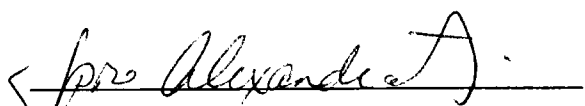


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Spiro D. Alexandratos, Major Professor

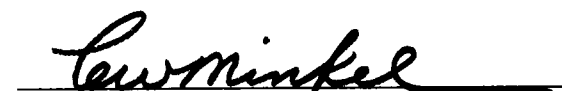
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**SYNTHESIS, CHARACTERIZATION, AND MECHANISTIC STUDIES
OF NOVEL DUAL MECHANISM BIFUNCTIONAL POLYMERS
FOR IONIC AND MOLECULAR RECOGNITION**

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Paul Timothy Kaiser

August 1990

Dedicated to my children - Nathan, Gretchen, and Benjamin - and most of all to my wife, Kathleen - all of whose patience and sacrifice has made this possible.

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ABSTRACT

Ion-exchange/redox resins of the phosphinic acid and phosphonic acid types have been synthesized using various Friedel-Crafts catalysts. The results of these syntheses show that AlCl_3 under forcing conditions forms bifunctional resins containing primary and secondary phosphinic acid groups, while FeCl_3 yields bifunctional resins containing primary phosphonic acid and secondary phosphinic acid groups. ZnCl_2 and SnCl_4 give only very low levels of functionalization. The order of catalyst activity was shown to be $\text{AlCl}_3 > \text{FeCl}_3 > \text{ZnCl}_2 > \text{SnCl}_4 \sim \text{no catalyst}$.

Subsequent work with the phosphinic acid resins has shown that the kinetics of the ion-exchange/redox reaction with mercury is most likely diffusion-limited, while silver displays reaction-limited ion-exchange/redox kinetics, and that removal of both metals from the resin by HNO_3 is diffusion-limited. Reduction back to a phosphinic acid resin subsequent to mercury or silver oxidation has been shown to be quantitative with a mixture of LAH/CeCl_3 in dioxane. After esterification of the metal oxidized phosphinic acid resin with ethanol and dicyclohexylcarbodiimide, a trichlorosilane/ N,N -dimethylaniline mixture was also shown to be effective for the reduction.

Molecular recognition was investigated using a linear free energy relationship. These investigations were carried out using carboxylic acid, sulfonic acid, phosphinic acid, phosphonic acid, phosphonate mono and diethyl ester, dimethylamine, trimethylamine, PEG, PEI, and PEG/phosphonic acid resins with a series of anilines, phenols, and benzoic acids in water, methanol, water/methanol mixtures, and

dioxane. It has been determined that selectivity of ion-exchange resins for organic compounds with ionizable groups from methanol is a direct consequence of the strength of the interaction between the target compound and the resin functional groups, and reaches a maximum when the acid and base strength of the two groups are fairly well matched, with selectivity decreasing rapidly with an increase in the difference in interaction strength. If the interactions are very strong or very weak, selectivity is not observed under non-competitive conditions. Under competitive conditions, selectivity is observed even for compounds which interact strongly with the resin. In water a hydrophobic effect was also observed, which decreased the selectivity of the resin, but caused a large increase in the overall amount of the target compounds absorbed. A solvent effect was also observed by carrying out the absorptions in dioxane, which caused a marked decrease in the amount of the compounds absorbed due to limited accessibility of the functional groups on the resins.

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INTRODUCTION

The phenomenon of ion-exchange has been known of for many years, the first written record being that of Aristotle, who indicated that sea water was partially desalinated by passing it through sand filters.¹ The first scientific study of ion-exchange was undertaken in the mid 1840's by Thompson and Spence. Spence, a New York analyst engaged by the English landowner H. S. Thompson to investigate the loss of ammonia from manure heaps, discovered that when a solution of ammonium sulfate was percolated through a column of soil all of the ammonium ion was removed, and was replaced by calcium.² This was a surprise because at that time, the dissociation of salts in water was not known. J. T. Way, an agricultural chemist, further studied the phenomenon,^{3,4} which came to be called "base exchange", and confirmed Spence's work, which had been presented to the Royal Agricultural Society in 1850. Zeolites were later determined to be responsible for the ion-exchange properties of soils.⁵

Since that time many other natural compounds which undergo ion-exchange processes have been found. Some of these compounds are: silicates, humic acids, wool, cellulose, hair, and certain seaweed components (e.g., agar and carrageen),⁶ as well as numerous other substances. Cell membranes act as ion-exchange materials, even in the absence of active transport. There are also a great many synthetic ion-exchangers.

The first practical use of ion-exchange compounds was by Gans, who used both natural and synthetic zeolites in the treatment of water and of sugar solutions.

The zeolites, however, are plagued by the problems of low capacity (typical values being 3 to 150 mequiv exchange sites/100g)⁷ and acid sensitivity.⁸ Sulfonation of coal in the mid 1930's made possible the first use of ion-exchangers in acidic media. The sulfonated coal had low capacities, though, which limited its practicality. In 1935 Adams and Holmes produced the first synthetic ion-exchange resin, a sulfonated phenol-formaldehyde condensation polymer.⁹ In 1944 G. F. D'Alelio, at General Electric's Pittsfield Laboratories synthesized the first polystyrene-based ion-exchange resin.¹⁰ These were sulfonic acid resins produced by emulsion copolymerization of sulfonated styrene and divinylbenzene. Polystyrene has now become the most commonly employed polymer support.

The early uses of ion-exchange resins were almost exclusively for water softening and purification. It soon became apparent that ion-exchange resins could also be of great advantage in other processes. Thus, they are also employed in such diverse applications as reduction of the amount of molasses produced during sugar refining, decolorization of Spanish green table olive fermentation brines,¹¹ removal of heavy or radioactive metals from power plant and plating bath waste streams, isolation and purification of pharmaceutical compounds, removal of calcium from blood (before storage, for improved shelf life), redox reactions (typical redox resins contain groups such as quinones, sulfides, and other organic groups capable of undergoing redox reactions), etc. The application of ion-exchange resins is so extensive in the chemical, process, food, pharmaceutical, and many other industries, that a book could be filled just with a bibliography of their uses. In fact, in a 1956 book¹² there are 2000 bibliographic references just on ion-exchange applications,

with another 400 on the theoretical aspects of ion-exchange, these only covering a period of about ten years.

Aside from their use in ion-exchange, ion-exchange resins are also used for catalyzing organic reactions. Thus, the general term polymer-supported reagents is often used instead of ion-exchangers, although it may be the same resin put to a different use. There are, as with the field of ion-exchange, a plethora of practical applications for polymer-supported reagents. The polymer-supported reagents are crosslinked (and therefore insoluble) compounds, and when used for syntheses, form heterogeneous solutions which can be easily filtered to remove the reagent, making isolation of the product compound much easier. If a linear polymer is used, it can be selected so as to be soluble in the reaction medium, while the reacted polymer may be insoluble, facilitating separation. Polymer-supported reagents also can provide environments or situations which would be impossible to obtain in a homogeneous solution. These can be high ion concentrations (which could not exist in organic solvents of low polarity), steric effects (such as asymmetric induction by neighboring functional groups or the formation of optically pure products due to geometry restrictions within the resin), hydrophobic effects, size-exclusion effects (allowing a small molecule to enter the resin and react, whereas one with the same functional group, but a much larger size would not be able to enter the resin, and therefore would remain unreacted), separation of a compound from a mixture based on size (previously mentioned), polarity (hydrophobic or hydrophilic), functional group interaction with the polymer-supported reagent, kinetics of absorption by a resin, or a combination of some or all of these. These same resins are not without

drawbacks though. They are not routinely used for high performance chromatography because of their resilience, which allows the beads in a column to be forced to one end under high pressure, thereby clogging the column. They also tend to abrade under conditions which cause movement of the particles against each other. The kinetics of any process using resins is usually significantly slower than in solution, and the use temperature of most ion-exchange resins is usually somewhat low, thus restricting their use typically to a maximum temperature of about 120°C-150°C. Even with these drawbacks, polymer-supported reagents have become irreplaceable in many fields.

Because of the importance of the polymer-supported reagents, much study has gone into their synthesis and mode of operation (be it ion-exchange, catalysis, different forms of chromatography, or redox). The kinetics of ion-exchange have been determined, in most cases, to be controlled by diffusion, which itself is influenced by the size of the diffusing ion. Because of the rather tortuous path that ions must follow inside the resin, the polymer support itself, even without considering the different nature of various functional groups, can have a large effect on the kinetics of diffusion, as well as on accessibility of the functional groups for reaction. Much work has also been done on the absorption of organic species from solution, both for the reason of using the resins to catalyze reactions (the compound must be able to gain access to the functional groups in the resin), and also for the purpose of molecular separations. The field of biochemistry has probably seen the greatest amount of study on the absorption of organic molecules for the purpose of protein and amino acid separations. These, however, are organic ions which are

absorbed. The protein or amino acid solution is pH adjusted with buffers to give the desired charge on the molecules, which will then be ionically absorbed by either a cation or anion-exchanger, followed by elution of the resin with another buffer solution to desorb the compound. While this has proved to be of great value, relatively little is known about the specific modes of absorption of completely neutral molecules from solution by ion-exchange resins, and how their selectivity can be enhanced, or possibly even predicted. Hydrophobic interactions which occur between polymer-supported reagents and organic compounds are well known, but it is within the context of unfunctionalized polymers, or those with hydrophobic functional groups that this knowledge has been applied. Basically, it is just an application of the general chemistry rule of thumb of "like dissolves like."

It is a generally accepted fact that the weak acid ion-exchange resins, such as the carboxylic acid resins, are highly selective towards metal ions, but because of their high pK_a values, are only of use in basic solution (above $pH=7$),¹³ the resin being almost fully protonated at low pH. The sulfonic acid resins, on the other hand, perform very well in absorbing metal ions from even very low pH solutions due to their low pK_a 's. Therein lies the problem with these resins: they absorb almost any metal ion from solution with only marginal selectivity, although they do show some preference for smaller ions of higher charge.¹³ The phosphorus-based resins are of intermediate acidity, and therefore can be used at fairly low pH, but their pK_a 's are still high enough that selectivity is not sacrificed. There are many industrially used phosphorus-based liquid extractants, and there is much that is known of the compounds and their use, as they are commonly used in the nuclear fuels industry.

Relatively little work has been done to determine the basic causes of selectivity of polymers for certain types of neutral organic compounds. Likewise, while the kinetics of ion-exchange of metals, and to some extent the absorption of organic molecules from solution have been studied in depth, they have all focused on diffusion-limited kinetics, with little work being done on kinetics with chemical reaction as the slow step. Because of this, the work contained in this dissertation was undertaken. To answer some of the questions concerning the kinetics of ion-exchange processes which are limited by chemical reaction rate, and not by diffusion, the work in Chapter II was undertaken. The aim of Chapter III was the regeneration of the metal-oxidized phosphinic acid resins in order to show that utilization of the redox characteristics of these resins leads to a commercially viable method of water purification. Chapter IV deals with the interaction of neutral organic molecules with functionalized polymer-supported reagents, and the causes for selectivity of polymer-supported reagents for certain classes of compounds. Before any of this work could be done, it was necessary to have various resins with which to work. The phosphorus-based resins, in particular, were synthesized, which is the focus of Chapter I. Therefore, the design of polymer-supported reagents with properties and functional groups specifically tailored to the specific project were synthesized. Many other types of resins were also synthesized, which are described in Chapters III and IV.

CHAPTER I

Synthesis of the Phosphorus-Based Ion-Exchange Resins

Introduction

The performance of ion-exchange resins is highly dependent on their properties. The bead size, crosslink level, porosity, level of functionalization, and character of the functional groups (hydrophilic, hydrophobic, acidic, basic, neutral, chiral, etc.) all play a role in the performance characteristics of the resin. If an ion-exchange resin is only partially functionalized, it tends to be fairly hydrophobic. It would then not be expected, when contacted with an aqueous metal solution, to pick up much of the metal, even if a highly functionalized resin of the same type removes much or all of that metal under the same conditions. The partially functionalized resin may perform very well, however, when used in a non-polar solvent to catalyze a reaction or to selectively extract an organic compound. The hydrophilicity (or hydrophobicity) of a resin can be an advantage or a disadvantage, depending on whether its projected use is in aqueous or non-aqueous media, and whether the species being absorbed is metallic (ion-exchange; Chapters I and II) or molecular (Chapter IV). If the target (that is, the compound being absorbed) is molecular (organic), the hydrophilicity (or hydrophobicity) of the resin may aid or hinder the extraction, depending upon the specific interaction between the resin and the compound. The performance of a resin can be altered without changing the

resin simply by the use of a different solvent, which will change the specific interaction between the polymer and/or its functional groups and the target, as well as the strength of the interaction.

The crosslink level can alter the hydrophilicity of a resin. A higher crosslink level will decrease its hydrophilicity, both by decreasing the maximum theoretical capacity (fewer functionalizable groups on the polymer backbone), and by lowering the overall polarity of the resin (the resin has a more of a non-polar organic character). Closely tied in with the crosslink level is the porosity. Decreasing the porosity will generally have the same effect as increasing the crosslink level. Both limit the accessibility of the functional groups. If a resin has functional groups which exert only weak swelling forces on the polymer beads, then a low porosity resin will have only a portion of the total number of functional groups accessible to reagents in solution. Increasing the porosity of a resin (either by decreasing the crosslink level or by the use of macroreticular (MR) rather than gel type beads) should increase its useful capacity because of full accessibility of the functional groups. It most likely will also increase the rate of the reaction because of a much higher diffusion rate of reagents into and out of the bead, where the majority of the functional groups are. Using a smaller particle size (smaller beads) can also have this effect because of the increase in the ratio of surface area to interior volume of the beads, with the resulting higher percentage of accessible functional groups.

The acidity or basicity of the functional groups will determine the pH range over which an ion-exchange resin is useful, and is one of the important factors in determining the selectivity of a resin toward one chemical compound (or species)

over another. Thus, a strongly acidic resin would not be expected to be selective toward a strongly basic compound in a mixture containing several other strongly basic compounds, but it may be in a mixture containing both strongly and weakly basic entities. In order to make an ion-exchange resin with good performance characteristics, a catalyst study was done to determine the optimum synthetic conditions for high capacity phosphorus-based resins.

Synthesis of Bifunctional Phosphorus Resins

Polystyrene in the form of beads, crosslinked with 2% to 15% divinylbenzene, of both the gel and macroporous types¹⁴ was the polymer support used for the phosphorus resins, with a size before functionalization of -20+40 mesh using American Standard Testing Sieves. The first number indicates the mesh screen which the beads will pass through, while the second number is the mesh screen which will trap the beads. See Table 1 for a list of bead sizes in both ASTM mesh and diameter in microns (μ). Functionalization of the polystyrene is accomplished

Table 1

Comparison of Bead Sizes
Mesh # vs Bead Diameter

Mesh #	16	20	30	40	60	80	100	200	325
Bead Diameter (μ)	1180	850	600	425	250	180	150	75	45

via a Friedel-Crafts type electrophilic aromatic substitution reaction (phosphorylation) with PCl_3 using AlCl_3 catalysis to produce a bifunctional phosphinic acid resin (primary and secondary phosphinic acid groups, Figure 1) or FeCl_3 to produce a bifunctional phosphonic acid resin (phosphonic acid and secondary phosphinic acid groups, Figure 2).

An investigation of the effect of the particular Friedel-Crafts catalyst, the amount used, the reaction time, and the reaction temperature was done using the two catalysts mentioned above, as well as SnCl_4 and ZnCl_2 . The ratio of the catalyst used was, 0.77, 1.2, or 2.0 (moles catalyst/mole polystyrene phenyl rings) or no catalyst (as a control), with reaction times and temperatures from 15 minutes to 72 hours at 15°C to 73°C (reflux). The reaction mixture containing the polymer functionalized with chlorophosphine groups was then hydrolyzed by pouring into icewater saturated with salt. It was then rinsed several times until the water was clear, and conditioned by eluting in the sequence: H_2O , 1M NaOH , H_2O , 1M HCl , H_2O : each being one liter of solution over a one hour time period. The resins were then analyzed for the amount of phosphorus incorporated into the resin (tot(P)) by phosphorus elemental analysis; the number of ionizable acid sites (tot(OH)) by stirring the resin in excess 0.1M NaOH to neutralize the acid groups, and titrating the solution for remaining hydroxide; the number of oxidizable P-H bonds (primary acid capacity) by iodine oxidation of the P-H bonds (Figure 3), followed by titration of the solution for remaining iodine; and the amount of water contained within the pores of a suction-dried sample of the resin (% solids) by the difference in weight before and after drying the resin at 110°C for 16 hours. These synthetic conditions

