constants), defined by:

$$K' = M_M \cdot m_{Na}^2 / M_{Na}^2 \cdot m_M \qquad [6]$$

for adsorption of divalent cations M^{n+} on a carboxyl resin initially in the Na^+ form. Here M_M is the molal concentration of M^{n+} in the resin phase and m_M its molality in the solution phase. Although K' and K are only roughly comparable, the carboxyl resin is clearly more selective among these four divalent cations.

Chelating Resins

Ion exchangers incorporating chelating groups have higher selectivity among cations than conventional strong or weak acid resins. (In one sense, adsorption of a di- or trivalent cation by any resin is a chelation process, since the ion is coordinated by two or more ligands linked by a chain of covalent bonds, but the term chelating resin is more usually reserved for resins containing discrete chelating groups, each attached to a single monomer unit. A given cation may be coordinated by one or more of these chelating units.) Technical aspects of their use were outlined by Waitz in 1979. A review and a monograph emphasizing analytical applications were published by Warshawsky and Marhol, respectively, in 1982. A comprehensive review by Sahni and Reedijk appeared in 1984, and a shorter update by Beauvais and Alexandratos in 1998.

Resins with an enormous variety of chelating ligands have been synthesized in the laboratory, but few have been manufactured commercially. Essentially any complexing agent used in analytical chemistry can be coupled to a resin, although the challenge to the synthetic chemist is to avoid sacrificing ligand groups such as thiol or primary amino groups in the coupling reaction. Many published syntheses have been too complex to be economic on an industrial scale or have yielded resins of low stability, but new resin structures continue to be reported. In this review we can consider only a few illustrative examples.

Table 1 Selectivities of strong and weak acid cation exchangers[a]

Ion	*Na^+*	*K^+*	*Mg^{2+}*	*Ca^{2+}*	*Zn^{2+}*	*Ni^{2+}*	*Cu^{2+}*	*Pb^{2+}*
K	1.00	1.5	4.3	11	4.8	6.1	5.9	39
K′	1.00			14	98	38	550	

[a] Rational selectivities *K* of a sulfonated polystyrene resin (8% cross-linked); molal selectivities *K′* of a methacrylic acid resin (5% cross-linked, degree of ionization 0.85, background electrolyte 1 mol L^{-1} $NaNO_3$), relative to Na^+.

Table 2 Some commercial chelating resins

Chelating group	*Examples*
Amidoxime	Duolite ES 346[a], Diaion CR-50[b]
Aminophosphonate	Duolite ES 467, Lewatit OC 1060[c]
Iminodiacetate	Dowex A-1[d], Diaion CR-10, Duolite ES 466, Lewatit TP 208
Diphosphonate	Diphonix[e]
Bis(2-picolyl)amine	Dow 3N (Dowex XFS 4195)
2-Picolyl-2′-hydroxypropylamine	Dow 2N (Dowex XFS 43084)
Oligoamine	Diaion CR-20, Lewatit E 304, Sumichelate MC10[f]

[a] Rohm and Haas; [b] Mitsubishi Chemical; [c] Bayer; [d] Dow Chemical; [e] Eichrom Industries; [f] Sumitomo Chemical.

Early chelating resins based on phenolic polymers were largely displaced by styrene-divinylbenzene resins, functionalized via chloromethylation, because of their greater stability. More recently, acrylic polymers have gained ground, with glycidyl methacrylate being a favoured monomer because ligands are easily coupled by reaction with its epoxide group, although possible hydrolysis of the ester link at extremes of pH limits the applicability of these resins. Sherrington, Driessen and their co-workers have used this strategy to prepare a suite of chelating resins containing nitrogen heterocycles. Similarly, Chanda and Rempel have coupled a wide range of chelating groups to polybenzimidazole beads activated with epichlorohydrin.

Table 2 lists some commercially available chelating resins. The order of preference for iminodiacetate resins is typically:

Univalent cations:	Ag > Li > Na > K > Rb > Cs
Divalent cations:	Hg > U(VI) > Cu > Pb > Ni > Cd ≈ Zn > Co > Fe > Mn > Ca > Mg > Ba > Sr
Trivalent cations:	Cr > In > Fe > Ce > Al > La

Structures for the iminodiacetate and aminophosphonate groups are shown in **Figure 1**. Some selectivity coefficients (no definition given) for iminodiacetate resins, recalculated from Waitz, are collected in **Table 3**.