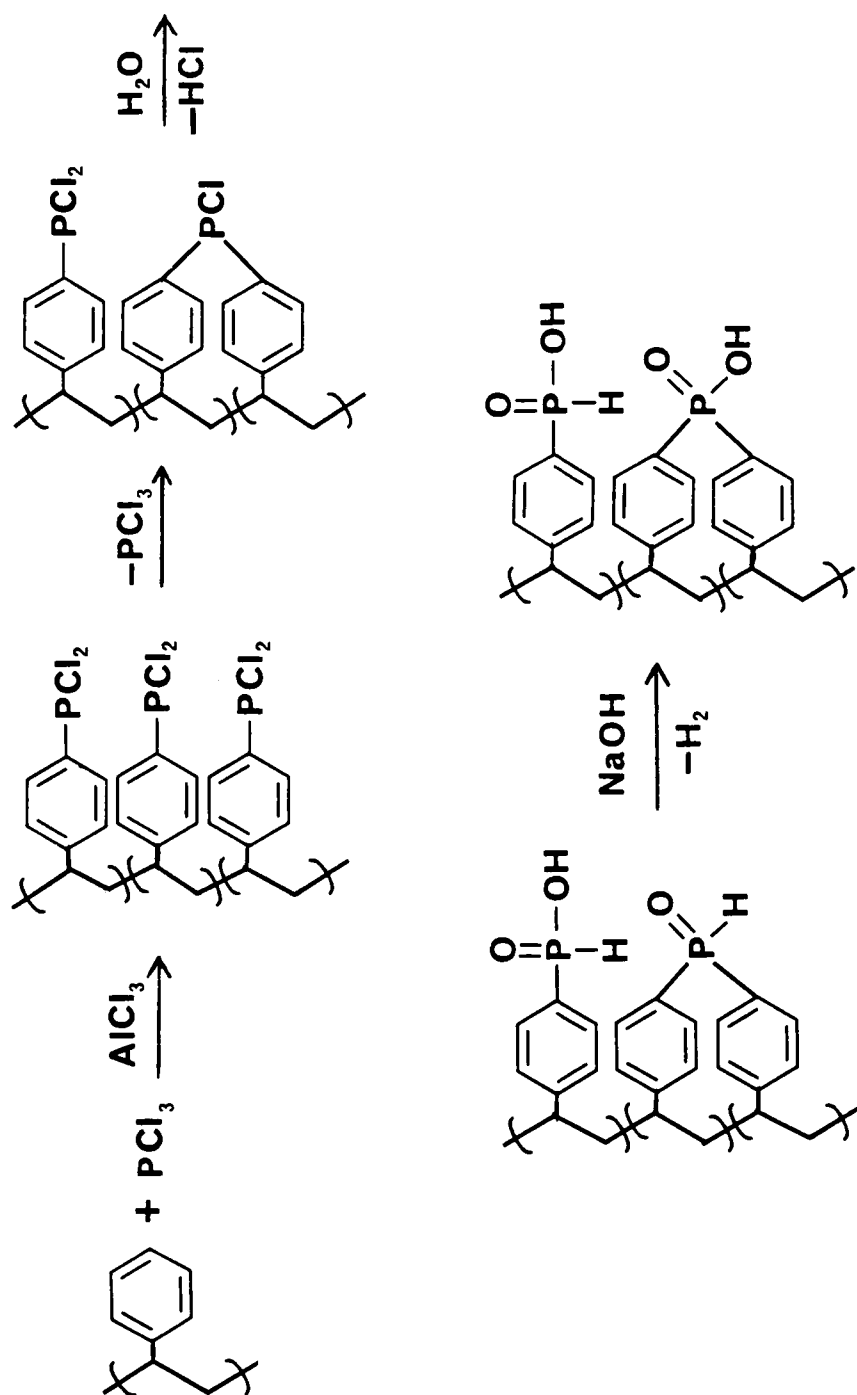


Figure 1. Synthesis of the Phosphinic Acid Resin

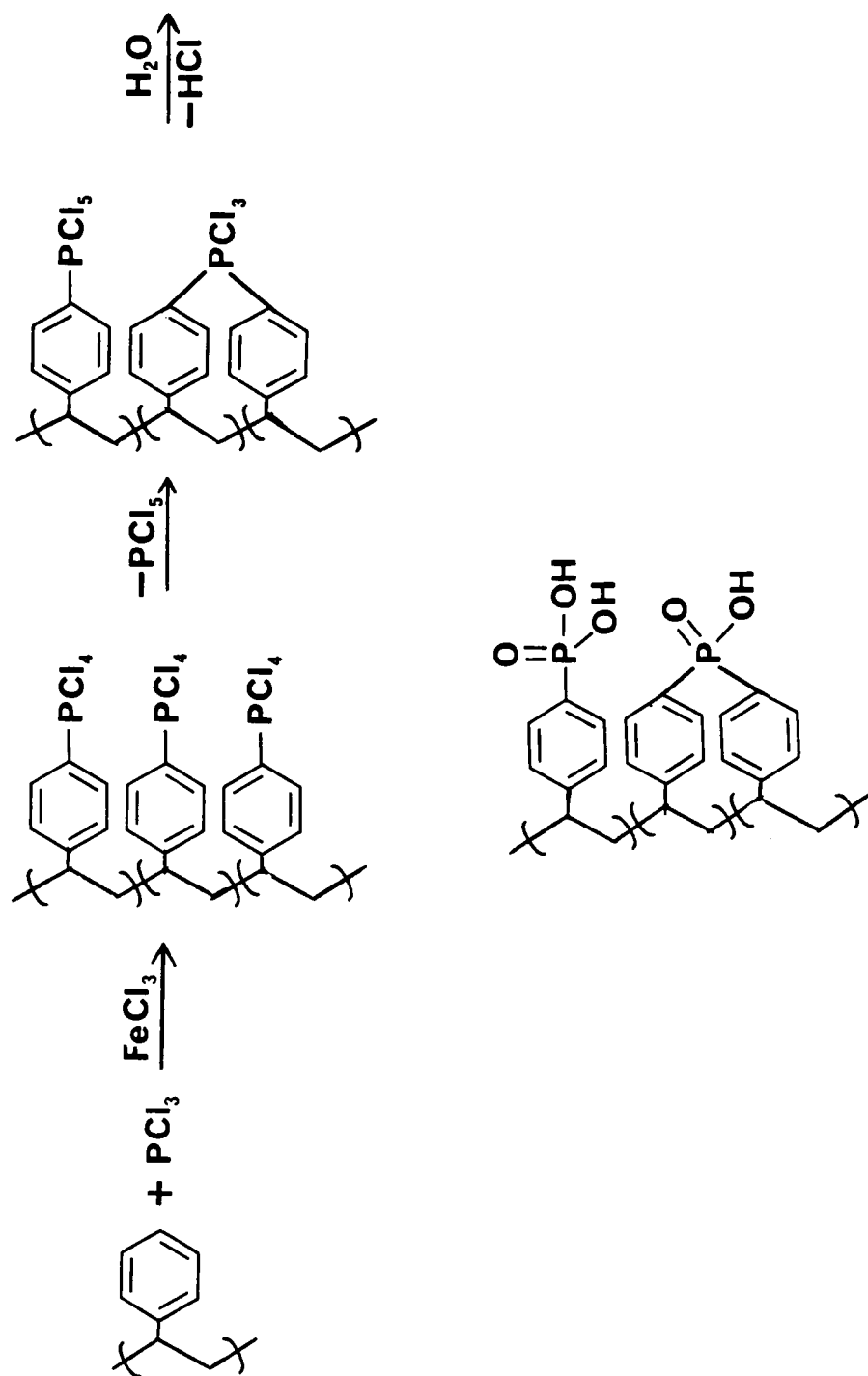


Figure 2. Synthesis of the Phosphonic Acid Resin

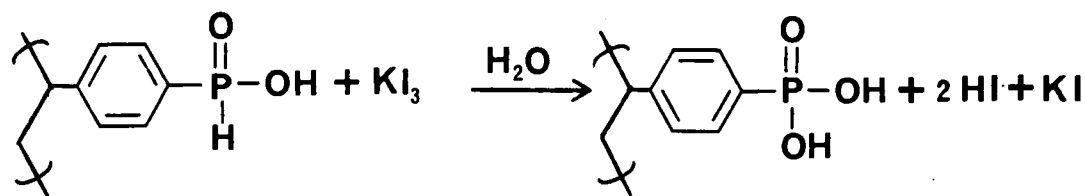


Figure 3. Iodine Oxidation of the Phosphinic Acid Group

were chosen because previous work done in this laboratory¹⁵ on the effect of both the temperature and catalyst level used in the phosphorylation reaction indicated that further investigation was needed in order to better define the resins produced. No functionalizations had been performed with catalysts other than AlCl_3 . Therefore, the other catalysts mentioned above were chosen because they cover a fairly wide range in catalytic activity for Friedel-Crafts type reactions.

Friedel-Crafts Catalysis by Aluminum Trichloride

One of the most active of the common Friedel-Crafts type catalysts is AlCl_3 .^{16,17} Phosphorylation of polystyrene in PCl_3 with a 0.77 mole ratio of AlCl_3 at 15°C , 30°C , and 73°C produces resins with various functional levels and different primary acid/secondary acid ratios. Under forcing conditions (high temperature, high catalyst

level, long reaction times) a highly functionalized resin is produced which contains both primary and secondary phosphinic acid groups. Under milder conditions (low temperature, low catalyst level, short times) the functional groups are mostly primary phosphinic acid, with only a small number of secondary acid sites and a much lower level of functionalization.

As can be seen in Table 2, with a 4 hour reaction time at a catalyst level of 0.77 moles AlCl_3 , there is a steady increase in the amount of functionalization of a 2% crosslinked gel bead¹⁴ as the functionalization temperature increases. Since the resin contains only phosphinic acid groups, the $\text{tot}(\text{OH})$ should be equal to the $\text{tot}(\text{P})$. However, the resin synthesized at 15°C has a much lower $\text{tot}(\text{OH})$ than $\text{tot}(\text{P})$ value. This is due to the hydrophobicity of the resin, which causes a large portion of the acid groups to be inaccessible for neutralization by the NaOH in the $\text{tot}(\text{OH})$ analysis. This is typical of ion-exchange resins which are only partially functionalized (below approximately 50% of the theoretical maximum functional level for the phosphinic acid resins).¹⁸

The maximum functional level for a phosphinic acid resin, calculated on the basis of 96.39% of the weight of the unfunctionalized 2% crosslink level gel type polystyrene having substitutable phenyl rings (from the styrene monomer), is 6.01 milliequivalents/gram (mequiv/g) based on dry weight of the resin. The other 3.61% of the weight of the polymer is due to the divinylbenzene (DVB) used as a crosslinking agent. This DVB is a mixture, of which only 55.4% is DVB, the remaining 44.6% being ethylvinylbenzene, thereby giving an overall 2% crosslink level.

Table 2

Characterization of 2% Crosslinked Gel Phosphinic Acid Resins
 Synthesized with 0.77 moles AlCl_3 at 15°C, 30°C, and 73°C

Resin Code	Temperature	Capacity (mequiv/g dry resin)			%Solids
		tot(OH)	tot(P)	primary acid	
PK-01-086A	15°C	1.28	2.08	1.54	48.00
PK-01-086B	30°C	3.06	3.58	1.75	50.34
PK-01-052A	73°C	4.62	4.70	2.30	52.20

Secondary Crosslinking of the Resin

It is apparent from Table 2 that seemingly none of the resins obtain the theoretical maximum level of functionalization. There are two possible reasons for this: inaccessibility of some of the phenyl rings of the polystyrene to the PCl_3 during functionalization, or some other reaction which consumes the phenyl rings without contributing to the amount of phosphorus incorporated into the polymer. The first of these can be discounted by noting that when placed in PCl_3 , the polystyrene beads swell to a volume about four to five times their dry volume in less than five minutes. This is the same amount by which gel beads with 0.6% and 2% crosslink levels are swelled by toluene, which is a good solvent for polystyrene, while 5% crosslink level gel type beads swell to about three to four times their dry volume. If there was incomplete swelling of the beads, a white core would also be visible. In their swollen state, gel type beads with crosslink levels as high as 25% are completely transparent. This statement is not meant to imply that higher crosslink level beads may not also be transparent in toluene or PCl_3 . It is, rather, the highest crosslink level copolymer which has been functionalized in this laboratory. The change in size and lack of a visible core indicates that the beads are completely swelled. The reason for the lower than possible functional level, then, is that secondary crosslinking occurs via the formation of secondary phosphinic acid groups. This can be seen by observing that the values for the primary acid sites are substantially lower than the tot(P) or the tot(OH) values (by 48.88% and 48.94% for the 30°C and 73°C resins, respectively, based on tot(P)).

A disproportionation reaction can occur with the resin to produce secondary crosslinks, as shown by Kosolapoff and Huber¹⁹ who refluxed benzene and PCl_3 in the presence of AlCl_3 to produce a mixture containing both dichlorophenylphosphine and monochlorodiphenylphosphine (Figure 4). When the dichlorophenylphosphine was isolated and heated with AlCl_3 , a disproportionation reaction occurred in which monochlorodiphenylphosphine and PCl_3 were produced. Substitution of dichlorostyrylphosphine onto a second polystyrene phenyl ring may also occur, as shown by the formation of triphenylmethylchloride in the AlCl_3 catalyzed addition of CCl_4 to benzene²⁰ (Figure 5). Analogous trisubstituted phosphorus groups (tristyrylphosphine) are most likely precluded by the steric constraints of placing three polymer chains on one phosphorus atom. A higher level of secondary crosslinking is observed under conditions which give 100% substitution of the polystyrene phenyl rings than under milder conditions, which have been shown to give only partial functionalization of the polymer. Disproportionation, then, is most likely the dominant mechanism for the formation of secondary crosslinks with the fully functionalized resins. Lower temperatures should favor secondary crosslinking via attack of dichlorostyrylphosphine on unsubstituted polystyrene rings because of their availability, while higher temperatures should favor secondary crosslinking via disproportionation, since unsubstituted phenyl rings most likely do not exist under the more forcing conditions.

Further supporting evidence of the formation of secondary crosslinks was obtained from the functionalization of linear polystyrene in PCl_3 with AlCl_3 . Linear polystyrene dissolves in PCl_3 . Yet when AlCl_3 was added, the functionalized polymer

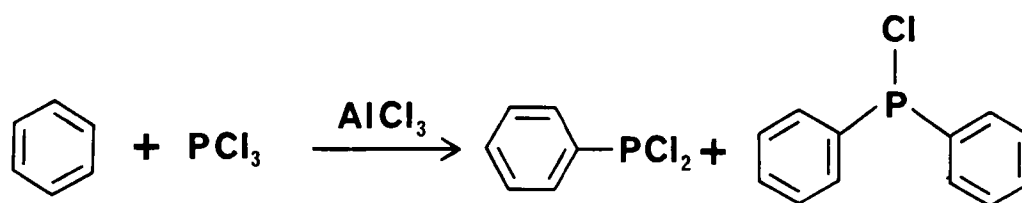


Figure 4. Synthesis of Mono- and Dichlorophosphine

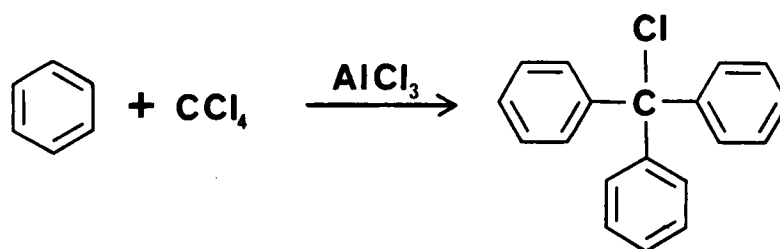


Figure 5. Synthesis of Triphenylmethyl chloride

precipitated within five to ten minutes after the mixture had begun heating; indicating a crosslinking reaction had occurred.

If the value for the secondary acid sites (tot(P) minus the primary acid capacity) is added to the tot(OH) for the resin synthesized at 73°C , after adjusting for the change in molecular weight by the addition of primary phosphinic acid groups the tot(P) would be 6.13 mequiv/g, which would be the same as the tot(OH) if the formation of only dichlorostyrylphosphine groups occurred during the functionalization. This value is in very good agreement with the 6.01 mequiv/g previously stated for the theoretical maximum capacity of the resin.

The Phosphine Oxide Form of the Resin

There is an intermediate form of the resin which has not yet been mentioned. Before conversion of the chlorostyrylphosphine resin to the phosphinic acid resin by treatment with water, both dichlorostyrylphosphine and monochlorodistyrylphosphine groups are present (Figure 1, page 11). The dichlorostyryl groups are hydrolyzed directly to primary phosphinic acid groups. The monochlorodistyryl groups are not hydrolyzed directly to secondary phosphinic acid groups, but rather to secondary phosphine oxide groups, which are then oxidized with 1M NaOH to secondary phosphinic acid groups. It is observed that when the resin is conditioned, there is a sizable quantity of gas evolved during the NaOH elution. A glowing splint test on the gas indicated (rather dramatically) that it was hydrogen. A resin on which the NaOH elution had been omitted had a much lower tot(OH) than the same resin which had been fully conditioned (see Table 3). After contact with 1M NaOH, the

Table 3

Comparison of Phosphinic Acid Resin
Synthesized at 73°C for 4 Hours
Conditioned With and Without NaOH Elution

Resin Code	Elution	Capacity (mequiv/g dry resin)			
		tot(OH)	tot(P)	primary acid	%Solids
PK-01-052A	A	4.62	4.70	2.30	52.20
PK-01-052A'	B	3.39	4.85	2.62	42.60

A H₂O, 1M NaOH, H₂O, 1M HCl, H₂O
B H₂O, 1M HCl, H₂O

tot(OH) was the same as that for the resin which had been contacted with 1M NaOH prior to analysis. That the tot(OH) for the unoxidized resin does not correspond to the primary acid capacity is most likely due to partial oxidation of the distyrylphosphine oxide by the dilute NaOH used in the tot(OH) analysis. The resin which had not been contacted with 1M NaOH, but had been stored for 12 months in a bottle filled with water had a tot(OH) of 4.76 mequiv/g, which agrees with the tot(OH) value for the 1M NaOH oxidized resin (4.62 mequiv/g). Frank²¹ has also shown that when monochlorodiarylphosphine containing bulky aryl substituents is hydrolyzed, phosphine oxide groups are formed.

Residual Catalyst on the Resin

An analysis for aluminum (from the AlCl_3 catalyst) was done on the resin which had not undergone the NaOH oxidation, but the results were inconclusive as to the type of groups present (there were 0.84 mmoles/g of aluminum on the resin giving almost a 6:1 ratio of tot(P):aluminum). Apparently, some of the aluminum had been removed from the resin by the water washes and the conditioning sequence, even without the NaOH. The NaOH, as well as oxidizing the secondary phosphine oxide groups, serves to assure that there is no aluminum in the pores of the resins, which would be detrimental to their use if allowed to remain.

The Effect of Crosslink Level and Porosity on the Resins

Phosphorylations at reflux (73°C) for four hours with a 0.77 mole ratio of AlCl_3 using copolymers with various crosslink levels show much the same trend

(Table 4). The 10% crosslinked resin gives the same type of resin as a 2% crosslinked resin, but the percentage of primary acid capacity is greater (69.25% as compared to 48.94% for the 10% and 2% crosslinked resins, respectively) due to steric constraints imposed by the DVB, thereby lowering the probability of two polystyrene phenyl rings being in close enough proximity for secondary crosslinking to occur. There is also a corresponding decrease in the overall functional level as the crosslink level of the copolymer increases, due to a lower number of functionalizable phenyl rings from the polystyrene (the 10% copolymer is only 81.95% styrene, the remainder being the DVB mixture mentioned on page 14). Macroporous resins have no secondary crosslinking, at least within the detection limits of the analysis, because the interchain distance is too great for the presence of bridging phosphorus groups (secondary acid sites). It has been shown²² that a styrene/DVB gel copolymer has microchannels of approximately 50 Å in diameter, while a 5% crosslinked macroporous styrene/DVB copolymer has large channels (on the order of 500Å). This means that in a 2% gel, the polymer chains are close enough, given their mobility during the functionalization at 73°C, for secondary crosslinking to occur. The macroporous copolymer, on the other hand, has a chain spacing in the polymer matrix which is too far apart for an appreciable amount of secondary crosslinking to occur. Thus for the 5% and 10% MR resins listed in Table 4, the primary acid capacity is the same value as the tot(OH).

The Effect of Catalyst Level on the Resins

Increasing the catalyst level from 0.77 moles to 1.2 moles to 2.0 moles AlCl_3 produces resins with increasing functionalization levels and decreasing primary acid

Table 4
Characterization of Phosphinic Acid Resins Synthesized
at 73°C for 4 Hours with 0.77 moles AlCl₃
with Various Porosity and Crosslink Level Copolymers

Resin Code	Copolymer Type	Capacity (mequiv/g dry resin)			
		tot(OH)	tot(P)	primary acid	%Solids
PK-01-152E	linear	3.64	3.32	N.A.	35.87
PK-01-052A	2% gel ^a	4.62	4.70	2.30	52.20
PK-03-131	10% gel ^a	3.43	3.48	2.41	68.56
PK-03-095	5% MR ^b	4.06	4.76	4.08	31.34
PK-03-148	10% MR ^b	3.52	4.10	3.23	31.38

^a 2%, 10% crosslink level gel type copolymer

^b 5%, 10% crosslink level MR type copolymer

capacities (Table 5). This is due to the more forcing conditions, which favor the disproportionation mentioned earlier.

The Effect of Functionalization Time on the Resins

A series of resins were synthesized at 73°C with a 0.77 mole ratio of AlCl_3 for 15 minutes to 48 hours (see Table 6), and the same trend was seen: that the more forcing conditions (longer time in this case) lead to a resin with a higher level of functionalization and a higher percentage of secondary acid groups. The same was true when a series of resins was synthesized at room temperature with a 0.77 mole ratio of AlCl_3 , although the level of functionalization is quite a bit lower than the theoretical maximum functionalization level (Table 7). In this case, both mechanisms for secondary crosslinking may play a role.

Friedel-Crafts Catalysis by Zinc(II) and Tin(IV) Chloride

Resins were synthesized at reflux (73°C) for 4 and 48 hours with catalysts of low activity (ZnCl_2 and SnCl_4) in mole ratios of 0.77, 1.2, 2.0, and with no catalyst at all. These resins have a minimal degree of phosphorylation, and only primary phosphinic acid functionalities (Tables 8 and 9). Based on the results of the AlCl_3 phosphorylations performed under mild conditions, the lack of bifunctionality does not come as much of a surprise. These resins confirm with phosphorylations the results of other catalyst activity studies,^{16,17} which show that ZnCl_2 and SnCl_4 are weak catalysts for Friedel-Crafts type reactions.

Table 5

Characterization of 2% Crosslinked Gel Phosphinic Acid Resins
Synthesized at 73°C for 4 Hours with
0.77, 1.2, and 2.0 moles AlCl_3

Resin Code	Catalyst Level ^a	Capacity (mequiv/g dry resin)			
		tot(OH)	tot(P)	primary acid	%Solids
PK-01-052A	0.77	4.62	4.70	2.30	52.20
PK-01-152A	1.2	5.54	5.43	1.75 ^b	53.18
PK-01-139A	2.0	5.78	5.69	1.51	50.16

^a moles AlCl_3 /mole styrene phenyl rings

^b interpolated by graphing the tot(P) for PK-01-052A and PK-01-139A

Table 6

Characterization of 2% Crosslinked Gel Phosphinic Acid Resins
 Synthesized at 73°C with 0.77 moles AlCl_3
 for 15 Minutes to 48 Hours

Resin Code	Time ^a	Capacity (mequiv/g dry resin)			
		tot(OH)	tot(P)	primary acid	%Solids
PK-01-005C	0.25	4.34	4.48	3.20	40.04
PK-01-005D	0.50	4.22	4.52	2.32	48.71
PK-01-005B	0.75	4.29	4.68	2.92	41.61
PK-01-005A	1	4.53	4.61	2.88	43.84
PK-01-052A	4	4.62	4.70	2.30	52.20
PK-01-163A	24	5.28	5.16	2.00 ^b	50.64
PK-01-146A	48	5.37	5.38	1.79	53.65

^a Time at reflux (hours)

^b Estimated graphically

Table 7

Characterization of 2% Crosslinked Gel Phosphinic Acid Resins
Synthesized at Room Temperature with
0.77 Moles AlCl_3 for 30 Minutes to 72 Hours

Resin Code	Time (hours)	Capacity (mequiv/g dry resin)			
		tot(OH)	tot(P)	primary acid	%Solids
PK-01-026A	0.5	0.43	1.19	1.81	42.30
PK-01-026B	2	0.99	1.76	1.96	45.99
PK-01-026C	3	1.80	2.58	2.49	44.72
PK-01-026D	4	1.72	2.65	2.11	47.42
PK-01-048B	6	2.50	2.25	2.43	50.22
PK-01-048C	30	3.67	3.86	2.76	53.26
PK-01-048D	48	3.72	3.65	2.56	53.79
PK-01-048E	72	3.78	3.86	2.79	44.65

Table 8

Characterization of 2% Crosslinked Gel Phosphinic Acid Resins
Synthesized at 73°C for 4 Hours with
Weak Catalysts at Various Levels

Resin Code	Catalyst/level ^a	Capacity (mequiv/g dry resin)			
		tot(OH)	tot(P)	primary acid	%Solids
PK-01-092B	ZnCl ₂ /0.77	0.36 ^b	1.27 ^c	0.91 ^d	54.85
PK-01-101A	ZnCl ₂ /1.2	0.19 ^b	1.37 ^c	0.89 ^d	53.33
PK-01-101B	ZnCl ₂ /2.0	0.25 ^b	1.37 ^c	0.84 ^d	57.25
PK-01-124C	SnCl ₄ /0.77	0.17 ^e	1.02 ^f	0.67 ^g	52.40
PK-01-110A	SnCl ₄ /1.2	0.01 ^e	0.99 ^f	0.83 ^g	52.24
PK-01-110B	SnCl ₄ /2.0	0.06 ^e	1.04 ^f	0.92 ^g	55.00
PK-01-124D	no catalyst	0.21	0.91	0.81	46.57

^a level = moles catalyst/mole copolymer

^b average = 0.27, standard deviation = 0.09

^c average = 1.34, standard deviation = 0.06

^d average = 0.88, standard deviation = 0.04

^e average = 0.08, standard deviation = 0.08

^f average = 1.02, standard deviation = 0.02

^g average = 0.80, standard deviation = 0.13

Table 9

Characterization of 2% Crosslinked Gel Phosphinic Acid Resins
Synthesized at 73°C with 2 mole Ratio of
Weak Catalysts at 4 and 48 Hours

Resin Code	Catalyst	Time ^a	Capacity (mequiv/g dry resin)			
			tot(OH)	tot(P)	primary acid	%Solids
PK-01-101B	ZnCl ₂	4	0.25	1.37	0.84	57.25
PK-01-101A	ZnCl ₂	48	0.52	1.61	0.97	46.24
PK-01-101B	SnCl ₄	4	0.01	0.96	0.92	49.55
PK-01-124C	SnCl ₄	48	0.23	1.17	0.74	53.58

^a time at reflux (hours)

Friedel-Crafts Catalysis by Iron Trichloride

The final catalyst used in the phosphorylation study was FeCl_3 . This catalyst gives an intermediate level of functionalization, confirming the order of catalyst activity^{16,17} in the electrophilic aromatic phosphorylation reaction of polystyrene with PCl_3 , which is: $\text{AlCl}_3 > \text{FeCl}_3 > \text{ZnCl}_2 > \text{SnCl}_4 \approx \text{no catalyst}$.

Oxidation of the Chlorophosphine Intermediate by Iron(III)

It can be seen (Table 10) that the $\text{tot}(\text{OH})$ is higher than the $\text{tot}(\text{P})$ by a factor of almost two for the resins synthesized using FeCl_3 . The FeCl_3 catalyzed resin contains phosphonic acid groups rather than phosphinic acid groups as do the resins made with the previously discussed catalysts. Some secondary crosslinking also occurs to give secondary phosphinic acid groups, as evidenced by the ratio of $\text{tot}(\text{OH})/\text{tot}(\text{P})$ of only 1.6 to 1.8. The phosphonic acid groups are formed by oxidation of the phosphorus by the Fe^{3+} to give pentavalent chlorophosphine groups. To prove this, a sequence of reactions was done (Figure 6) in which a phosphinic acid resin was synthesized using AlCl_3 . This resin was not quenched, but washed several times with PCl_3 to remove AlCl_3 , then refluxed for 4 hours with a 2.0 ratio of FeCl_3 in PCl_3 .²³ It was then quenched and analyzed for $\text{tot}(\text{OH})$ and $\text{tot}(\text{P})$. A fully functionalized and conditioned phosphinic acid resin (PK-02-111) was contacted with 0.2M $\text{Fe}(\text{NO}_3)_3$ for 17 hours. The resins were then analyzed to determine whether oxidation of the phosphorus groups had occurred. It was found that for the first resin, the $\text{tot}(\text{P})$ was the same before and after the $\text{PCl}_3/\text{FeCl}_3$ reaction, but the $\text{tot}(\text{OH})$ for the resin after the $\text{PCl}_3/\text{FeCl}_3$ reaction was approximately 50% higher than before. No attempt was made to analyze the iron for its oxidation state.

Table 10

Characterization of 2% Crosslinked Gel Phosphonic Acid Resins
Synthesized at 73°C with FeCl₃ for
Various Times and Catalyst Levels

Catalyst Level	Time (hours)		
	4	24	48
2.0	PK-01-139B	PK-01-120D	PK-01-120C
	<u>5.04</u> 1.85	<u>5.35</u> 1.66	<u>5.54</u> 1.45
	2.72	3.22	3.81
1.2	PK-01-152B	PK-01-120B	PK-01-120A
	<u>4.11</u> 1.84	<u>3.53</u> 1.63	<u>3.94</u> 1.70
	2.23	2.17	2.32
0.77	PK-01-124B	PK-01-163C	PK-01-146C
	<u>2.85</u> 1.72	<u>2.48</u> 1.78	<u>2.81</u> 1.77
	1.66	1.39	1.59

key: **Resin Code**
 $\frac{\text{tot(OH)}}{\text{tot(P)}}$ Ratio of tot(OH)/tot(P)

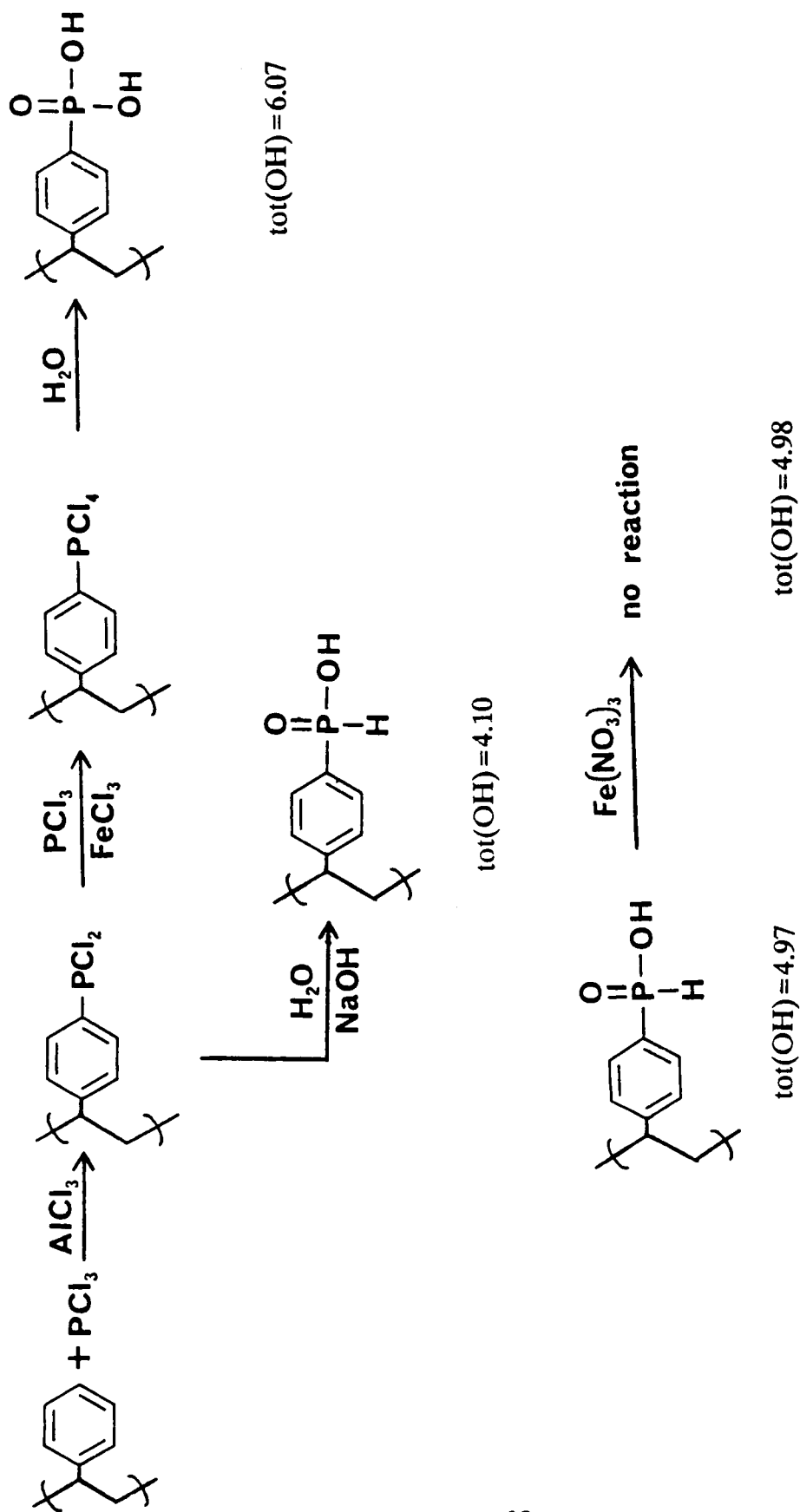


Figure 6. Oxidation of the Phosphinic Acid Resin by Iron Chloride

The tot(OH) for the Fe(NO₃) contacted resin remained unchanged. Thus, it was shown that the phosphorus is oxidized by Fe³⁺ while in the chlorophosphine form, but not in the phosphinic acid form in aqueous solution.

The Effect of Crosslink Level on the Resins

The effect of the crosslink level of the copolymer used is the same with FeCl₃ catalyzed resins as it is with AlCl₃ catalysis: the higher the DVB crosslink level, the lower is the secondary crosslinking by phosphorus (Table 11). Since the level of functionalization of the resin is lower with FeCl₃ than with AlCl₃, the resin is less hydrophilic, and there is a problem of accessibility of the acid groups for the higher crosslink level resins. This is also indicated by the high % Solids of the 10% and 15% crosslinked resins in Table 11, which gives a tot(OH) value which is much lower than it should be. This effect is also shown in Table 11 by comparison of the linear polystyrene resins functionalized with 0.77 moles and with 2.0 moles of FeCl₃, which both have a tot(OH)/tot(P) ratio of two (within experimental error), even though the resin synthesized with 0.77 mole FeCl₃ has a fairly low functional level, which was shown before to affect accessibility of the acid groups.

Conclusion

The best synthetic conditions for producing a fully functionalized phosphorus resin are reflux in PCl₃ for at least 4 hours with a high catalyst level of AlCl₃. Under these conditions, a hydrophilic (high functional group accessibility) bifunctional resin is produced which is capable of ion-exchange and redox reactions by virtue of the

Table 11

Characterization of Phosphonic Acid Resins Synthesized
at 73°C for 4 Hours with 2.0 moles FeCl₃
with Various Crosslink Level Copolymers

Resin Code	Crosslink Level	Capacity (mequiv/g dry resin)			%Solids
		tot(OH)	tot(P)	tot(OH)/tot(P)	
PK-01-139B	linear ^a	2.77	1.24	2.23	31.68
PK-01-152C	linear ^b	4.16	1.94	2.14	28.36
PK-01-139B	2% gel ^c	5.04	2.72	1.85	55.48
PK-01-198A	5% gel ^c	3.78	2.20	1.72	57.13
PK-01-198B	10% gel ^c	2.08	1.59	1.31	74.97
PK-01-198C	15% gel ^c	0.92	1.20	0.77	82.87

^a 0.77 mole ratio FeCl₃

^b 2.0 mole ratio FeCl₃

^c 2%, 5%, 10%, and 15% crosslink level gel type copolymer

primary and secondary phosphinic acid groups present. This resin is formed via an intermediate form which contains dichlorostyrylphosphine and chlorodistyryl phosphine moieties. Upon hydrolysis, these yield primary phosphinic acid and secondary phosphine oxide groups. Oxidation of the phosphine oxide groups with aqueous NaOH gives a bifunctional phosphinic acid resin. Long reaction times at reflux with a high catalyst level of FeCl_3 produce a moderate functional level resin which contains phosphonic acid and secondary phosphinic acid groups. This resin is hydrophilic in spite of its intermediate functional level, due to two -OH groups on each primary phosphorus group. ZnCl_2 and SnCl_4 used under any conditions produce primary phosphinic acid groups and only very low levels of functionalization. They are therefore not of synthetic utility for producing the phosphorus based ion-exchange resins, although they may be useful in producing a partially functionalized resin for subsequent reactions which would ultimately produce a resin with two completely different types of functional groups (i.e. a mixture of phosphinic acid and sulfonic acid groups, etc. on the same resin). These types of resins could have vastly different selectivities or other properties which a monofunctional resin, or one with similar functional groups do not possess.

CHAPTER II

Kinetics of the Ion-Exchange/Redox Reaction with the Phosphinic Acid Resins

Introduction

The redox characteristics of the dual mechanism bifunctional phosphinic acid resins can be put to very good use for the selective extraction of metals with a high enough standard reduction potential (greater than approximately 0.3 volts²⁴). These metals include copper, mercury, and silver. It has been shown that reduction of copper by these resins is very slow²⁴, and thus rules out redox-driven extraction as a viable method of separating it from a solution containing a mixture of other metals. It does not, however, preclude selective copper extraction based strictly on ion-exchange. On the other hand, the kinetics of the redox-driven extraction of mercury and silver are fast enough to make it a useful method for the selective removal of these metals from waste streams or for reclamation (Figures 7, 8, and 9).

It was with this in mind that kinetic studies were done with the phosphinic acid resins in order to determine the rate of the redox reaction as compared to ion-exchange. In these studies, an equivalent amount of 0.2N mercury or silver solution (with standard reduction potentials of 0.85 volts and 0.80 volts, respectively²⁵) and resin (based on tot(OH)) were contacted (with and without sodium ions present) for various times up to 24 hours at solution pH's of 0, 1, 1.5, 2, and 5 at temperatures of 6°C, 15°C, 30°C, 45°C, and 60°C with various size, crosslink level, and porosity beads. After contact, the solution was separated from the beads and analyzed for

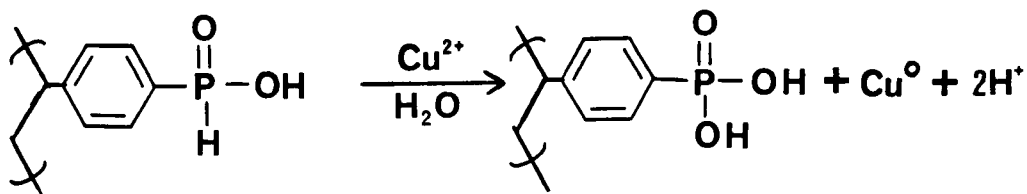


Figure 7. Reduction of Copper by the Phosphinic Acid Resin

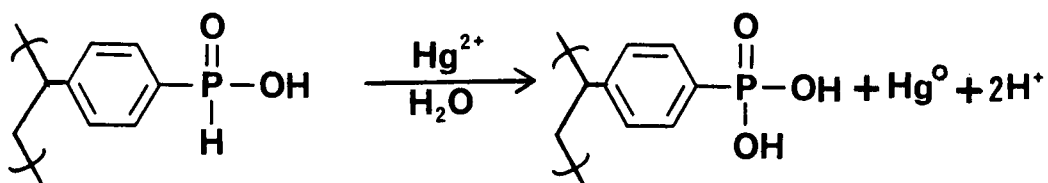


Figure 8. Reduction of Mercury by the Phosphinic Acid Resin

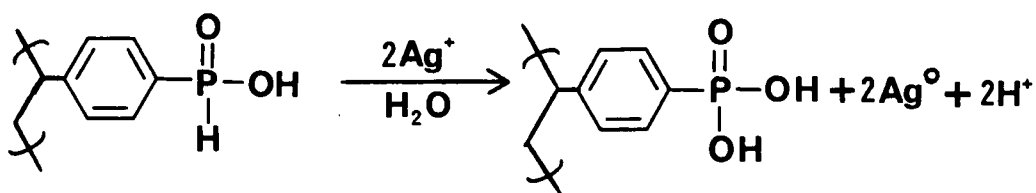


Figure 9. Reduction of Silver by the Phosphinic Acid Resin

remaining metal. The resin was eluted with HNO_3 to remove both the exchanged and the reduced metal, and the change in $\text{tot}(\text{OH})$ (due to oxidation of the primary phosphinic acid groups with concomitant reduction of the metal) was determined. Because of a standard reduction potential of -0.23 volts²⁵, ion-exchange is the sole mechanism of extraction when nickel is contacted with the phosphinic acid resin. Therefore, nickel solution was also contacted with the resin under the same conditions as for mercury and silver in order to determine the kinetics of ion-exchange in the absence of a redox reaction.

The equivalent conductivities of the ions used are all approximately the same. The diffusion coefficients for these ions are therefore also similar, since the mobility of an ion is directly proportional to its conductivity. The equivalent conductivities²⁶ for Ag^+ , Na^+ , Ni^{2+} , and Hg^{2+} (in $\text{mho cm}^2/\text{equiv}$) at 25°C are, respectively: 61.9, 50.11, 50, and 53. Differences in the observed rates of ion-exchange and redox will, therefore, not be due to a significant difference in the relative mobilities of the different ions. The resins used are listed in Table 12.

The Kinetics of Nickel Ion-Exchange

Figure 10 (page 65) shows the results obtained with the phosphinic acid resin after contact with $\text{Ni}(\text{NO}_3)_2$ solution at $\text{pH}=1.5$. It is apparent that at 60°C (Figure 10b) the rate of ion-exchange is very fast, and the resin attains its maximum percent loading in less than 15 minutes. Thus, the system was already at equilibrium when the first point in the graph was taken. At 2°C (Figure 10a), ion-exchange is slower, and equilibrium is not reached until about one hour. That the equilibrium

Table 12

Phosphinic Acid Resins used for Kinetics
of the Ion-Exchange/Redox Reaction

Resin Code	Figure	Resin Type ^a	Capacity (mequiv/g dry resin)			
			tot(OH)	tot(P)	primary acid	%Solids
PK-03-017	10a-b; 15a-d; 16a	2% gel -30+40	5.25	4.97	3.40	49.31
PK-03-068	11a-d; 14d	2% gel -30+40	5.25	4.57	2.48	55.34
PK-03-095	18c; 20c	5% MR -30+40	4.06	4.76	4.08	32.14
PK-03-130	12a-d; 13a,c,d 14a-c; 16b-d	2% gel -30+40	5.06	4.86	3.48	57.07
PK-03-131	18b; 20b	10% gel -30+40	3.43	3.48	2.41	71.88
PK-03-148	18d; 20d	10% MR -30+40	3.52	4.10	3.23	32.43
PK-03-192	13b; 18a; 20a	2% gel -30+40	5.16	4.93	2.72	49.35
PK-03-205	17a-d	2% gel -80+100	5.12	4.87	2.78	54.02
PK-03-209	19a,b	2% xerogel -30+40	5.23	5.07	2.66	37.12
PK-03-226	19c	10% gel -80+100	4.50	4.66	3.50	69.04

^a denotes: 1) bead crosslink level and type, e.g., 2% gel is a 2% crosslinked (DVB) gel type copolymer, and 2) mesh size of the functionalized resin

percent loading of nickel on the resin is nearly the same at 2°C and 60°C is a good indication that the ion-exchange equilibrium constant does not vary significantly over the temperature range investigated (17.5% and 20.3% nickel absorbed at 2°C and 60°C, respectively).

Boyd²⁷ has determined ion self-diffusion coefficients of various ions in ion exchange resins, and obtained the following results for silver and sodium : at 0.3°C, the self-diffusion coefficients are $2.62 \text{ cm}^2 \text{ sec}^{-1} \times 10^7$, respectively, while at 25°C they are $6.42 \text{ cm}^2 \text{ sec}^{-1} \times 10^7$, respectively. This confirms that the slower ion-exchange at lower temperature is indeed due to slower movement of the ions, and not to a change in the equilibrium constant. The slower rate for ion-exchange at 2°C, then, is not due to a lower "driving force", but to a lower rate of diffusion.

In order to ensure that ion-exchange was the only mechanism responsible for nickel absorption, after removal of the nickel the resin which was contacted with nickel solution for 24 hours at both 2°C and 60°C (PK-02-088) was analyzed. The tot(OH) for both of the resin samples was identical before and after contact ($\text{tot(OH)} = 5.15$), thereby confirming that there was no redox reaction.

It may also be noted here that the binding constant between Ni^{2+} and the phosphinic acid resin is exceptionally high. After elution with 4M HNO_3 , only a small amount of the nickel that was on the resin was removed. The rest of the metal remained on the resin (as was attested to by only a slight green tinge to the HNO_3 and by the prominent green color of the resin, which was white before contact with the nickel solution). Different methods were tried in order to attempt the removal of nickel from the resin. These were: elution with 4M and 8M HNO_3 at

room temperature and at $\sim 50^{\circ}\text{C}$, elution with 6M HCl, elution with 4M H_2SO_4 , and elution with 0.5M EDTA solution at $\text{pH}=9.5$. Only the EDTA elution was satisfactory, as evidenced by the prominent green color of the resin after elution with all but the EDTA solution. Analysis of the EDTA solution after elution of the resin showed that all of the nickel had been removed by the EDTA and was in solution.

The Theory of Ion-Exchange Kinetics

It is well known^{28,29} that in the absence of chemical reactions (chemical reactions being defined as anything which consumes any of the exchanging ions, such as neutralization, complexation, etc.), ion-exchange kinetics are controlled solely by the rate of diffusion of the ions involved. Moreover, there are two types of diffusion control: diffusion of the metal ions at the resin/solution interface, known as film-controlled diffusion, and diffusion within the pores of the beads, termed particle-controlled diffusion. It should be noted that there is not a well defined film around the polymer beads which ions must diffuse through, provided the solution is agitated well enough. It is, rather, a way of describing mass transfer in dilute solution due to inhomogeneity of the solution at the particle/solution interface. This inhomogeneity is caused by a decay of turbulent or laminar flow very near the surface of the resin. It is this area of changing dynamics which is modeled using the fictitious "Nernst Film", defined as a zone of constant thickness and impedance to diffusion. The farther from the particle surface the disruption of mixing occurs, for example from poor agitation, the thicker the film is.