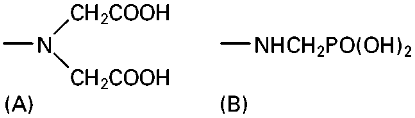


Figure 1 Chelating functionalities: (A) iminodiacetic acid and (B) aminophosphonic acid.

Iminodiacetate Resins: Mercury

Iminodiacetate resins are clearly more selective among the transition metals than are weak acid resins. Adsorption of all metal cations decreases with decreasing pH, and uptake of moderately preferred ions such as Ni^{2+} and Zn^{2+} becomes negligible at pH 1–2, but Hg^{2+} and Cu^{2+} are still strongly adsorbed. For Hg^{2+} in sulfuric acid, $D \approx 2\ \mathrm{L\ g^{-1}}$ at pH 1. The advantage of this high selectivity is illustrated by some results for treatment of a highly acidic, mercury-containing smelter wastewater. Simulated wastewater containing Hg(II), Zn(II), Fe(III), Cd(II) and Pb(II) salts at pH 1.5 was treated with an iminodiacetate resin in bench-scale column runs. **Table 4** and **Figure 2** show the composition of the column effluent over 157 bed volumes. Uptake of Hg(II) was close to 100%, while most of the other cations were not significantly adsorbed. Adsorption of mercury can be represented by:

$$\mathrm{RN(CH_2COOH)_2 + Hg^{2+} \rightarrow RN(CH_2COO^-)_2Hg^{2+} + 2H^+} \qquad [7]$$

It appears that a small amount of Pb(II) is adsorbed initially, then displaced by Hg(II). Fe(III) is adsorbed more strongly than Pb(II), but still less strongly than Hg(II). Uptake of iron can essentially be eliminated by reducing Fe(III) to Fe(II), which is not significantly adsorbed at this low pH.

Regeneration with Complexation

Chelating resins are commonly regenerated with mineral acid, but in some cases the resin's affinity for the target metal is too great for this to succeed. In the Hg(II)-iminodiacetate system desorption with nitric acid failed because of the very strong complexation of Hg(II). Concentrated NaCl solution was an effective regenerant because Cl^- ions convert Hg^{2+} to a series of chlorocomplexes (**Figure 3**). In other words, Hg^{2+} is adsorbed more strongly than H^+, but can be displaced even by Na^+ because it is simultaneously complexed by Cl^-. In this example, both adsorption and desorption steps are selective for Hg(II) over

Table 3 Selectivities at pH 4 of an iminodiacetate chelating resin, relative to Ca^{2+}

Ion	*Ca^{2+}*	*Fe^{2+}*	*Co^{2+}*	*Cd^{2+}*	*Zn^{2+}*	*Ni^{2+}*	*Pb^{2+}*	*Cu^{2+}*	*Hg^{2+}*
K″	1.00	4.0	6.7	15	17	57	1200	2300	2800

Table 4 Selective removal of Hg(II) on a chelating resin[a]

	Hg(II)		*Zn(II)*		*Fe(III)*		*Cd(II)*		*Pb(II)*	
	mg L^{-1}	*%*	*mg L^{-1}*	*%*	*mg L^{-1}*	*%*	*mg L^{-1}*	*%*	*mg L^{-1}*	*%*
Feed	11.8	100	78	100	37	100	1.7	100	4.6	100
Bed volumes										
23	<0.015	<0.1	73	94	1	3	1.6	94	4.0	87
47	0.015	0.1	74	95	7	19	1.7	100	5.5	120
77	0.015	0.1	78	100	14	38	1.7	100	5.0	109
111	0.030	0.3	78	100	17	46	1.7	100	4.7	102
157	0.035	0.3	76	97	28	76	1.7	100	4.9	107

[a] Metal concentrations before and after treatment of a simulated smelter wastewater (pH 1.5) with an iminodiacetate resin. Reproduced with permission from Becker NSC and Eldridge RJ (1993) *Reactive Polymers* 21: 5.