The Nernst-Planck equation (equation 1)³⁰ has been used with relative success in describing ion exchange kinetics with particle-control in which there are no chemical reactions, assuming a highly ideal case in which the ion mobility remains constant. This equation consists of three parts: D_i (grad C_i), which describes the diffusion of ion i in the resin due to its concentration, C_i grad ln a_i , which is a term for the change in activity coefficients due to the concentration gradient within the resin, and $z_i C_i (F/RT)$ grad ϕ , which is called the electric transference (again, inside

$$J_i = -D_i (\text{grad } C_i + C_i \text{grad ln } a_i + z_i C_i (F/RT) \text{ grad } \phi) \quad 1$$

J_i = the diffusional flux of ion i

D_i = the diffusion coefficient of ion i

C_i = the concentration of ion i

grad ln a_i = the activity coefficient gradient of ion i

grad C_i = the concentration gradient of ion i

z_i = the charge of ion i

F , R , T = Faraday constant, gas constant, and temperature, respectively

grad ϕ = the electric potential gradient

the resin). It should be noted that D_i is assumed to be independent of both concentration and composition, as well as of the mobility of the individual ions. In reality, however, it is dependent on these and on the concentration gradient in the resin. As the ion concentration of the metal ion in the resin increases, its diffusion coefficient decreases, lowering the overall ion flux. To circumvent this difficulty, it is customary to speak of an average diffusion coefficient, rather than variable

individual diffusion coefficients. It is strictly applicable, though, only near equilibrium.

The electric transference term is due to the difference in mobilities of the exchanging ions (M^{n+} and H^+). This difference causes an electric potential gradient (in the direction of the slower ion) which increases the mobility of the slower ion while decreasing the mobility of the faster ion. Because the exchange sites in the polymer are fixed, there is a charge disparity between the resin and the solution. Charge neutrality must, however, be maintained. Thus, diffusion of H^+ from the resin is impeded, while diffusion of M^{n+} into the resin is enhanced.

The charge disparity between the inside and the outside of the resin (the bulk solution) is a result of the Donnan exclusion principle, which states that the product of the cation and anion concentrations inside the resin must equal that of the bulk solution (equation 2).³⁰ Since the anion concentration inside the resin is constant (fixed exchange sites), anions in solution are effectively excluded from entering the

$$[X^+]_R[Y^-]_R = [X^+]_S[Y^-]_S \quad 2$$

pores of the resin. As an example; if a resin has a nominal exchange site concentration of 5N, and the solution concentration is 0.1N, then according to equation 2 the concentration of the mobile anion in the resin is 0.002N. Thus, the exchanging cations must have equivalent flux rates into and out of the resin in order to preserve the charge neutrality, as stated previously.

Diffusion of metal ions within the pores of the resin, diffusion of metal ions from one exchange site in the resin to another (provided the binding constant between the metal ion and exchange site is low enough to allow redistribution of the ions within the resin), and diffusion of the exchanged ion (H^+) through the pores of the resin all are involved in particle controlled diffusion. Also needed to fully describe particle controlled diffusion are: the diffusion rate of counterions within the resin (even though in very low concentration) to maintain charge neutrality, convective flow of solvent molecules in the pores of the resin (due to mass transfer action of the ions, i.e., the solvent being "dragged" in the direction of the ions with the larger overall flux), and the "tortuosity" of the path the ions must follow to get into or out of the resin, for which an approximate diffusion coefficient can be calculated (equation 3, derived from the diffusion of ions through membranes).³⁰ This equation does not take into account variables other than tortuosity, but it is, nonetheless, good for comparison purposes. For example, the equation predicts a decrease in the diffusion coefficient of an ion in a 10% gel phosphinic acid resin by

$$D_R = D_s[\epsilon/(2-\epsilon)]^2 \quad 3$$

D_R = the diffusion coefficient in the resin

D_s = the diffusion coefficient in solution

ϵ = the fractional pore volume of the resin

a factor of 1.78 as compared to a comparable 2% gel resin, based on 60% and 50% solids of the resins, respectively. The tortuosity is itself affected by the crosslink level of the resin, by the pore size in the resin, and by the extent of swelling or shrinkage of the resin due to the degree of ionization or to the ionic strength of the solution.

The Effect of Stir Speed on the Ion-Exchange/Redox Reaction with Silver

Helffferich^{28, 31} has shown that the kinetics of ion exchange are particle diffusion-controlled (as opposed to film diffusion-controlled) in 0.1M solutions. This concentration is half the initial concentration of the solutions used in these kinetic studies (0.2N). The beads used here were also larger than the size normally associated with film-controlled diffusion, and the mixing was such that the beads remained suspended in the solution. These factors rule out film-control and limit the kinetics to either particle-control or reaction-control. To ensure that this was the case, an investigation of the effect of the stir speed was performed by stirring 10 mequiv resin (PK-03-008) with 10 mequiv 0.2M AgNO₃ solution at 2°C for 30 minutes at various stir speeds. There was no dependence of the rate of silver extraction by the resin on the stir speed (see Table 13). The conditions which favor film or particle controlled rates are given in Table 14.

Kinetics of the Ion-Exchange/Redox Reaction with Silver

If fast reactions, such as neutralization of the protonated form of a cation-exchange resin with hydroxide accompany ion-exchange, as soon as the ions reach

Table 13

The Effect of Stir Speed on Silver Extraction at 2°C
for 30 Minutes: Stir Speed (rpm) vs Percent Absorbed

Stir Speed	0	100	200	450	700
Total	22.78	26.12	24.69	28.78	25.64
Redox	23.34	17.82	19.79	26.56	21.46
ion-exchange	-0.56	8.30	4.90	2.22	4.18

Table 14

Factors which Determine Film or Particle-Controlled
Kinetics of Ion-Exchange

Film Diffusion Control	Particle Diffusion Control
High mobility of ions in the resin because of: Low Crosslink Level Highly Swollen Matrix High Capacity Resin	Restricted mobility of ions in the resin because of: High Crosslink Level Swelling Slight to None Low Capacity Resin
Small Particle Size	Large Particle Size
Dilute Solution	Concentrated Solution
Inefficient Mixing	Good Mixing

a site in the resin with which they can react, they are consumed. This changes the nature of the diffusion-controlled rate equation because of the added "driving force" of the consumption of the ions, but the rate is still controlled by diffusion. This is often termed a diffusion-limited rather than diffusion-controlled rate.³¹

Reaction-controlled kinetics are possible only when the chemical reaction taking place is much slower than diffusion of the ions into the resin. There has so far not been any well demonstrated case of true reaction-controlled ion-exchange kinetics, nor has the theoretical treatment of such a possibility been developed. Silver absorption by the phosphinic acid resin, though, appears to be reaction rate limited (*vide infra*).

The Effect of pH and Temperature on the Ion-Exchange/Redox Reaction with Silver

Figures 11-14 (pages 66-69) show the effect of both temperature and solution pH on the absorption of silver by the phosphinic acid resin. All of the resins used for the kinetic studies had been sieved in water after functionalization and a full conditioning sequence so the size of the resin itself, and not the copolymer from which it was made, was -30+40 mesh (see Table 1, page 9).

It can be seen that there is a limiting pH below which there is essentially only a redox reaction, with minimal ion-exchange. Thus at pH=0, the redox reaction is the only significant mechanism which is responsible for silver absorption from solution. It has been shown, using radiotracer techniques at low R_i (initial ratio of mequiv of metal in solution/total mequiv of functional sites on the polymer), that even in 4M HNO_3 , silver is almost quantitatively absorbed from solution by a

phosphonate diethyl ester resin³² (see Figure 21, page 82 for the resin structure). It has been postulated³³ that there is: 1) an access mechanism, which is either coordination at low pH (or with a resin such as the phosphonate diester which is capable only of coordination) or ion-exchange at moderate pH's for resins with exchangeable protons, and 2) a recognition mechanism, which for the phosphinic acid resin with mercury and silver is the redox reaction. Thus, the access mechanism for silver changes from coordination to ion-exchange somewhere between a pH of 0 and 1 (see Figures 13a and 16a; pages 68 and 71). Calculations of the $[H^+]$ (based on one proton released for each Ag^+ absorbed, whether by ion-exchange or by reduction of the metal) of the pH 1.5, 2, and 5 solutions contacted for 24 hours consistently show a final solution pH of between 0.7 and 0.76. This final pH value is also confirmed by titration of the solutions for acidity after contact with the resin. Thus, with silver, the point at which there is an access mechanism change appears to be at a pH of approximately 0.7.

It is noticed, on looking at Figures 11a, 12a, 13a, and 14a (pages 66-69) compared to any of the other graphs in Figures 11-14 that there is significantly less silver absorbed at pH=0 than at any of the other pH's. The reason for this may be a change in the redox potential of the silver/phosphinic acid at low pH, but this is most likely not the case. Since the Nernst equation predicts a change of only approximately -0.06 volts for one pH unit, it is improbable that there should be such a drastic a change in the potential between pH=0 and pH=1. The large decrease in the amount of the redox reaction which occurs at low pH values is most likely due to a suppression of ion-exchange as the access mechanism.

Oxidation of a phosphinic acid to a phosphonic acid is a 2-electron oxidation.²⁴ There are, therefore, two silver ions required for the oxidation to proceed. These must be in close enough proximity to the P-H bond and have the proper orientation for a redox reaction to occur. The only way for this to happen is for the silver to be accessed by the resin. Recall that the anion concentration inside the resin is predicted to be fairly low, so the silver must be exchanged in order to be near enough to the functional groups in the resin for the redox reaction to occur. Even though it has been demonstrated that coordination of silver to phosphorus acids and esters occurs at low pH, this was at a very low R_i .³² Because of the low R_i , the anion concentration can be approximately equal to the metal ion concentration, allowing entrance of AgNO_3 into the resin. Therefore, at higher R_i and in the absence of ion-exchange, coordination is plausible as the access mechanism, but the redox reaction would be slow due to the small amount of silver which could be favorably positioned. The low amount of silver coordinated on the resin at low pH may also be due simply to competition with protons for coordination sites. It has also been shown that at a very low percent loading of silver on the resin (from the before mentioned low R_i studies) there is no reduction of silver, showing that the oxidation requires two silver ions at one phosphorus, and furthermore, that it is most likely a 2-electron transfer and not two single-electron transfers, although two single-electron transfers in rapid succession can not be ruled out without further mechanistic study of the redox reaction. When mercury is contacted with a phosphinic acid resin, even at a very low R_i the phosphinic acid groups are oxidized (mercury ion is divalent, and only requires one ion to approach the phosphorus closely enough for the oxidation to

occur). Therefore, the redox reaction should be much faster when the resins are contacted with mercury than with silver.

At pH values of 1.5, 2, and 5 and temperatures of 6°C, 15°C, 30°C, and 45°C (Figures 11-14; pages 66-69) there is almost no qualitative difference in the graphs. The overall amount of silver absorbed increases by quite a bit in going from lower to higher temperature, as would be expected from the increase in both the rate of diffusion of the silver ions and the increase in the favorability of the redox reaction at higher temperatures.

For any of the four different isothermal pH series (Figures 11-14; pages 66--69), the three higher pH plots are nearly identical, with only the pH=0 results being different. There is a very slight increase in the overall amount of silver absorbed with increasing pH (about 2%-3% more for each successive pH) which appears to be due only to an increase in the amount of metal reduction. The amount of ion-exchange may very well also increase with increasing pH, but this only leads to a larger amount of resin oxidation due to the statistically higher probability for the proper orientation of two silver ions. The overall effect is that as the facility for ion-exchange increases, so does the redox reaction. Conversely, as the resin becomes more highly oxidized, the difficulty of 2 silver ions from the now depleted solution being in the proper orientation for the redox reaction is much greater. Therefore, the level of ion-exchange should remain fairly constant.

It will be noticed (figures 11-14; pages 66-69) that ion-exchange does not remain constant, but decreases with time. This is due to the fact that even though the probability of two silver ions in the proper orientation is decreased when the

solution becomes depleted, given enough time, there still can be a small amount of metal reduction occurring. At long times, the statistical distribution of both the oxidized and exchanged phosphorus groups allows for a slow depletion of the exchanged silver. There is almost always a residual amount of exchanged silver left on the resin, except at higher temperatures, where the increased mobility of both the ions and the polymer backbone allow for a higher level of resin oxidation. Thus, the redox portion of the extraction of silver from solution does not reach a true equilibrium within 24 hours. Given enough time, the amount of resin oxidation may equal the total amount of silver absorbed from solution.

Post-Oxidation of the Resin

A more important factor in the kinetic runs, which was alluded to in the previous section, can be seen by considering the way in which the experiments were done. After the resin was contacted with the silver solution for a set time, the mixture (beads and solution) was poured into a fritted glass funnel, the silver solution forced through the frit, the resin quickly washed with about 50ml H_2O , and then eluted with 4.2M HNO_3 , followed by elution with water until neutral, and the resin analyzed for the change in $tot(OH)$. During the HNO_3 elution, yellow-brown vapors (NO_x) were generated from the silver being oxidized for removal from the resin. This gas evolution was fairly slow, which also means that during the elution, if the mobility of the silver ions was not fairly high, there would be a buildup of the ions inside the resin. This would allow for what shall be termed "post-oxidation"; that is, oxidation of the resin by silver (or, to be discussed later, by mercury) during

the nitric acid elution. Several of the kinetic runs were repeated twice, and a few of them up to four times because of an unacceptable level of scatter in the redox portion of the graph, and therefore in the ion-exchange portion, since it is simply the difference between the total amount absorbed and the amount absorbed due to the redox reaction because of post-oxidation. It is not apparent whether the fault of the scatter in the earlier graphs was due strictly to post-oxidation or to incomplete removal of all of the silver ions from the resin. It had been noticed with some resin samples that if they were allowed to remain in water overnight (after removal of the silver, followed by elution with H_2O until neutral) the resin had turned grey or black by the next morning, indicative of Ag^+ or Ag^0 in the resin. Thus, it was deemed imperative that the resin not be allowed to remain in water any longer than necessary after removal of the metal before the $\text{tot}(\text{OH})$ analysis was performed. This never entailed any longer than 6 hours, but is a major source of error.

Silver Cycling During the Ion-Exchange/Redox Reaction

There is one other phenomenon which occurs with silver extraction by the phosphinic acid resin, the effect of which can be seen in Figure 15 (page 70). As originally planned, the kinetic studies were to be done at 0°C , 15°C , 30°C , and 60°C . The lowest temperature obtainable with the apparatus being used (a multipoint stirrer and water bath were set up in a walk-in coldroom) was 6°C (2°C on the day the first Ni^{2+} work was done, but at a constant 6°C thereafter). Therefore, 6°C was settled upon as the low temperature. The high temperature of 60°C revealed a very interesting problem: This temperature was apparently high enough to be above the

activation energy for the oxidation of Ag° by either the nitric acid in the solution, or by the nitrate ion itself. There was a noticeable pressure buildup in the 60°C samples during the contact, and enough yellow-brown vapor to be visible was released when the container was opened. What had happened was that the silver was cycling, allowing for a higher amount of oxidation than there was silver absorbed. This cycling was also noticed to some extent at 45°C with the lower pH's, although none of the NO_x vapors were observed at this temperature.

Although there were no studies done to determine the temperature at which cycling of the metal becomes important, a test was done by stirring Ag° in 1M HNO_3 (pH=0) at 30°C and at 60°C for 17 hours to determine whether the metal is oxidized under these conditions. Out of 10 mequiv of Ag° , at 30°C only 0.02 mequiv were present in solution as ions, the rest remaining as Ag° . This amount is so low as to be well within the experimental error of the technique (Volhard titration), and it can therefore be concluded that there is no oxidation of silver after 17 hours at 30°C in 1M HNO_3 . Identical results were obtained at 45°C . At 60°C , 35% of the Ag° was oxidized (out of 10 mequiv Ag° originally present, 3.52 mequiv were present in solution as ions), showing that at 60°C , over-oxidation of the resin is indeed due to cycling of the silver. This effect is probably even more prominent inside the resin because of the finely divided state of the silver, whereas in these tests, it was in only relatively small pieces. Thus, in the microenvironment inside the resin, silver oxidation is also possible at 45°C , as is suggested by Figures 14a-c (page 69).

HNO₃ Oxidation of the Phosphinic Acid Resin

To assure that silver cycling, and not HNO₃ itself was responsible for the over-oxidation of the resin at higher temperatures and lower pH's, some of the resin was contacted with 4M HNO₃ for 24 hours at 60°C. After contact, the tot(OH) was found to be identical to the tot(OH) before contact. It can therefore be concluded that oxidation of the resin is due only to Ag⁺ (and, as will be discussed later, Hg²⁺). A series of HNO₃ contacts of the phosphinic acid resin were also performed at room temperature and at 30°C for 16 hours, the results of which are given in Table 15. It has also been suggested (by their explosive nature when held in a Bunsen burner flame)^{34,35} that the resins are probably nitrated when contacted with relatively concentrated nitric acid solutions at elevated temperatures.

It is a general observation that there is an increase in the tot(OH) after a resin is heated in solution. This is most likely due to the increased mobility of the polymer backbone at the higher temperature, which allows for reorganization of the polymer chain, and therefore slightly increases the functional group accessibility.

The Effect of Sodium Ions on the Ion-Exchange/Redox Reaction with Silver

The effect of adding Na⁺ to the solution can be seen in Figures 16b-d (page 71). The amount of ion-exchange which occurs at 30°C and comparable pH's in the presence of sodium ions (see Figures 13b-d; page 68 for silver extraction in the absence of sodium) is only slightly less than without sodium. There is a noticeable decrease in the amount of resin oxidation which occurs (5%-10% less).

Table 15

HNO₃ Oxidation of the Phosphinic Acid Resin

[HNO ₃]	Room Temperature				30°C			
	4	6	8	10	4	6	8	10
tot(OH) ^a	4.88	4.96	5.02	4.79	5.10	5.09	5.10	8.13

^a Resin used was PK-02-111; tot(OH)=4.97

The explanation for this is that in the solution composed of 3.8M NaNO₃ and 0.2M AgNO₃, the resin exchanges with sodium, even though it is much more selective toward silver. This is shown by only a slight decrease in the amount of silver absorbed, even with a sodium to silver ratio of 19:1, as well as by the competitive lowering of the rate (about 8 hours to attain equilibrium without sodium, and between 12-24 hours to reach equilibrium with sodium). This has also been shown to be true at tracer levels,³² where the phosphinic acid resin absorbed nearly all of the silver from solution, even with a Na⁺/Ag⁺ of 19:1 (and presumably in the absence of a redox reaction forcing the equilibrium). Since the sodium ions occupy exchange sites, the decreased amount of Ag⁺ on the resin lowers the probability of the requirement of two silver ions being in position for the reduction to occur, thereby hindering the reaction. The result, then, is a decrease in the amount of

metal reduction which occurs, and a corresponding decrease in the total amount of silver absorbed from solution (see Figure 21; page 76).

The Effect of Bead Size on Silver Kinetics

In order to further test the possibility of diffusion control on the rate of silver extraction by the phosphinic acid resin, 2% gel phosphinic acid resin of -80+100 mesh was contacted with silver solution at 30°C at pH's of 0, 1.5, 2, and 5. If there was diffusion limitation of the rate of extraction, then smaller beads should show a higher overall rate. It can be seen in Figures 17a-d (page 72) that the rate of silver extraction by ion-exchange and by the redox reaction are nearly identical to the larger -30+40 mesh resin. It can also be seen that the amount absorbed by ion-exchange is almost perfectly superimposable on the ion-exchange curve of the larger resin (at the same pH). The amount absorbed by the redox reaction, and therefore the total amount absorbed, is approximately 10% higher with the smaller beads.

Because of the nearly identical rates between the smaller and the larger beads, diffusion control is not operative under these conditions. The reason for the higher amount absorbed by the smaller beads is most likely due to better accessibility of the reactive sites. The smaller beads have a slightly higher primary acid capacity and tot(OH) than the larger resin, thereby placing the functional groups closer to each other. This would increase the tendency for the redox reaction to occur. Another possibility for the lower equilibrium value of silver absorbed with the larger beads compared to the smaller ones is that Ag^0 precipitates as the redox reaction occurs. The opportunity for lower accessibility of the exchange sites in the

core of the resin due to clogging by the silver metal is greater with the larger beads simply because the ions have farther to go to get inside the beads than in the smaller ones.

The Effect of Crosslink Level on Silver Kinetics

The crosslink level, as was shown on page 45, should have a significant effect on the rate of diffusion of ions in the resin. Viewing Figures 18a-b (page 73), which are -30+40 mesh 2% gel and 10% gel beads, respectively, at 30°C and a pH of 1.5, it is seen that the total amount of silver absorbed from solution, and its rate, are exactly the same between the two graphs. The curve for the redox reaction for the 10% gel resin (Figure 18b) is about 10% higher than for the 2% gel resin. It has been argued that the phosphinic acid resin with silver exhibits reaction-limited kinetics. It was also stated that during removal of the reduced silver from the resin, post-oxidation can occur. The reaction between nitric acid and the silver metal, especially as finely divided as it is in the resin, is quite vigorous. This should not be affected by the crosslink level of the resin, but the diffusion of the silver ions out of the resin should be. Therefore, while the redox-driven absorption of silver by the phosphinic acid resins is reaction rate limited, the removal of silver from the same resins is diffusion rate limited. Thus, the higher amount of silver absorbed by the redox reaction, considered along with identical performance between the two resins for total Ag^+ absorbed shows, along with the lack of any bead size effect on the kinetics, that silver absorption is reaction rate limited, while the oxidation and removal of silver from the resin is diffusion-limited.

The Effect of Porosity on Silver Kinetics

Further evidence for reaction-controlled silver absorption but diffusion-controlled removal of metal from the resin is obtained by using -30+40 mesh MR type beads with 5% and 10% crosslink levels (Figures 18c and 18d, respectively; page 73) at 30°C and a pH of 1.5 (2% MR beads are too fragile to use, and would be crushed from stirring during the contact, negating any particle size or even crosslink effects). The results of these contact studies are shown in Figures 18c-d (page 73). The total amount of silver absorbed from solution for both resins is the same as that for the 2% gel beads (note the difference in the y-axis). Equilibrium is reached with these resins in about 3 hours, as compared to 8-12 hours with the 2% gel resin under the same conditions. This is a result of the large increase in surface area of the MR beads compared to the gel beads. The higher surface area allows for much higher access to the functional groups, with a corresponding increase in the rate of absorption. Two runs were also done with -30+40 2% MR beads with smaller macropores due to the way the copolymer was synthesized, but these exhibit the same behavior as the -30+40 mesh gels, indicating that they are not truly macroporous (see Figure 19, page 74).¹⁴

The exceptionally high level of resin oxidation which occurred with the MR beads was a result of a very fast oxidation of Ag^0 during the condition after contact with the silver solution. As soon as the 4.2M HNO_3 contacted the beads, large volumes of NO_x were evolved. The rate of gas evolution was such that the beads were mixed into the solution about 8 inches above the bottom of the fritted funnel in which the conditioning was performed (the unperturbed resin bed depth was

about 0.25 inches). Diffusion of the silver ions out of the resin can not keep up with such a high rate of oxidation, and post-oxidation prevails, again showing diffusion-controlled kinetics during the conditioning.

The Combined Effect of Bead Size and Porosity on Silver Kinetics

Contact studies were also done with small beads (-80+100 mesh) with different crosslink levels (2% and 10% crosslinked). As with the other kinetic runs, there was no observable size or crosslink level effect that has not been noted previously (e.g, see Figure 19; page 74).

Kinetics of the Ion-Exchange/Redox Reaction with Mercury

The final set of kinetic studies were done using mercury rather than silver. Looking at Figures 20a-d (page 75), which are graphs of mercury at 30°C at pH 1 contacted with -30+40 gel phosphinic acid resins (2% gel, 10% gel, 5% MR, and 10% MR, respectively), it can be seen that the only one which does not exhibit over-oxidation is the 2% gel (Figure 20a), although it appears that if longer times had been used, the amount of mercury absorbed by the redox component would have exceeded the total amount absorbed from solution, since the resin oxidation increases steadily, and is almost at the same level as the total amount of mercury absorbed from solution. The other three graphs show a large amount of over-oxidation. Whereas with silver there must be two ions in the vicinity of the phosphorus in order for reduction to occur, with mercury, only one ion is necessary for oxidation of the resin. During conditioning, as the mercury was oxidized (the

oxidation of mercury was much more difficult than for silver: 8M HNO₃ was required to remove the mercury from the resin) it could immediately oxidize another phosphorus group if it came into close enough proximity to it. It was therefore decided not to continue with the mercury kinetics, as removal of the mercury from the resin could not be optimized to give reliable results.

Removal of Mercury from the Resin

As was mentioned, mercury was very difficult to remove from the resin. After 2 hours of elution with 8M HNO₃, the resin still had a slight silver-grey color (the resin does not turn black when contacted with mercury as it does with silver, but turns to a dark silver or grey color). This color becomes a little darker after sitting in water for a few hours. Sodium thioglycolate, thiourea, and EDTA solutions were used in order to attempt the removal of mercury from the resin, but with no better results than with the 8M HNO₃. A mass balance for mercury with the resin and solution also showed that some of the metal remained on the resin after conditioning.

Mercury Cycling During the Ion-Exchange/Redox Reaction

There was no attempt made to determine whether the large amount of resin oxidation occurred during the contact due to mercury cycling, or to post-oxidation during the conditioning. It was shown that mercury cycling occurs at 60°C by contacting a phosphinic acid resin with mercury at an $R_1=0.05$. In this experiment, there were four different mercury solutions used. Table 16 lists the solutions used

Table 16

Test for Mercury Cycling at 60°C
with the Phosphinic Acid Resin

Solution	pH	$\Delta_{\text{tot}}(\text{OH})$	mequiv required	% Absorbed by Redox ^a
$\text{Hg}(\text{NO}_3)_2/\text{NaNO}_3$	1	0.31	0.74	125%
$\text{Hg}(\text{NO}_3)_2/\text{HNO}_3$	0	0.48	1.15	194%
$\text{Hg}(\text{NO}_3)_2/\text{HNO}_3$	4	0.41	0.98	165%

^a 0.595 mequiv Hg^{2+} were originally present in each of the samples

and the results obtained. It is obvious from these results that the mercury is indeed cycling during the contact. Whether or not this is true at 30°C can not be concluded from the data, but it certainly can not be ruled out. It should also be mentioned that when there is competition for exchange sites (such as from Na⁺), the amount of resin oxidation decreases (compare the first and third entries in Table 16). Even though the lower pH should favor cycling, there is less due to the sodium ions which are present. This indicates that mercury ions must be accessed by the resin (either by ion-exchange or by coordination), for reduction to occur, and not just be near enough to the phosphorus.

Conclusion

It has been demonstrated that the rate of redox-driven silver extraction by phosphinic acid resins is reaction-controlled because of the need for two ions to be favorably positioned around the phosphinic acid group, as opposed to diffusion-controlled ion-exchange with nickel. Because it is a divalent ion, mercury exhibited a fast redox reaction during removal of the metal from the resin, which caused more of the resin to be oxidized than there was mercury in solution. This leads to the conclusion that the removal of mercury from the resin is diffusion-limited, diffusion being slower than the redox reaction between mercury and the phosphinic acid resin. Under conditions which favor reoxidation of the reduced metal (low pH and high temperatures), the metal cycles, thereby oxidizing more of the resin than the metal content of the solution would allow in the absence of cycling. The practical use of this resin in the selective removal of silver or mercury from solution would be best

aided by balancing the temperature (higher temperature will speed the reaction) and the pH of the solution (higher pH will help to limit the amount of cycling inside the resin).

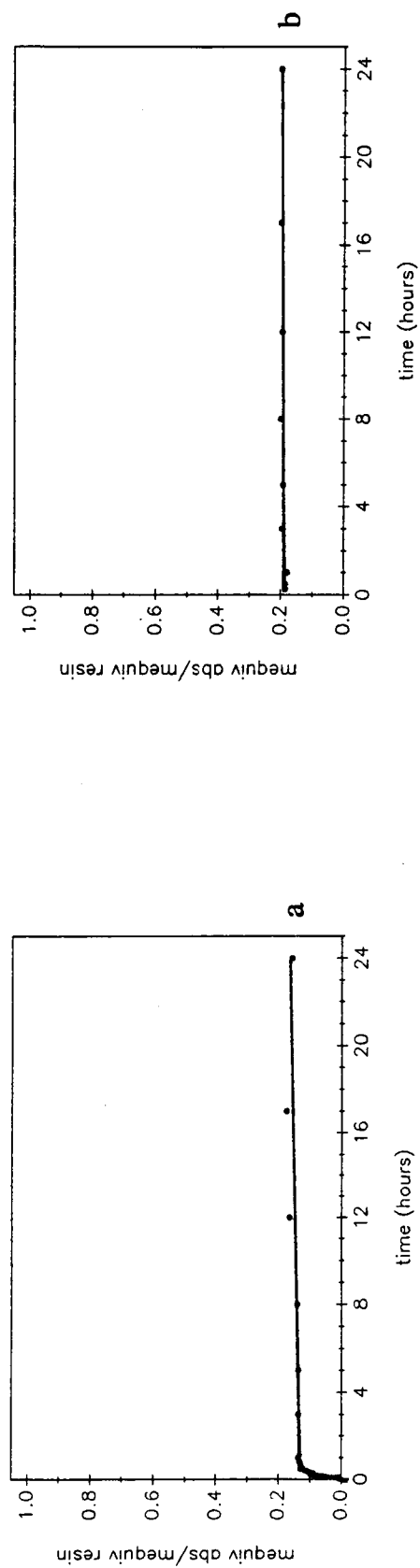


Figure 10. Nickel contacted with -30+40 2% Crosslinked Gel Phosphinic Acid Resin at 2°C (a) and 60°C (b) at pH=1.5

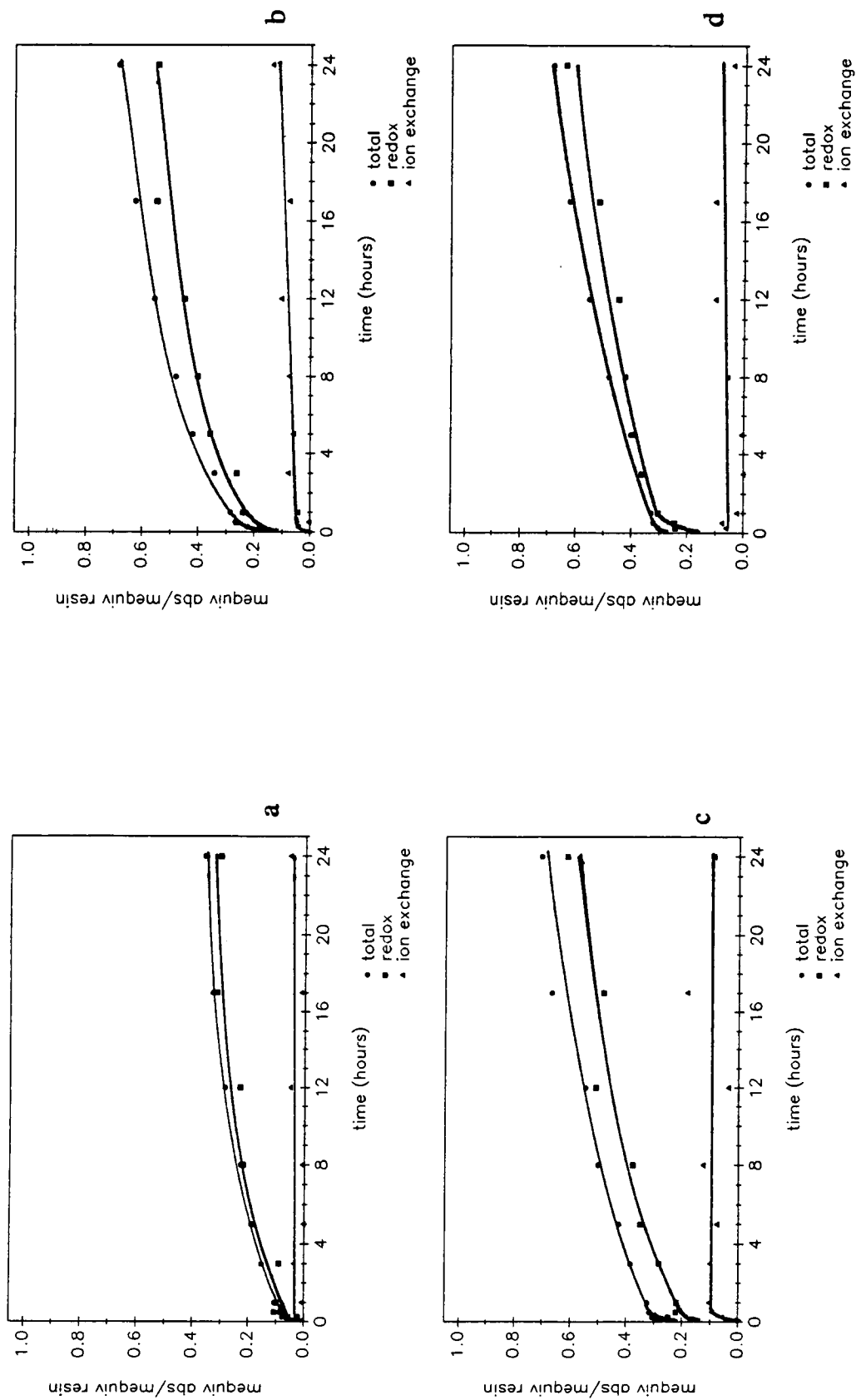


Figure 11. Silver Contacted with -30+40 2% Crosslinked Gel Phosphonic Acid Resin at pH=0 (a), 1.5 (b), 2.0 (c), and 5.0 (d)

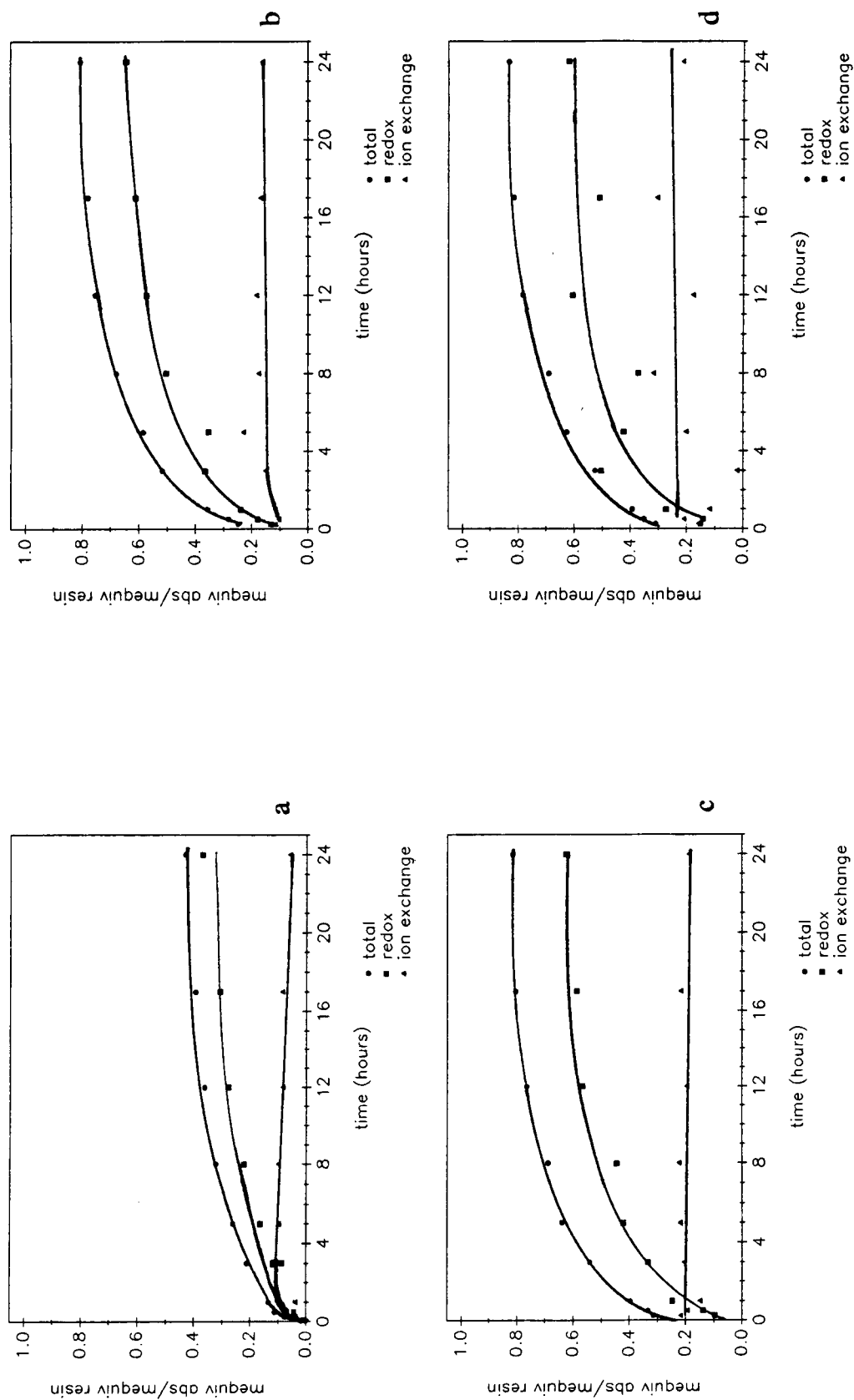


Figure 12. Silver Contacted with -30+40 2% Crosslinked Gel Phosphonic Acid Resin at 15°C at pH=0 (a), 1.5 (b), 2.0 (c), and 5.0 (d)

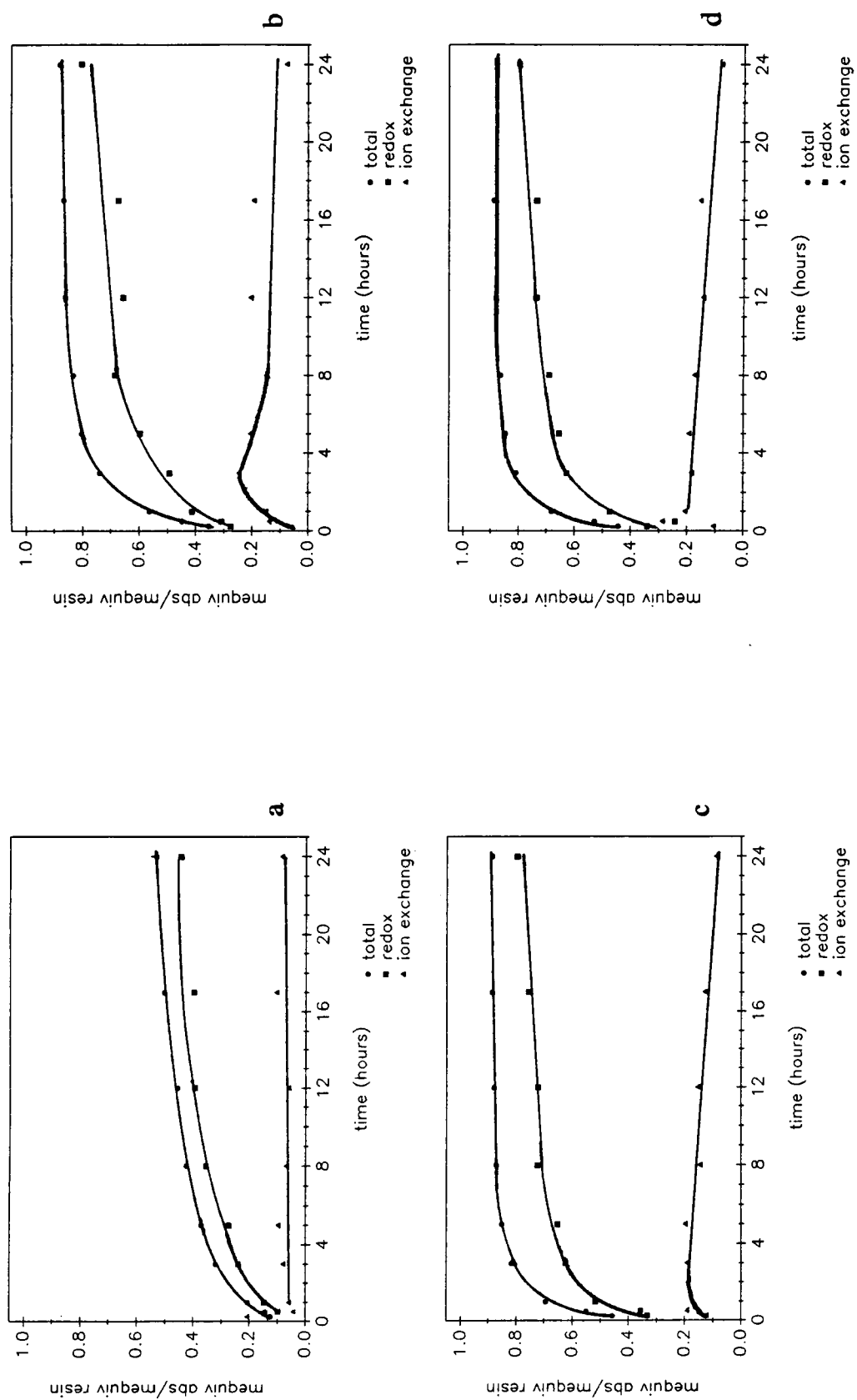


Figure 13. Silver Contacted with -30+40 2% Crosslinked Gel Phosphonic Acid Resin at 30°C at pH=0 (a), 1.5 (b), 2.0 (c), and 5.0 (d)