most elements, although Fe(III) shares the ability of Hg(II) to adsorb as a cation and desorb as a chlorocomplex. The regeneration reaction can be written:

$$\mathrm{RN(CH_2COO^-)_2Hg^{2+} + 2Na^+ + 2Cl^-} \rightarrow \mathrm{RN(CH_2COO^-Na^+)_2 + HgCl_2} \qquad [8]$$

Alkaline Earths

The formation of chelate complexes is often regarded as an exclusive property of transition metal cations, but both iminodiacetate and aminophosphonic resins chelate alkaline earth cations and consequently are highly selective for them relative to the alkali metal cations. Separation factors achievable with iminodiacetate resins are reported to be 50–60 for Mg/Na and 500–600 for Ca/Na at pH 7–10; for aminophosphonate resins $\alpha_{\mathrm{Na}}^{\mathrm{Mg}} \approx 1000$ and $\alpha_{\mathrm{Na}}^{\mathrm{Ca}} \approx 20\,000$. These resins are very effective in softening applications, including, as an extreme case, the removal of low levels of unwanted divalent cations from brine in caustic chlorine plants, despite the great excess of sodium ions.

Amidoxime Resins: Uranium from Seawater

The possibility of recovering valuable metals from the oceans presents a challenge to designers of chelating resins. Uranium is present in seawater at about 14 nmol L^{-1} (3 μg L^{-1}), predominantly as the tricarbonatouranate(VI) anion $\mathrm{UO_2(CO_3)_3^{4-}}$. Recovery by ion exchange would require an extremely selective sorbent, since seawater also contains Na$^+$ at

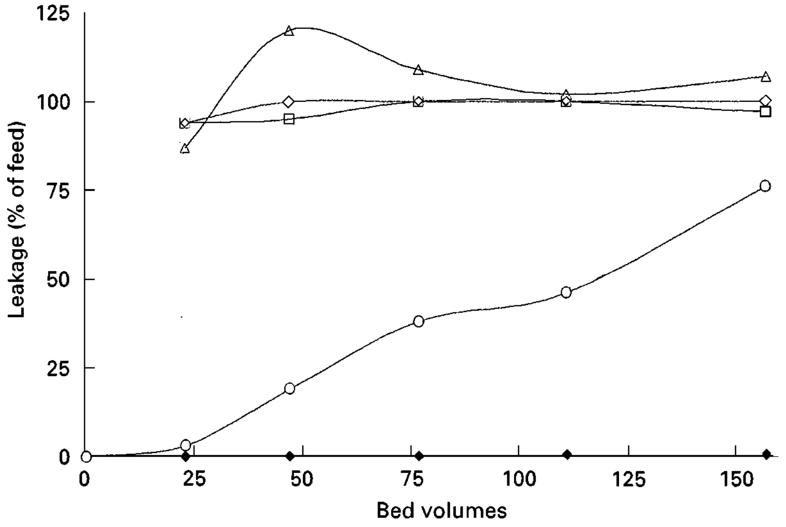


Figure 2 Separation of metal cations on an iminodiacetate resin at pH 1.5. Triangles, Pb(II); open diamonds, Cd(II); squares, Zn(II); circles, Fe(III); filled diamonds, Hg(II). (Reproduced with permission from Becker NSC and Eldridge RJ (1993) *Reactive Polymers* 21: 5.)