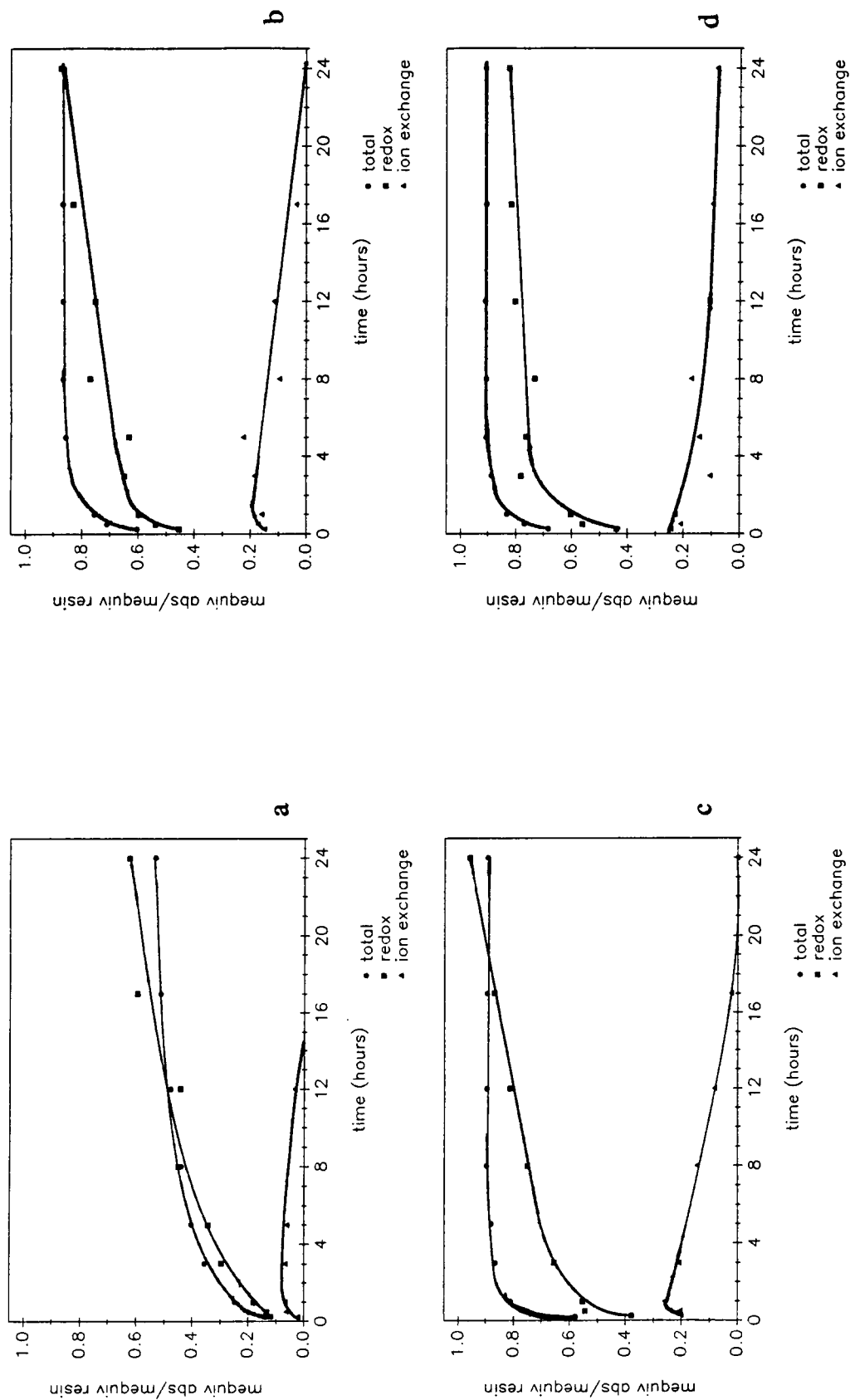


Figure 14. Silver Contacted with -30+40 2% Crosslinked Gel Phosphonic Acid Resin at 45°C at pH=0 (a), 1.5 (b), 2.0 (c), and 5.0 (d)

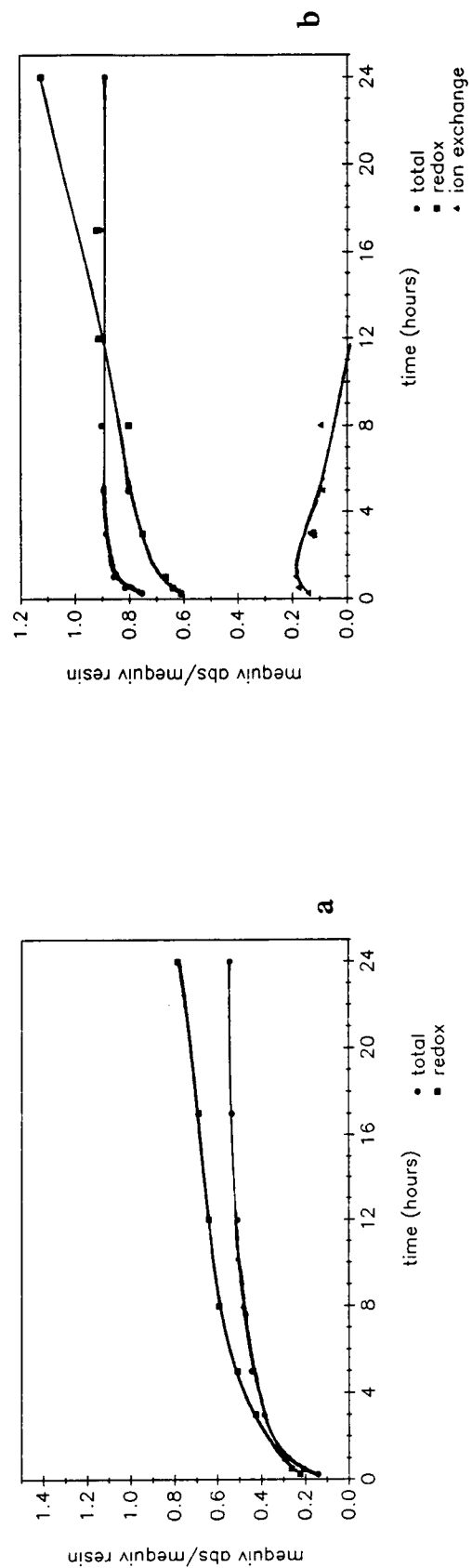


Figure 15. Silver contacted with -30+40 2% Crosslinked Gel Phosphinic Acid Resin at 60°C at pH=0 (a) and 2.0 (b)

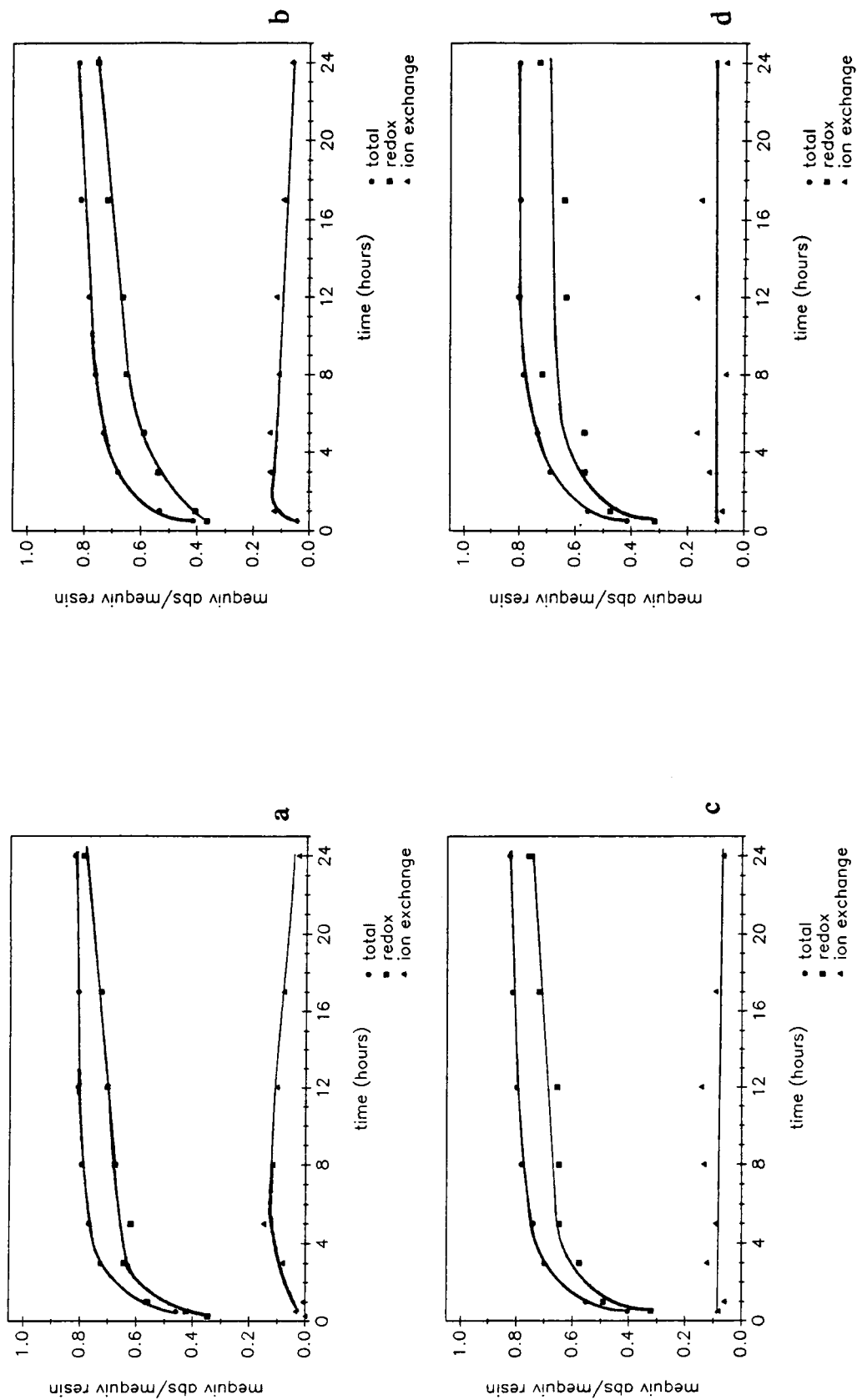


Figure 16. Silver contacted with -30+40 2% Gel Crosslinked Phosphonic Acid Resin at pH=1.0 (a); Silver (with Sodium) Contacted with -30+40 2% Crosslinked Gel Phosphonic Acid Resin at pH=1.5 (b), 2.0 (c), and 5.0 (d)

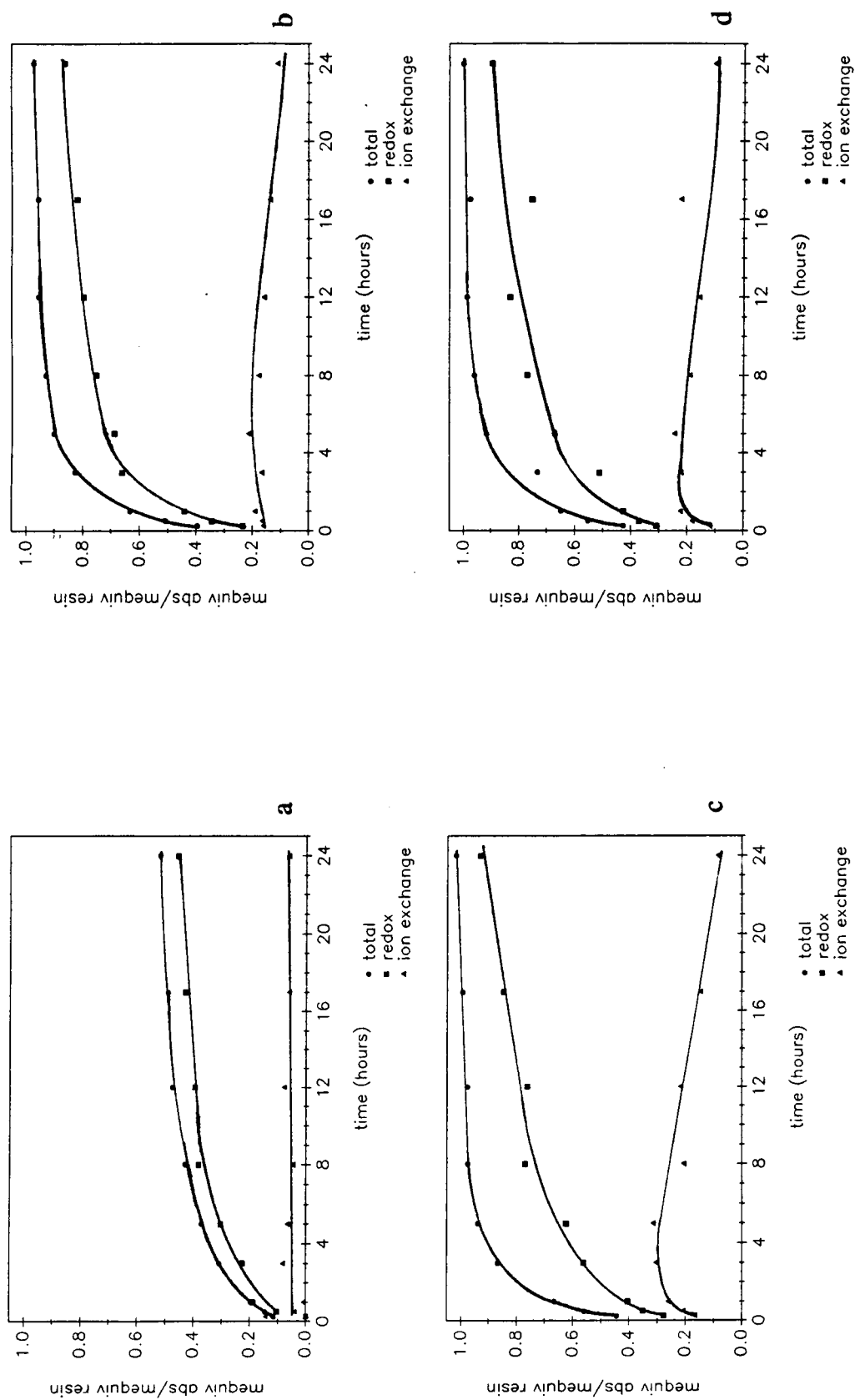


Figure 17. Silver Contacted with -80+100 2% Crosslinked Gel Phosphonic Acid Resin at 30°C at pH=0 (a), 1.5 (b), 2.0 (c), and 5.0 (d)

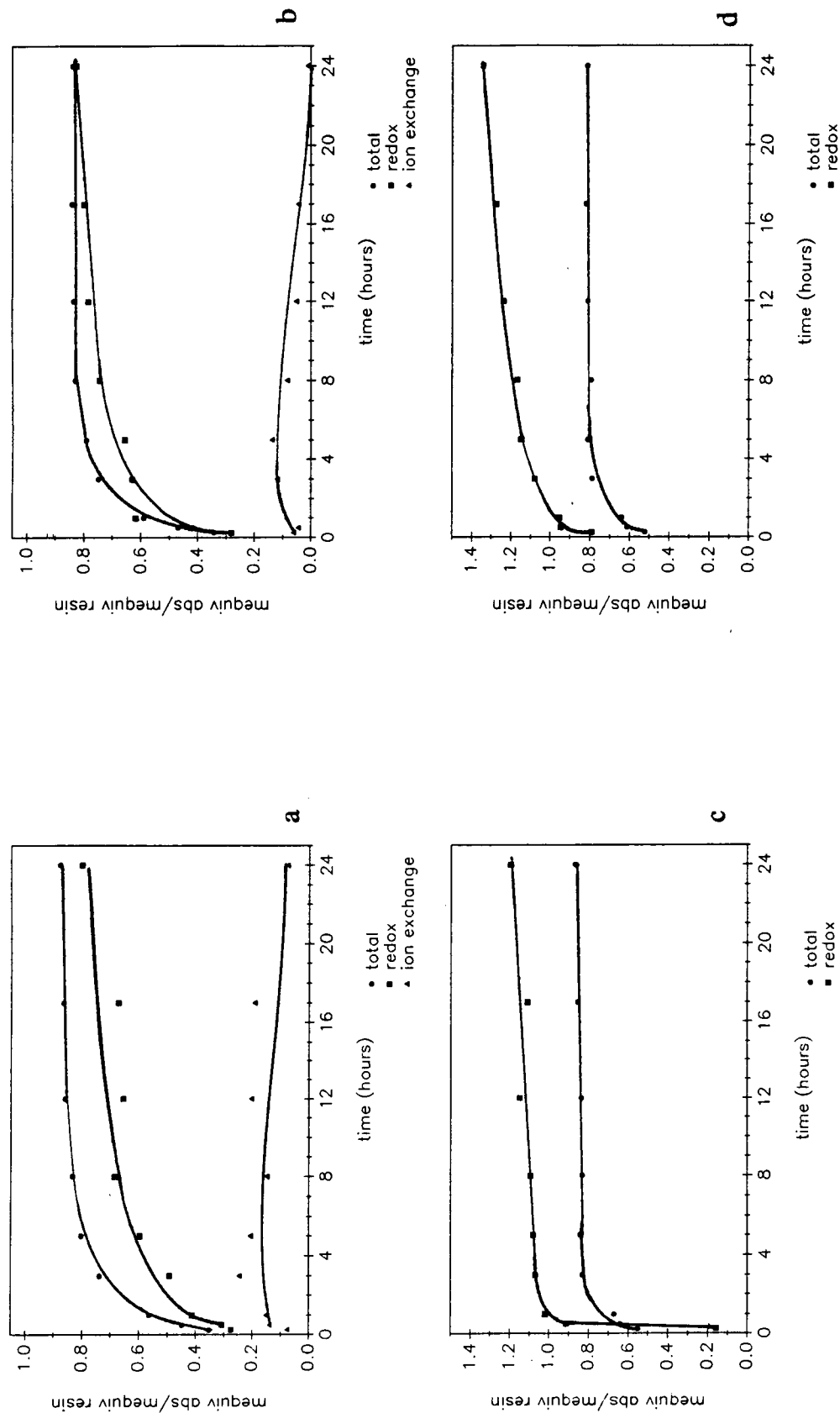


Figure 18. Silver Contacted with -30+40 2% (a), 10% (b) Crosslinked Gel and 5% (c), 10% (d) Crosslinked MR Phosphinic Acid Resins at 30°C and pH=1.5

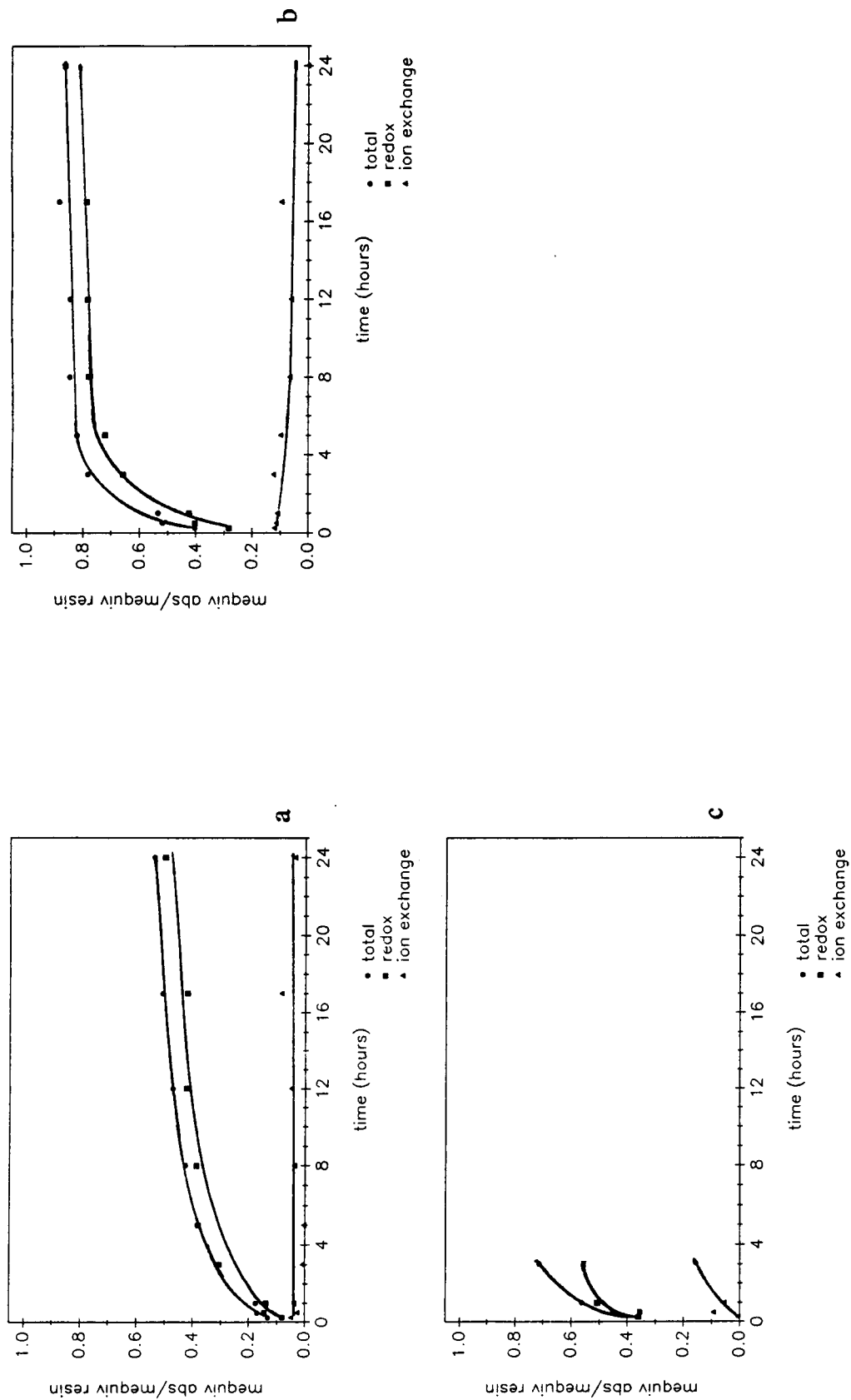


Figure 19. Silver Contacted with -30+40 2% Crosslinked Xerogel Phosphinic Acid Resin at 30°C at pH=0 (a) and 1.5 (b); Silver Contacted with -80+100 10% Crosslinked Gel Phosphinic Acid Resin at 30°C at pH=1.5 (c)