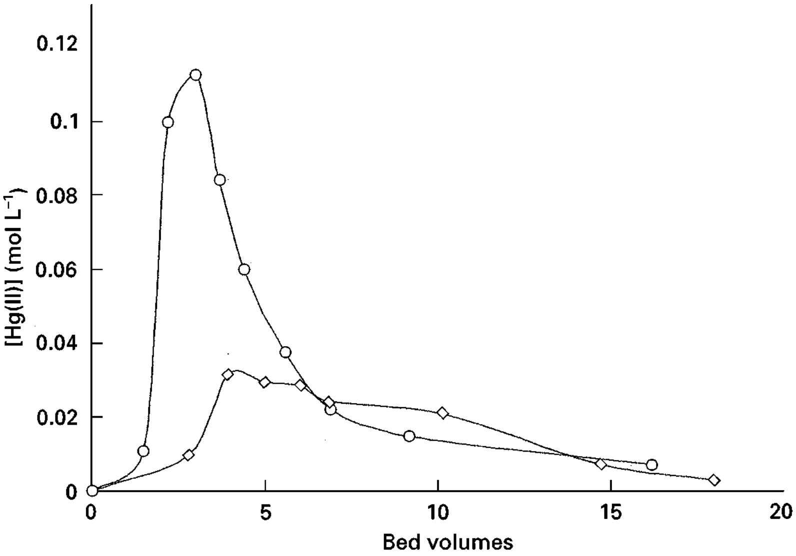
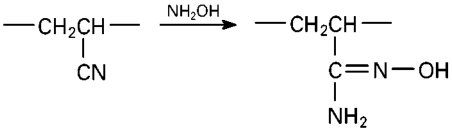


Figure 3 Regeneration of a chelating resin may require a complexing eluant: desorption of Hg(II) from an iminodiacetate resin with 3 mol L^{-1} sodium chloride (circles) or 2 mol L^{-1} nitric acid (squares). (Reproduced with permission from Becker NSC and Eldridge RJ (1993) *Reactive Polymers* 21: 5.)

0.6 mol L^{-1}, Mg^{2+} at 0.4 mol L^{-1} and transition metal ions such as Fe^{3+}, Cu^{2+} and Zn^{2+}, at 10–100 nmol L^{-1}. Iminodiacetate resins fail to adsorb significant amounts of uranium from seawater, since their UO_2^{2+}/Mg^{2+} selectivity coefficient is only ~ 600. During the 1980s, amidoxime resins derived from polyacrylonitrile (**Figure 4**) were extensively investigated by several research groups, particularly in Europe and Japan, and shown to adsorb up to about 1 mg U g^{-1} resin from spiked seawater. Distribution coefficients decrease in the order:

$$\mathrm{Fe(III)} \approx \mathrm{U(VI)} > \mathrm{Cu(II)} > \mathrm{Ni(II)} > \mathrm{Co(II)} > \mathrm{Zn(II)} \gg \mathrm{Ca(II)} > \mathrm{Mg(II)}$$

from ~ 300 L g^{-1} for Fe(III) and U(VI) to ~ 20 mL g^{-1} for Mg(II). UO_2^{2+} cations are believed to be complexed by two deprotonated amidoxime groups, which displace the carbonate ligands. Adsorption rates are higher for resins incorporating hydrophilic cross-linkers or comonomers. Hydrochloric acid at 0.5–1 mol L^{-1} is an effective regenerant, but causes some hydrolysis of the amidoxime groups.



$$-CH_2CH(CN)- \xrightarrow{NH_2OH} -CH_2CH(C(=N-OH)NH_2)-$$

Figure 4 Synthesis of an amidoxime resin from polyacrylonitrile.

In one experiment with unspiked seawater, an experimental amidoxime resin adsorbed 1 mg g^{-1} uranium ($D \approx 300$ L g^{-1}). Fe^{3+}, Cu^{2+} and Zn^{2+} were concentrated by similar factors. Isolation of pure uranium would therefore need selective regeneration or post-treatment of the regeneration effluent.

Amidoxime resins are also highly selective for Ga(III) at high pH and have been used to recover gallium from Bayer liquor. Again, capacity loss is a problem.

Oligoamine Resins

Many of the transition metal cations are strongly coordinated by uncharged nitrogen-containing ligands. Consequently, chelating resins possessing strongly electron-donating nitrogens will selectively remove Cu^{2+}, for example, from solutions containing alkali and alkaline earth cations. Since the resin is uncharged, the adsorbed cations must be accompanied by mobile counterions to maintain electroneutrality. SenGupta has exploited this effect to adsorb anions such as phosphate, selenite, oxalate and phthalate on copper-loaded picolylamine resins (Dow 2N or 3N). These coordinating anions displace anions, such as sulfate, that are associated with adsorbed Cu(II) only by electrostatic attraction. Loss of copper from the resin during ligand exchange is extremely small.

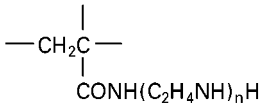
Even conventional weak base resins – usually used as anion exchangers – are capable of separating transition metals from alkaline earths. Uptakes of

Cu(II) have been demonstrated at pH 5 on the phenolic weak base resin Duolite A7 and the acrylic weak base Amberlite IRA35 comparable to their anion exchange capacities (1–2 meq g^{-1}). Uptake of Ni(II) or Zn(II) was smaller. Regeneration with mineral acid was efficient. An aminophenol resin of similar structure to Duolite A7 was found to adsorb Cu(II), presumably accompanied by sulfate ions, from $CuSO_4$ solutions at pH 4–7. Other transition metal ions (Fe^{2+}, Co^{2+}, Ni^{2+}, Zn^{2+}, Cd^{2+} and Hg^{2+}) were scarcely adsorbed in this pH range, but in the protonated form (pH $\approx$ 2) the resin became highly selective for Fe^{3+}.

The transition metal affinity of resins having aliphatic oligoamine substituents increases with chain length (number of amino groups in each chelating group). It has been reported that acrylic oligoamine resins (**Figure 5**) can adsorb significant amounts of Cu^{2+}, Ni^{2+}, Zn^{2+} or Cd^{2+} from solutions containing ethylenediaminetetraacetic acid (EDTA), provided alkaline earth cations are also present. Transition metal uptakes were highest on resins derived from tetraethylenepentamine or pentaethylenehexamine.

Diphonix

A similar coordination mechanism operates in the adsorption of some metal ions from highly acidic solution on phosphonic acid resins, for example actinide ions on Diphonix®, one of very few new chelating resins to be introduced commercially in the 1990s. The chelating groups in this resin are contributed by vinylidene-1,1-diphosphonic acid monomer units, but the resin also contains acrylic acid and styrenesulfonic acid units (**Figure 6**). As with the amidoxime resins described above, hydrophilic monomers are essential for high reaction rates. Diphonix is the outcome of work at the Argonne National Laboratory on 1,1-diphosphonic acid ligands and at the University of Tennessee on ion exchangers possessing two or more types of functional group, operating by different mechanisms. It was developed primarily for actinide separations in highly acidic media, but also strongly adsorbs divalent transition metal cations at pH 1–2 and trivalent cations at pH 0–2.



$$-CH_2\underset{\displaystyle CONH(C_2H_4NH)_nH}{\overset{|}{\underset{|}{C}}}-$$

Figure 5 Acrylic oligoamine resin.

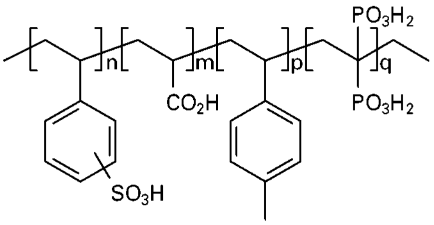


Figure 6 Structure of Diphonix®.

In pH 1 nitric acid distribution coefficients on Diphonix decrease in the order:

$$\mathrm{Cu(II)} > \mathrm{Zn(II)} > \mathrm{Co(II)} \approx \mathrm{Ag(I)}$$

from $\sim 3\ \mathrm{L\,g^{-1}}$ to $\sim 500\ \mathrm{mL\,g^{-1}}$. For these ions a double-logarithmic plot of the distribution coefficient against $[H^+]$ has slope $-n$, where n is the cation charge. This indicates that adsorption occurs by simple exchange of M^{n+} for H^+. In 1 mol L^{-1} nitric acid, the order of selectivity is:

$$\mathrm{Th(IV)} > \mathrm{Fe(III)} \approx \mathrm{U(VI)} > \mathrm{Np(VI)} \approx \mathrm{Pu(IV)} > \mathrm{Bi(III)}$$

$$\approx \mathrm{Eu(III)} > \mathrm{Am(III)} \gg \mathrm{Al(III)} > \mathrm{Cr(III)}$$