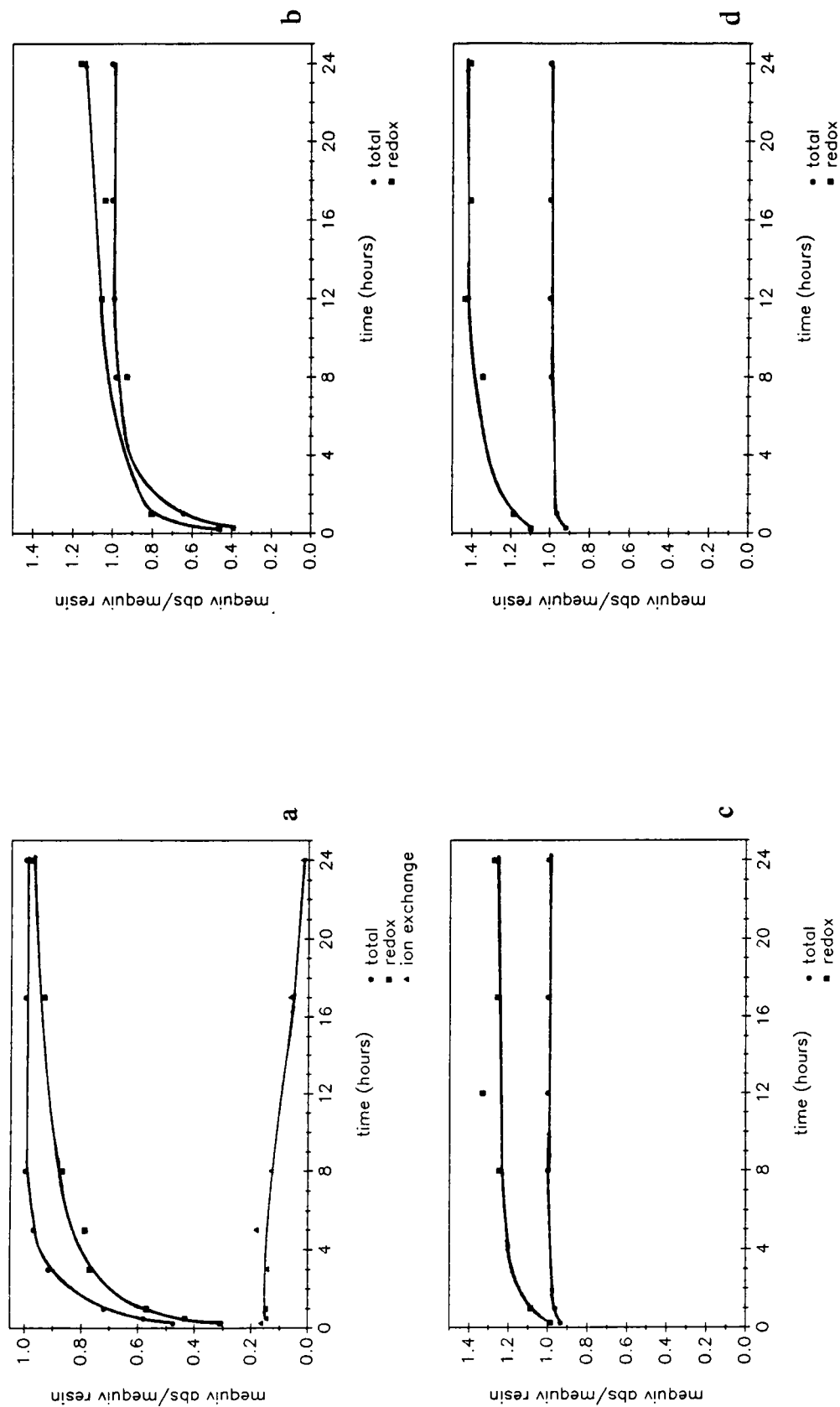


Figure 20. Mercury Contacted with -30+40 2% (a), 10% (b) Crosslinked Gel and 5% (c), 10% (d) Crosslinked MR Phosphinic Acid Resin at 30°C and pH = 1.0

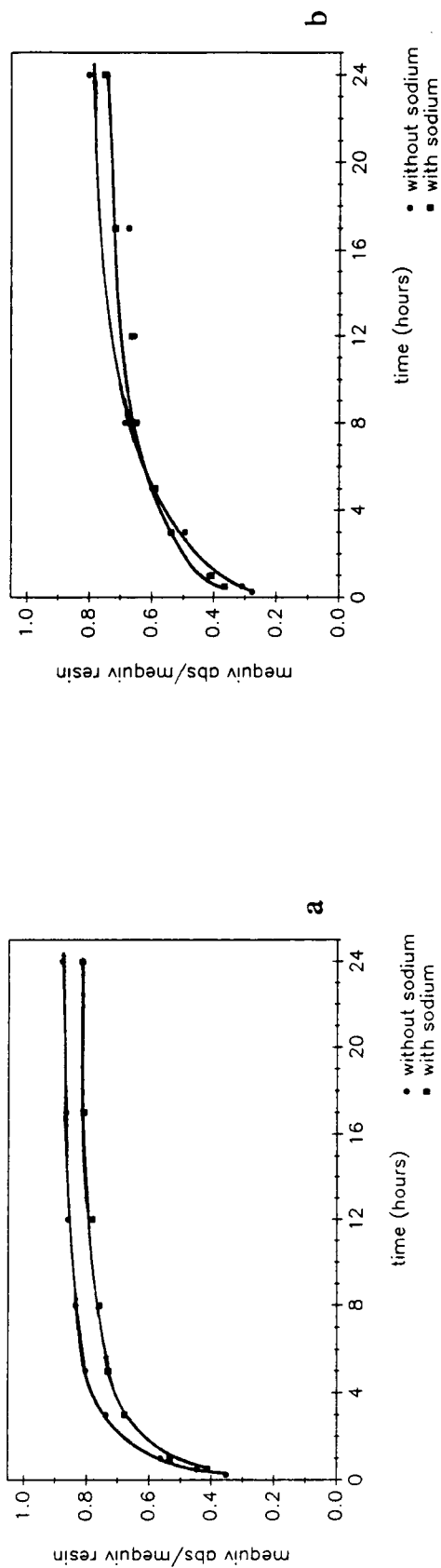


Figure 21. Comparison of the Total Amount of Silver Absorbed (a) and the Amount of Silver Absorbed by the Redox Reaction (b) With and Without Sodium

CHAPTER III

Regeneration of the Phosphinic Acid Resins

Introduction

The phosphinic acid resins have been shown to have exceptional selectivity for mercury and silver because of extraction by both ion-exchange and redox. In order to fully utilize this characteristic on a commercial basis, the resin should be capable of regeneration because of the high cost of a one-time use scheme. In a practical large scale application of the phosphinic acid resin for the removal of, e.g. mercury contamination from water, it would be packed in a column and the solution passed through the resin bed. The metal would then be removed from the resin with HNO_3 for disposal or reclamation. The ideal case would then be to pass an aqueous solution of a reducing agent through the column without having to disturb the packing in order to regenerate the resin.

This chapter deals with reduction of the phosphonic acid resin to a phosphinic acid resin in order to make the redox characteristics of the resin of practical commercial use, and not just a novelty, or of a very limited use as could follow from the high cost of a one-time use. The chemical literature is relatively devoid of information on the reduction of phosphorus-oxygen compounds. The reductions in this chapter, therefore, were exploratory in nature in order to find reducing agents which would work with the phosphonic acid resins.

Hydrogen Peroxide Oxidation of the Phosphinic Acid Resin

In order to assure that there were no effects on the reductions from possible incomplete removal of the oxidizing metal from the resin (either mercury or silver), a phosphonic acid resin was made by H_2O_2 oxidation of the phosphinic acid resin in 20% hydrogen peroxide. However, this reaction tended to give variable results. There was a $\text{tot}(\text{OH})$ after the reaction of more than $2 \times \text{tot}(\text{P})$ observed for some resins, indicating that all of the primary phosphinic acid groups were oxidized to phosphonic acid groups, and that some other type of acidic groups had also been formed. If the peroxide oxidation is refluxed for periods longer than 4-6 hours, the beads turn into a very soft, transparent jelly-like mass, especially when converted to the salt form, with a solids level as low as 4% (DW-02-119A), indicating possible polymer chain degradation by the peroxide. No attempt was made to determine the exact nature of the groups on these resins. By using milder conditions during the oxidation, a reasonable $\text{tot}(\text{OH})$ value is obtained. Even though the $\text{tot}(\text{OH})$ of the resin is reasonable when the peroxide oxidation is carried out under slightly milder conditions, it is not known to what extent there is polymer backbone degradation, or if there are functional groups present other than phosphonic and phosphinic acids. Table 17 lists some different H_2O_2 oxidized resins and their $\text{tot}(\text{OH})$ before and after the oxidation.

Sodium Borohydride Reduction of the Phosphonic Acid Resin

Sodium borohydride is a rather selective (i.e. fairly weak) reducing agent and is only of practical use in the reduction of aldehydes and ketones,³⁶ although it can

Table 17

Results of the Peroxide Oxidation of the Phosphinic Acid Resin^a

Resin Code	Reaction Temperature	Heat-Up Time (Hours)	Time at Temperature	tot(OH)	Increase in tot(OH)
PK-01-277	reflux	4	1	8.84	3.68
PK-02-033	reflux	4	1	9.03	3.87
PK-02-109A	reflux	1	-	7.30	2.14
PK-02-109B	reflux	1	1	9.01	3.85
PK-02-109C	reflux	1	4	9.33	4.17
PK-02-109D	reflux	1	6	9.07	3.91
PK-02-113A	room temp.	-	8	5.27	0.11
PK-02-113B	room temp.	-	16	5.43	0.27
PK-02-113C	room temp.	-	32	5.51	0.35
PK-02-113D	room temp.	-	64	5.93	0.77

^a The resin used was PK-01-244:

tot(OH)=5.16 Primary Acid Capacity=3.15

reduce phenolic esters containing electron withdrawing groups.³⁷ It is the ideal type of reagent sought for regeneration of the phosphinic acid resins, given its water solubility and relatively low price. A carbonyl group and a phosphoryl group may or may not be that similar as far as reduction is concerned, and it was therefore decided that borohydride reduction of the resin would be a reasonable first attempt for regeneration of the phosphinic acid resins.

The reduction was performed in 0.1M aqueous NaOH with a 10 to 1 ratio of hydride to phosphoryl groups, stirred at room temperature for 45 hours with the resin converted to the sodium salt form before reaction. After the reaction was finished, the resin was washed with water, and eluted with NaOH, H₂O, HCl, and H₂O. It was then analyzed for tot(OH). The analysis showed that there had been no reduction, the tot(OH) values being 9.47 and 9.81 before and after "reduction", respectively. This was a little surprising, since the resin was a light pink color in the sodium salt form before the reaction, but yellow afterwards, indicating that some type of reaction had occurred. The phosphonic acid is usually yellow in its acid form, but it would certainly have been deprotonated by the 0.1M NaOH in the reaction mixture, as shown by titration curves of phosphorus resins, and by the fact that the tot(OH) analysis is done in this concentration of base. The cause for the change in color was not investigated, but is interesting to note.

Sodium borohydride was also used on a phosphonate diethyl ester resin in order to see if the ester functionality would be reduced, -OR being a better leaving group than -OH. It should be noted at this point that there are two different types of ester resin: one is made from a vinylbenzyl chloride/DVB copolymer (VBC) by

quenching the tetrachlorophosphine intermediate of the Friedel-Crafts phosphorylation of with ethanol, and the other by esterifying a polystyrene phosphonic acid resin (see the section later in this chapter on esterification, starting on page 101). Therefore, the two ester resins differ in the way they are made, and also in the benzylic carbon separating the phosphorus group from the aromatic ring in the VBC ester, which is absent in the styrene ester resin (see figures 22 and 23). The ester resins were hydrolyzed by refluxing in concentrated HCl to cleave the ester to a phosphonic acid group (or, if reduction had occurred, to a phosphinic acid group) before the tot(OH) analysis. The results were the same as with the phosphonic acid resin previously discussed; there was no reduction (the tot(OH) was 7.08 and 7.13 before and after "reduction" for the hydrolyzed resin, respectively). NaBH_4 is apparently too weak a reducing agent to be of any use in the regeneration of the phosphinic acid resins.

Sodium Ascorbate Reduction of the Phosphonic Acid Resin

Sodium ascorbate is known to reduce Ag^+ in aqueous ammonia,³⁸ and thus it was thought possible that it would have the same effect on the phosphonic acid resin. It has the advantages of being very readily available, inexpensive, environmentally benign, easy to work with, and water soluble. Three reactions were done using sodium ascorbate with the peroxide oxidized phosphonic acid resin. Two of these were at reflux, while the third was at room temperature, all with a ratio of ascorbate/phosphoryl groups of about 12. All were in water acidified with HCl to a pH of about 1, and the reactions were allowed to stir overnight. Ascorbic acid is

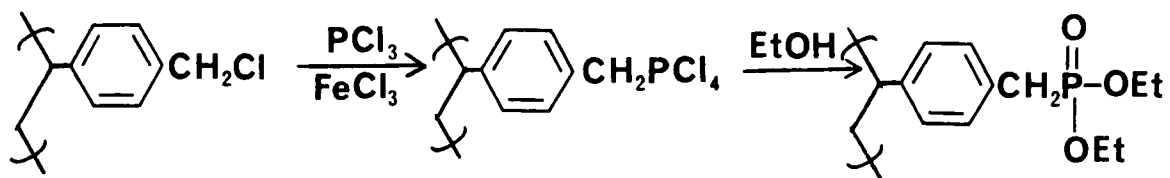


Figure 22. Synthesis of the VBC Phosphonate Diethyl Ester Resin

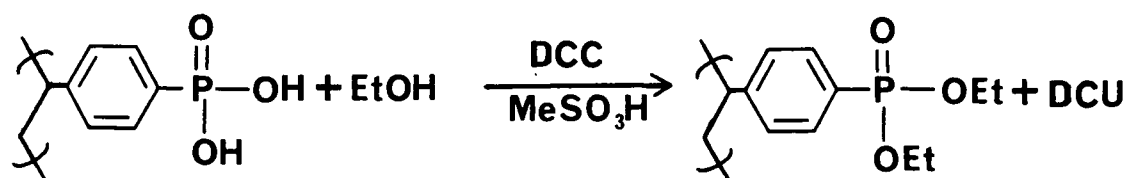


Figure 23. Synthesis of Styrene Phosphonate Diethyl Ester Resin with DCC

heat sensitive, and decomposed in the acid solution, as shown by the solution having turned dark brown-black by morning. The room temperature reaction was also dark colored by morning, but not to the extent to which the higher temperature reactions were. None of the three reactions showed any significant amount of reduction of the resin, the results being (before and after reaction, respectively): 9.47 and 8.72; 10.08 and 10.12 for the reflux reactions, and 10.08 and 9.53 for the room temperature reaction. Because of these results, no more was done with ascorbate.

Sodium Hydride Reduction of the Phosphonic Acid Resin

The need for a stronger reducing agent was the reason for the use of NaH in the attempted reduction of the phosphonic acid resin, although the anhydrous conditions necessitated by hydride reductions were viewed as a drawback for the stated purpose of the project. These reactions were done concurrently with the LAH reductions discussed in the next section. They were done in THF and in dioxane, because of the ability of these solvents, if not to swell the resins well, to at least to not collapse the polymer network. The resins used were a peroxide oxidized phosphonic acid resin in the sodium salt form, a VBC phosphonic acid resin (made by Friedel-Crafts phosphorylation of the VBC/DVB copolymer, which produces a phosphonic acid resin directly, and not a phosphinic acid resin as is obtained when the starting copolymer is polystyrene, see figure 22), and a VBC phosphonate diethyl ester resin.

Of the four reduction attempts made using NaH, all showed some reduction, with a VBC phosphonic acid resin being reduced quantitatively (see Table 18).

Thus, it was shown that the phosphoryl group can be reduced by hydride type reducing agents.

Carboxylic acids are notoriously difficult to reduce, with only a very limited number of reagents suitable for the purpose. If an analogy can be made between a carboxyl group and a phosphoryl group, then the phosphoryl group should be equally as hard to reduce, if not more so due to its higher charge in basic media. The difficulty with which the phosphoryl group is reduced is indicated by the fact that the reaction required a 25 to 1 ratio of hydride to phosphoryl group.

Lithium Aluminum Hydride Reduction of the Phosphonic Acid Resin

A stronger hydride type reducing agent was used because of the results with NaBH_4 . This was LiAlH_4 (LAH), and is known to reduce almost any type of carbonyl group.³⁶ It was thought, therefore, that LAH would reduce the phosphoryl group as well. It was necessary to thoroughly dry the resin before contact with the LAH, which was done by azeotroping the water out with heptane. This is rather harsh treatment of the resin, though, and there is a noticeable size decrease after drying compared to the water-wet resin. This causes severe accessibility problems, and if a very good swelling solvent is not used, the functional groups inside the resin are effectively isolated from any reagents in solution.

There were two different types of resin used with this reduction method, specifically, a phosphonic acid resin (synthesized by peroxide oxidation of a phosphinic acid resin) in the sodium salt form, and a VBC phosphonate diethyl ester resin, as was used for the attempted reduction with NaBH_4 . Both reductions were

Table 18

Regeneration of the Phosphinic Acid Resin with Sodium Hydride

Resin Code	Ratio ^a	Reaction Time (Hours)	tot(OH) ^e Before Reduction	tot(OH) ^e After Reduction
PK-01-239 ^b	3	42	8.46	7.57
PK-02-253 ^c	3	27	8.00	6.70
PK-02-007D ^c	20	72	7.06	6.63
PK-02-019 ^d	25	20	5.83	2.39

^a Ratio of hydride/phosphoryl groups

^b peroxide oxidized phosphonic acid resin, sodium salt form

^c VBC ester resin

^d VBC phosphonic acid resin, sodium salt form

^e after hydrolysis for the ester resins

allowed to react for 7 days. The reactions were set up in ether with a hydride/phosphoryl group ratio of 1.02 and 1.51 for the sodium phosphonate and the phosphonate diethyl ester resins, respectively. Neither of the resins were reduced, as was shown by the tot(OH) analysis, which was 7.18 and 7.85 mequiv/g for the sodium phosphonate resin before and after reaction, respectively, and 7.06 and 7.34 mequiv/g for the hydrolyzed diethyl ester resin before and after reaction, respectively. The reason for the lack of reduction of the sodium phosphonate resin may be due to the non-swelling conditions of the reaction (ether is too non-polar to swell the resin, as was noticed by the lack of any size change of the heptane azeotroped resin in the ether or during the reaction), but is more likely of chemical origin, since the ester resin reduction was done in dioxane, which is at least a moderately good swelling solvent for the polar phosphorus resins, and swells the ester resin noticeably.

It has been shown that the phosphoryl group is not reduced by LAH, but that when CeCl_3 is used in conjunction with a mixture of LAH and NaBH_4 in THF, the reduction gives reasonable results (62-96 % isolated yield, figure 24).³⁹ It is also stated³⁹ that the reaction proceeds equally well without NaBH_4 . The compounds used, however, may or may not be directly comparable to the type of phosphorus groups on the resins because they contain only P-C bonds (other than the phosphoryl functionality itself), while the resins are all phosphorus acids or derivatives thereof, and contain P-O bonds. It may be noteworthy that the one compound in the paper which did contain a P-O bond (a phosphinate ester) gave the lowest yield (figure 24).

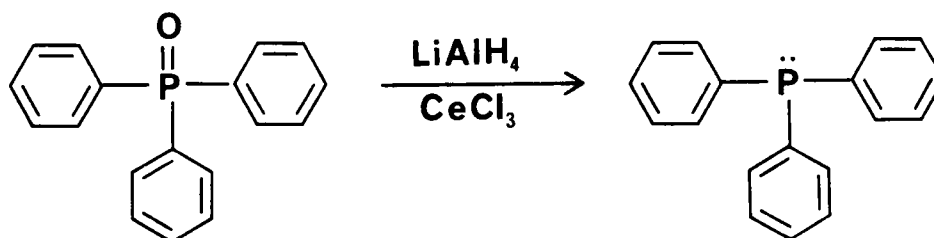


Figure 24. Deoxygenation of the Phosphoryl Group by CeCl_3/LAH

When the combination of $\text{CeCl}_3/\text{NaBH}_4/\text{LAH}$ in THF (which is about as good a swelling solvent for the resin as is dioxane) was reacted for 48 hours at reflux with a sodium phosphonate resin in a $\text{Ce}^{3+}/\text{LAH}/\text{NaBH}_4/\text{phosphoryl}$ group ratio of about 3/3/3/1, there was no reduction (tot(OH) before and after reaction was 9.30 and 9.61, respectively). The probable reason for the apparent lack of reactivity of the resin with this combination may be due to the fact that the phosphonate group, being in the sodium salt form already, is too highly polar for hydride to add to, since the phosphonate group is dianionic, and would require the formation of a trianion if the reaction proceeds analogously with the LAH reduction of carboxylic acids.⁴⁰ Another possible reason for the apparent lack of reactivity of the group also has to

due with the polarity of the resin, but as regards the ability of THF to swell it. THF typically causes an unionized phosphorus based resin to swell (relative to its air-dried volume) only by a factor of about 1.1 to 1.2. The large increase in polarity of the ionized resin decreases the ability of THF to swell it. The cause for the lack of reduction, then, is probably due to inaccessibility of the functional groups within the resin. This can not be unequivocally stated, since there were no model compound reactions done to verify whether the sodium phosphonate group is reduced by this combination of reagents.

When the phosphonic acid resin used in the previous experiment is esterified to give a polystyrene-based phosphonate diethyl ester resin (see the section on DCC esterification later in this chapter), there is reduction of the phosphonate group. The reduction of the polystyrene-based ester resin was set up in THF and refluxed for 45 hours with a Ce^{3+} /LAH/phosphonate group ratio of 1.6/9.7/1. There was quantitative reduction of the phosphonate group, as evidenced by a $\text{tot}(\text{OH})$ after hydrolysis of the ester which was identical to the $\text{tot}(\text{P})$, as shown in Table 19.