with D as high as 900 L g^{-1} for Th(IV) and 200 L g^{-1} for Fe(III) and U(VI), decreasing to 400 mL g^{-1} for Al(III) and 80 mL g^{-1} for Cr(III). Uptake of the strongly preferred ions shows little pH dependence, indicating adsorption without displacement of H^+ on phosphonic acid groups that are not significantly ionized under these conditions. To maintain electroneutrality, the complexed metal ions must be associated with anions from solution, either free or in mixed-ligand complexes containing phosphonic acid groups and small ion ligands such as Cl^-. The less preferred ions show simple ion exchange behaviour over a limited pH range, but uptake increases at high acid concentrations, indicating a change in mechanism.

The very high affinity of Diphonix for Fe(III) makes it very suitable for removing iron from acidic copper electrolytes in copper production by electrowinning. The process has been demonstrated in pilot-scale trials at copper refineries, with no decrease in resin performance over hundreds of cycles. Fe(III) is desorbed by reducing it to Fe(II).

Circumventing Limitations to Selectivity

The selectivity between two cations of a chelating resin should in principle be equal to that of the chelating ligand itself, but this is seldom true in practice. For example, iminodiacetate resins are very much less

Table 5 Comparison of an iminodiacetate resin with the iminodiacetate ion[a]

Ion	*Ca^{2+}*	*Fe^{2+}*	*Co^{2+}*	*Cd^{2+}*	*Zn^{2+}*	*Ni^{2+}*	*Pb^{2+}*	*Cu^{2+}*	*Hg^{2+}*
K''	1.00	4.0	6.7	15	17	57	1200	2300	2800
K_m	1.00	1600	2.3×10^4	600	2.8×10^4	4.7×10^5	7×10^4	9×10^7	1.5×10^9

[a] Selectivities for divalent cations (relative to Ca^{2+}) of an iminodiacetate chelating resin (K'') and the iminodiacetate ion (K_m).

selective than the free iminodiacetate ion, as shown in **Table 5**, which compares equilibrium constants for the reaction:

$$\mathrm{HN(CH_2COO^-)_2Ca^{2+} + M^{2+}}$$
$$\Leftrightarrow \mathrm{HN(CH_2COO^-)_2M^{2+} + Ca^{2+}} \qquad [9]$$

with the corresponding values from **Table 3** for iminodiacetate resins. There are several reasons for the discrepancy. In the first place the resin is heterogeneous on a molecular scale. Its chelating groups are located in environments that may vary in polarity, dielectric constant or steric crowding, depending for example on their closeness to cross-links. This variation in chemical environment affects the binding constant for different metal ions to differing extents, degrading the selectivity of the resin. Secondly, the high local concentration of ligands in the resin may lead to a mixture of 1 : 1, 2 : 1 and higher complexes. At loadings less than 100%, the number of ligands coordinated to each metal ion is almost impossible either to control or to measure. Thirdly, the exchange reaction itself changes the properties of the resin. Selectivities of simple ion exchangers are well known to vary with the extent of loading, and the same will be true of chelating resins, especially when adsorbed metal ions are coordinated by ligands attached to different polymer chains, reversibly creating additional cross-links. The result of these factors is not merely reduced selectivity of polymeric resins relative to low molecular weight ligands, but in some cases the order of selectivity is reversed (**Table 5**).

The mixed composition and additional cross-link effects can be eliminated by designing the resin to accommodate the maximum coordination number of the cation with a single multidentate ligand. Resins containing EDTA moieties are an example. These were synthesized by Takeda *et al.* at Asahi Chemical in 1985, with *m*-divinylbenzene as the essential building block. Addition of bromine across one double bond before polymerization allowed the introduction of an iminodiacetate group on each carbon of the pendant C_2 chains. However, even in these resins, ligands still experience a range of chemical environments.

Oligoamine weak base resins suffer an additional source of heterogeneity since the amine (diethylenetriamine (DETA), for example) can attach to the precursor resin (chloromethylated polystyrene-co-divinylbenzene) through either primary or secondary nitrogens, and can react with multiple chloromethyl groups, introducing additional covalent cross-links. This effect was eliminated in experimental resins: the primary nitrogens of DETA were blocked by forming Schiff base adducts, followed by amination exclusively through the secondary nitrogen and subsequent hydrolysis of the Schiff base groups to recover the primary amino groups (**Figure 7**). The latter were then converted by further reaction to iminodiacetate, aminophosphonate or other chelating groups. The selectivity sequence of the *bis*(iminodiacetate) derivative is:

Fe(III) > In(III) > Ga(III) ≈ Cu(II) > Zn(II) > Al(III)

with distribution coefficients decreasing from $\sim 10\ \mathrm{L\,g^{-1}}$ at pH 1 for Fe(III) to $\sim 10\ \mathrm{mL\,g^{-1}}$ for Al(III) at pH 2. The resin readily separates Ga(III) and In(III) from Zn(II) and Al(III) in acid solution, but Fe(III) and Cu(II) must first be removed (by precipitation as sulfides, for example). For most trivalent rare earth cations, $D \approx 100\text{–}500\ \mathrm{mL\,g^{-1}}$ at pH 2, with the highest values being observed for the medium atomic

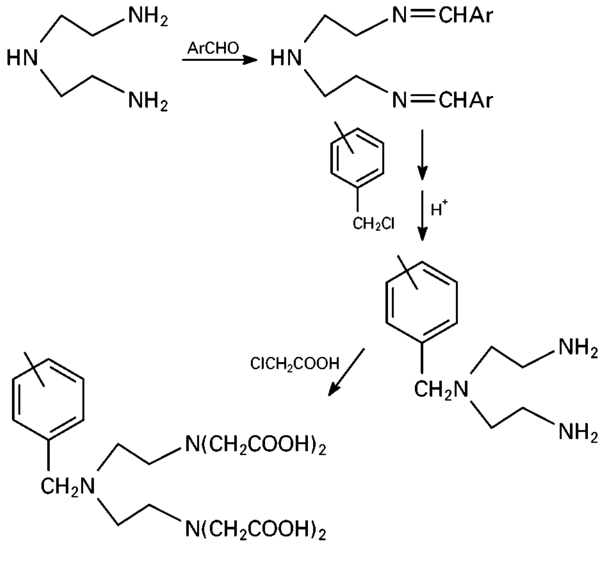


Figure 7 Synthesis of diethylenetriamine resin coupled exclusively through the secondary nitrogen, and conversion to a *bis*(iminodiacetic acid) derivative.

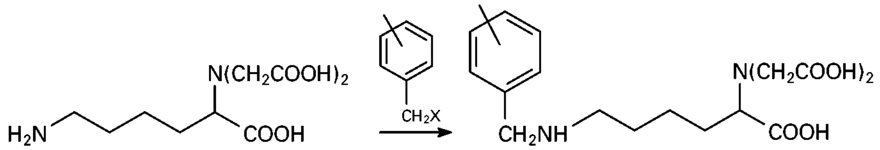


Figure 8 Lysine-N^α,N^α-diacetic acid resin.

weight lanthanides (Sm-Dy). The selectivity is great enough to permit chromatographic separation of pairs of lanthanides (La/Pr or Nd/Sm).

The effect of inhomogeneity can be minimized by introducing spacer groups between the chelating groups and the polymer backbone. A highly selective nitrilotriacetate-like resin was synthesized by functionalizing a polystyrene matrix with lysine-N^α,N^α-diacetic acid (**Figure** 8). This resin shows high selectivity for trivalent ions such as Ga(III) and In(III) over divalent cations. When loaded with Fe(III) it can be used to adsorb As(III) and As(V) oxyanions by ligand exchange.

Sulfur Ligands

In the quest for high affinity and high selectivity, many sulfur-containing ligands have been investigated, including thiol, thioether and thiocarbonyl groups, as well as sulfur–nitrogen heterocycles. Thiol resins are available from several manufacturers. Although falling outside the above definition of chelating resins, they can be regarded as the prototype of resins containing thiocarbonyl, thioether or dithiocarboxylate groups, or multiple ligands such as thiol/amino combinations. Thiol resins have been used for adsorption of mercury(II) and are effective in the presence of competing ligands such as Cl^-. However, regeneration is difficult, requiring concentrated acid, and the thiol group is prone to oxidation.

Sulfur-containing ligands tend to have high affinity for platinum group metals (PGM). Isothiuronium resins (**Figure** 9), first prepared in the 1960s by Koster and Schmuckler and subsequently commercialized in both gel (Srafion) and macroporous (Monivex) versions, adsorb PGM from strongly acidic solution and require complexing agents for regeneration. Adsorption is believed to be by simple ion exchange when the functional groups are fully protonated, but this not achievable in the gel resin, and adsorption then involves both electrostatic and complexing interactions.

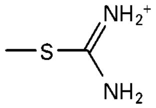


Figure 9 Isothiuronium group.

Isothiuronium resins have been used in laboratory- and pilot-scale PGM separations from HCl leach solutions, with thiourea or thiocyanate as regenerant. However, new sulfur–nitrogen resins are still being reported for heavy metal and PGM applications. Polybenzimidazole functionalized with dithiooxamide was found to be strongly selective for Pd(II) and Pt(IV) over first-row transition metals in acidic solution. Other researchers report similar behaviour with resins containing, for example, thiosemicarbazide, dithizone, thiadiazole or thiotetrazolium substituents.

Kinetics

Adsorption and desorption rates are an important consideration in ion exchange, as well as equilibrium behaviour. Complexation rates benefit from small particle size, high porosity and, as noted above, high hydrophilicity. Capturing the rate advantage of small size requires a solution to the problem of handling fine particles. Incorporating a magnetic component is one strategy that has been demonstrated. Resins can also be made in nonconventional formats, such as graft copolymers or fine fibres, to keep diffusion paths short. A range of fibrous sorbents was developed under the name Fiban, derived from polyacrylonitrile fibres or polypropylene fibres grafted with styrene, including a chelating material containing imidazoline groups derived from polyacrylonitrile. These sorbents could be used to form filaments or nonwoven fabrics. Similarly, others have reported amidoxime sorbents made from polyacrylonitrile fibre and woven into cloth for use in uranium recovery, and polyacrylonitrile-g-glycidyl methacrylate fibres (Tiopan) functionalized with ligands including thiosemicarbazide, 8-mercaptoquinoline and 2-aminothiazole.

Conclusion

Ingenious syntheses of chelating resins continue to be reported. However, large scale applications for such materials are limited, and few are likely to be produced industrially. The main markets appear to be in the production of low volume, high value elements: precious metals, rare earths with valuable optical properties and raw materials for electronic devices. Applications in lower value fields such as waste management or by-product recovery should benefit from novel resin formats designed for improved resin/liquid contacting.

See also: **II/Ion Exchange:** Historical Development; Novel Layered Materials: Non-Phosphates; Novel Layered Materials: Phosphates; Organic Ion Exchanger; Organic Membranes; Theory of Ion Exchange.

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CHEMICAL WARFARE AGENTS: CHROMATOGRAPHY

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Introduction

The development and application of analytical methods for the analysis of chemical warfare agents have received increased attention, due in large part to the recently ratified Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and their Destruction (commonly referred to as the Chemical Weapons Convention or CWC). After considerable effort the CWC was opened to signature in 1993, with the treaty coming into force on 29 April 1997. The treaty has been ratified by 120 states, all of which agree not to develop, produce, stockpile, transfer or use chemical weapons and agree to destroy their own chemical weapons and production facilities. A strong compliance-monitoring regime involving site inspections was built into the CWC to ensure that the treaty remains verifiable. The Organisation for the Prohibition of Chemical Weapons, or OPCW, based in The Hague, has responsibility for implementation of the treaty. Routine OPCW inspections have or will take place at declared sites, including small scale production, storage and destruction sites, and challenge inspections will take place at sites suspected of noncompliance.

An analytical capability will be required to help verify compliance with the treaty, since inspectors will have the option to take and analyse suspect samples to help establish compliance or noncompliance. Gas chromatography is the current method of choice for the separation and analysis of chemical warfare agents, with this technique being employed in the field-portable gas chromatographic–mass spectrometric (GC-MS) instrumentation in use by the OPCW inspectorate.