Sodium Metal Reduction of the Phosphonic Acid Resin

While the LAH reduction work was in progress, other reduction methods were being investigated. NaBH_4 , NaH , and LAH are all hydride reducing agents. Another class of reducing agents is that which operates via an electron transfer mechanism. Dissolving metal reductions are of this class of reactions,⁴¹ and here specifically, reduction using sodium metal. Thus, the Bouveault-Blanc procedure was used to attempt reduction of a peroxide oxidized phosphonic acid resin. This reaction was set up by adding an 8:1 excess of sodium metal to the heptane azeotroped

Table 19

Reduction of the Styrene Phosphonate
Diethyl Ester Resin^a by LAH/CeCl₃

Before Reduction			tot(OH)
tot(OH)	tot(OH) ^b	tot(P)	After Reduction
9.30	0.53	4.58	4.85

^a the resins used were, from left to right, PK-02-140, PK-02-142, PK-02-171A

^b After esterification

phosphonic acid resin (in the sodium salt form) in ethanol, and the mixture stirred at room temperature overnight (18.5 hours). There was no reduction effected by this reagent (tot(OH) before and after reaction was 7.18 and 7.37, respectively). This is most likely because there are two reaction pathways for the sodium itself: reduction of the phosphoryl group (the feasibility of which is not actually known) and reaction with the ethanol to produce hydrogen and sodium ethoxide. Since the Bouveault-Blanc reaction is known not to proceed via reduction by hydrogen produced from the reaction between sodium and ethanol, but by transfer of an electron to a carbonyl group⁴² (which, again, should be similar to the phosphoryl group, based on

their similar structures), the problem is apparently one of relative reaction rates. The sodium reacts with the ethanol before electron transfer can occur. Thus, while the procedure is effective in homogeneous or well stirred heterogeneous liquid mixtures, diffusion of the reagent into the resin is too slow to allow reaction before the sodium is consumed by the ethanol.

Because of this, the reaction was modified by using toluene, which is an inert solvent. The resin used was a peroxide oxidized phosphonic acid resin converted to the sodium salt form, with water being removed from the resin afterward by ethanol elution. The reaction was set up using a Na° /phosphoryl group ratio of 12. The reaction was allowed to reflux for 4 hours before being quenched with water. Analysis of the resin showed that, with a $\text{tot}(\text{OH})$ before and after reaction of 7.18 and 7.36, respectively, there was no reduction. It was observed during the reflux that the sodium stayed in relatively large droplets (it is molten at the reflux temperature of toluene, but the drops of Na° were not dispersed in the solution). Another reaction was set up, but with the modification of forming a fine sodium "sand" first. This was accomplished by placing Na° in toluene and heating to reflux with vigorous overhead stirring. The stirring was continued as the solution was allowed to cool to below the melting point of sodium (98°C). The resin was then added to the solution, and the heat turned back on to reflux the mixture for 4 hours while still being stirred rapidly. With this procedure, the solution turned a lavender color, indicative of free electrons in solution,⁴² but turned to a murky grey color upon the addition of the quench water. In spite of this, however, there was no reduction of the resin (the $\text{tot}(\text{OH})$ before and after reaction was 7.36 and 7.62, respectively). The reaction was also tried with the addition of ethylenediamine, with no better results.

Since the presence of free electrons was indicated, there are two possible reasons for the lack of reduction of the resin: the phosphoryl group (or at least the phosphonic acid group) is inherently unreactive towards reduction by Na° , or the electrons were not getting into the resin (the usual problem of accessibility). To try to increase the movement of the electrons into the resin, the reaction was repeated, but with the addition of an electron transfer co-reagent; this being naphthalene. Sodium naphthalide, in inert (non hydroxylic) solvents, is well known to be capable of the formation of a solution which has a fairly high concentration of free electrons (which actually exist as the naphthalide radical anion).⁴² Thus, when a solution of either a peroxide oxidized phosphonic acid resin (converted to the sodium salt) or a VBC phosphonate diethyl ester (both eluted with ethanol to remove water) in toluene, THF, or dioxane containing naphthalene has Na° added to it, the characteristic dark green color⁴² of sodium naphthalide is observed.

Several of these reactions were done in toluene. Though this is a good solvent for the reaction itself, it is not a swelling solvent for the resins, and therefore did not allow for their reduction. Thus, more polar solvents were used (THF and dioxane) in order to effect swelling of the resins. Some reduction was observed with the more polar solvents, indicating that the phosphoryl group can be reduced by electron transfer type reducing agents, and also reinforcing the importance of functional group accessibility (see Table 20 for results).

Two reactions were attempted using Zn° as the reducing agent. Both were done on a peroxide oxidized phosphonic acid resin in water, with NaOH added to one (the final pH was 14), with a Zn° to tot(OH) ratio of 10 to 1. Both showed

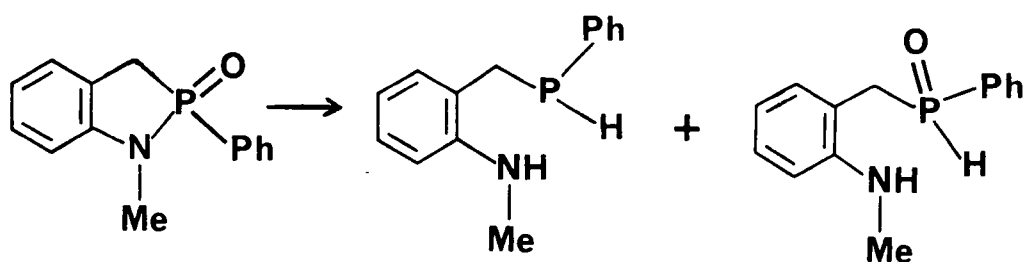
some reduction, the reaction with NaOH added doing better (the tot(OH) before reaction was 9.03 for both, while the tot(OH) after reaction was 7.89 and 8.63 for reactions with and without NaOH, respectively). No more work was done with zinc.

Trichlorosilane Reduction of the Phosphonic Acid Resin

Because of the high reactivity of LAH, as well as its price, another reducing agent was sought which would be more commercially applicable, even though LAH performed very well in combination with CeCl₃. This reagent was HSiCl₃ (trichlorosilane, which is an extensively used industrial chemical for the production of transistor grade silicon),⁴³ and efficiently reduces many types of carbonyl compounds, especially the benzoate group. It has also been used for the "reductive silylation",⁴³ (also termed hydrosilation⁴⁴ and ionic hydrogenation⁴⁵) of the phosphine oxide form of polymer-supported Wittig reagents to regenerate the phosphine.⁴⁶ It is known to be capable of the deoxygenation of many other types of phosphine oxide compounds as well.^{47,48,49,50}

It has been shown that when 1-methyl-2-phenyl-2,3-dihydro-1*H*-1,2-benzazaphosphole 2-oxide is treated with HSiCl₃ in refluxing benzene, two reduction products were obtained. It is worth noting that LAH reduction gave the same two compounds (see figure 25).⁵¹

If the phosphorus based resins resemble the above compound closely enough in reactivity, which is reasonable to assume based on the general structure around the phosphorus atom, then it should be possible to reduce them to a phosphinic acid from a phosphonic acid (or to a phosphinate ester from a phosphonate ester). Fritzsche⁵² has also shown that the reduction of phosphonate diesters and phosphinic



HSiCl₃

20%

61%

LAH

60%

30%

Figure 25. Reduction of a Benzazaphosphole 2-Oxide by HSiCl₃ and LAH

acids to give phosphines proceeds in reasonable yield with trichlorosilane. It was therefore reasonable to assume that the reaction should work equally well with a phosphonic acid resin. The results of all of the silane reductions are given in Table 21.

The first two reduction attempts using HSiCl₃ on the phosphorus resins were done on VBC diethyl ester resins. These reactions were both run at reflux for 170 hours in benzene with N,N-dimethylaniline (referred to from here as DMA) added. The addition of an amine has been shown to assist the reaction,^{43,50,53} and has therefore been used in all of the silane reductions here. One of the resins was in the acid form (the VBC diester resins always have a small amount of acid functionality present) and the other was converted to the sodium salt form. Both

Table 20

Results of Sodium Naphthalide Reductions of the Phosphonic Acid Resins

Resin Code	Solvent	Ratio ^a	Reaction Time (Hours) ^c	tot(OH) Before Reduction	tot(OH) After Reduction
PK-01-234A ^b	toluene	14:14:1	46	7.30	7.41
PK-01-234B ^b	toluene	14:29:1	46	7.30	7.42
PK-01-236B ^b	toluene	30:20:1	44	7.30	7.62
PK-01-283 ^c	THF	40:15:1	42	7.06	6.59
PK-02-007C ^c	dioxane	43:7:1	72	7.06	4.96
PK-02-016A ^c	dioxane	37:6:1	72	8.34	7.53
PK-02-016B ^d	dioxane	37:6:1	165	5.83	4.95

^a Ratio of Na⁺/naphthalene/phosphoryl groups

^b Peroxide oxidized phosphonic acid resin, sodium salt form

^c VBC phosphonate diethyl ester resin

^d VBC phosphonic acid resin

^e all at reflux, except for PK-02-007C, which was at room temperature

Table 21

Results of the Trichlorosilane Reductions of the Phosphorus Resins

Resin Code	Solvent	Ratio ^a	Resin Type	Reaction Temperature	Reaction Time (Hours)	Beginning tot(OH)	Final tot(OH)
PK-01-281	ØH	1.5/1.5/1	A	90°C	170	7.06	5.76
PK-01-282	ØH	1.5/1.5/1	B	90°C	170	8.34	7.19
PK-02-020A	ØH	1.5/1.5/1	A	90°C	170	5.83	4.38
PK-02-020C	ØH	3/3/1	A	90°C	170	5.83	3.40
PK-02-020D	Ø(CH ₃) ₃	3/3/1	A	150°C	170	5.83	4.49
PK-02-023	ØH	10/10/1	A	90°C	170	5.83	3.69
PK-02-026B	ØH/THF	10/10/1	A	80°C	168	5.83	2.79
PK-02-028	ØH	10/10/1	A	90°C	17	5.83	3.16
PK-02-080A	CH ₃ CN	10/20/1	A	85°C	17	5.83	4.26
PK-02-080B	CH ₃ CN	10/20/1	C	85°C	17	9.03	8.71
PK-02-131B	ØH	10/10/1	A	90°C	17	3.18	2.40
PK-02-136A	ØH	3/3/1	A	90°C	17	3.18	2.58
PK-02-131A	ØH	10/10/1	E	90°C	17	7.50	5.06
PK-02-148A	ØH	5/5/1	E	90°C	17	7.50	4.73
PK-02-148B	CH ₃ CN	5/5/1	E	80°C	17	7.50	5.53
PK-02-148C	ØH/THF	5/5/1	E	80°C	17	7.50	4.43
PK-02-153A	ØH/THF	5/5/1	E	80°C	17	7.50	5.88
PK-02-153B	ØH/THF	5/5/1	F	80°C	17	8.05	8.45
PK-02-153C	ØH/THF	5/5/1	F	80°C	17	8.67	8.97
PK-02-164	THF	5/5/1	G	85°C	17	9.79	6.70
PK-02-166	THF	5/5/1	G	85°C	17	7.50	6.11

^a ratio of HSiCl₃/DMA/tot(OH), based on the hydrolyzed resin

A VBC phosphonic acid resin

B VBC phosphonic acid resin, Na⁺ salt form

C peroxide oxidized phosphonic acid resin

D VBC diethyl ester resin

E "C" followed by DCC esterification

F metal oxidized (Ag⁺ or Hg²⁺) phosphonic acid resin

G "F" followed by DCC esterification

were heptane azeotroped to remove water, and were set up using a silane/DMA/phosphorus ratio of 1.5/1.5/1. The reaction was halted by washing the beads with benzene, followed by THF. The beads were then fully conditioned, hydrolyzed in refluxing HCl to cleave the ester (where applicable), and analyzed for tot(OH). There was some reduction of both of the resins, but it was not quantitative.

It has been found that the reaction proceeds better with the addition of an amine. Although the exact mechanism of the reduction is dependent upon both the type of compound being reduced and the particular amine which is added, it has been shown that the silane is deprotonated by the amine. The fairly electropositive anion which is formed attacks the oxygen of the phosphoryl group, displacing the phosphorus. Thus, the silane gives the same final result as a hydride reduction, but is a much milder reagent, and can be used in almost neutral conditions.

Several other silane reductions were performed under the same conditions, but with a VBC phosphonic acid resin, with similar results. Upon increasing the ratio of HSiCl_3 /DMA/phosphorus to 3/3/1, better results were obtained. At this point, the method of halting the reaction was also changed. Instead of washing the resin with benzene (after removing the reaction mixture), 30% aqueous NaOH was added directly to the mixture after cooling. The method of quenching the reaction had no effect on the results of the reduction (the resin used was DQ-02-245B: tot(OH)=5.83 before reduction, 3.40 (PK-02-020C) and 3.69 (PK-02-025A) for H_2O and 30% NaOH quenches, respectively, after reduction).

It can be seen from Table 21 that the silane reduction does not give consistent results. Some general conclusions can be drawn, though. A mole ratio

(for a $\text{HSiCl}_3/\text{DMA}$ ratio of 1) of reducing agent to phosphorus of at least 3 is required for the reduction to give reasonable yields, but an excess over this does not help the reaction. There is no noticeable temperature effect within the temperature range used (80°C to 150°C), but there does appear to be a dependence on the solvent polarity. The more polar solvents help the reaction. This is most likely due to the ability of THF to swell the resins compared to benzene or acetonitrile. Even with THF, though, there is a high degree of variability in the results of the reaction. It can be seen from the small molecule silane reactions mentioned earlier that the yields are not always that good, nor does the reaction necessarily proceed cleanly.

There is literature precedent for P-C bond cleavage in the deoxygenation of the phosphoryl group.⁵⁴ An investigation was done, therefore, to determine whether the lower tot(OH) after the silane reactions was due to reduction of the phosphoryl group, or to the loss of phosphorus from the resins. It is apparent from Table 22 that the P-C bonds on the resin retain their integrity. It should be noted here that the differing amounts of phosphorus on the resins in Table 22 is due to a change in molecular weight of the resin with the different groups.

Esterification of the Phosphonic Acid Resins

It was noticed that, with the exception of PK-02-026B (see Table 21), the ester resins seemed to show a higher level of reduction than did the acid resins (although the difference in many cases was not that great). It was therefore decided to esterify the peroxide and metal oxidized resins before hydrosilation.

Chlorination of the Phosphonic Acid Resin

There were two different methods used to attempt the chlorination of the phosphonic acid resins (both VBC and peroxide oxidized), these being reactions with thionyl chloride (SOCl_2) and phosphorus pentachloride (PCl_5). If the phosphorus is chlorinated, then the reactive P-Cl bonds will readily react with alcohols to form phosphorus esters. The SOCl_2 reactions were performed both in neat SOCl_2 and in a mixture of SOCl_2 /pyridine (1:1 ratio) for times up to 3 days. The best that this reaction achieved was 1 mole of chlorine for two moles of phosphorus, which is certainly not of much utility for producing a fully chlorinated resin. The PCl_5 reactions, which were done in toluene on both VBC and peroxide oxidized phosphonic acid resins, did no better.

Azeotropic Esterifications

The condensation of organic acids with alcohols in the presence of an acid catalyst is a common method for the preparation of esters, but the equilibrium is sensitive to the amount of water (the by-product of the reaction) in the mixture. It is therefore necessary to remove the water as the reaction proceeds in order to obtain high yields. One method of doing this is by the use of a Dean-Stark trap and a water-immiscible solvent to effect separation of water from the reaction mixture. The solvent used in these experiments was toluene. The amount of water which would dissolve in the toluene was higher than acceptable, though, because of the ethanol in solution, with ethanol levels ranging from 2% to 6%. Thus, when the reaction was set up with heptane azeotroped resin, toluene, ethanol (2 moles ethanol

Table 22

**Phosphorus-Carbon Bond Integrity in HSiCl_3 Reductions
of the Phosphonic Acid Resins**

Resin	Reaction	tot(OH)	tot(P)
PK-02-138	$\text{PCl}_3/\text{AlCl}_3$	5.17	4.60 ^a
PK-02-292	AgNO_3 oxidation	8.29	4.53
PK-03-006	DCC esterification	0.86	3.86
PK-03-012	HSiCl_3 reduction	5.21	4.31
PK-03-012H ⁺	HCl ester hydrolysis	6.73	4.47
PK-03-016	AgNO_3 oxidation	7.41	4.58
PK-03-013	AgNO_3 oxidation	6.58	4.13
PK-03-013H ⁺	HCl ester hydrolysis	7.90	4.51

^a estimated based on typical values for phosphinic acid resins with similar tot(OH) and primary acid capacities

for each mole tot(OH) on the resin) and toluenesulfonic acid (as a catalyst), only about 10% esterification was observed (tot(OH) before and after reaction was 9.03 and 8.14, respectively). The yield was a little better when methanesulfonic acid was used in place of the toluenesulfonic acid; approximately 27% esterification was observed (tot(OH) before and after reaction was 9.03 and 6.62, respectively). This was the best yield obtained out of several reactions, including some to which calcium sulfate (Drierite[®]) had been added to help force the equilibrium. The problem may have been with the technique, or it may have been an accessibility problem because of the non-swelling nature of toluene with the resin. No further work was done, however, to determine the reason for the low yields.

Esterifications using a Drying Agent

Dimethoxypropane (DMP) is an acetal, and as such, is decomposed by water into methanol and acetone. It should, therefore, increase the amount of esterification by chemically removing water from the reaction. These reactions were all done in refluxing toluene for up to two days, with various amounts of ethanol (mole ratios of between 2 and 8 moles ethanol for each mole tot(OH) on the resin) and dimethoxypropane (mole ratios of between 1 and 12 moles DMP for each possible mole of water produced by the reaction). The results were about the same as for the azeotropic esterifications; the highest yield of esterified groups on the resin was 42%. These results, along with those obtained from the azeotropic esterification results, seem to indicate that the problem is one of accessibility, since they both give about the same amount of reaction. As with the azeotropic esterification, no further work was done with this reaction.

Esterifications using a Coupling Agent

Dicyclohexylcarbodiimide (DCC) is a commonly employed coupling agent in peptide synthesis.⁵⁵ When used in ethanol solvent in a ratio of 3 moles DCC for each mole of tot(OH) on the resin, and 0.5 moles methanesulfonic acid (as a catalyst) per mole tot(OH), it consistently gave nearly quantitative esterification (typical results being: tot(OH) before and after reaction 9.03 (PK-02-033) and 0.78 (PK-02-095B), respectively). The by-product of the coupling reaction is dicyclohexylurea (DCU), which precipitated from solution, necessitating a one week soxhlet extraction with ethanol to remove from the resin. The DCC reaction worked equally well with VBC, peroxide oxidized, and mercury and silver oxidized phosphonic acid resins, and was thus employed for all of the esterifications performed for use in the reductions previously discussed.

Oxidation/Reduction Cycling of the Phosphinic Acid Resin

Even though variable results had been obtained from the silane reduction of the resins, a cycle of silver oxidation followed by silane reduction in 50/50 (volume %) OH/THF (repeated three times) was done. The results are shown in table 23. As can be seen, this sequence of reactions gave very good results, with almost complete reduction of the resin in each cycle. It should also be noticed that the amount of reduction does not seem to depend upon the residual amount of unesterified acid on the resin. The resin was, however, noticeably fragmented from the harsh treatment of the series of reactions, and therefore would not be of much use in a practical application, since under these conditions, a resin and its performance must be known, and remain fairly constant.

Table 23

Oxidation/Reduction Cycle of the Phosphinic Acid Resin with Silver

Cycle #	tot(OH) ^a		
	After Ag ⁺	After DCC	After HSiCl ₃ ^b
1	8.54	1.00	5.95
2	9.22	0.20	6.23
3	8.66	0.50	5.82

^a analysis of the phosphinic acid resin (PK-02-088) was:

tot(OH)=5.21, tot(P)=4.84

^b After hydrolysis in refluxing concentrated HCl for 17 hours

Conclusion

Three methods have been shown to be capable of regenerating the phosphinic acid resins after their oxidation by mercury and silver: these being NaH, LAH and trichlorosilane, with reasonable (although somewhat variable) results obtained when the resin was esterified prior to reduction. The more selective reducing agents NaBH_4 and sodium ascorbate had no effect on the resins, nor did sodium metal or sodium naphthalide, while zinc metal in aqueous NaOH showed partial reduction of the resin.

Esterification of the resin (for subsequent reduction) was accomplished with a combination of DCC and methanesulfonic acid in ethanol. There was only partial esterification of the resin by using azeotropic esterification techniques, and by the addition of a drying agent to the solution to react with the water formed from the reaction. Chlorinations using SOCl_2 and PCl_5 did not work as well as was hoped. Chlorinations using PCl_5 have since been developed which give reliable results when carried out in dioxane and pyridine.⁵⁶

There is still much to be learned about the reduction of the phosphinic acid resins. The biggest problem which still remains is that of the variable results obtained with the silane reaction. A more careful study in which model compounds were used, and the intermediate determined, would most probably be of great help. Swelling of the resin, as stated earlier, is an important factor in determining how well the reaction will work, or if it will even work at all. Thus, a systematic solvent study for the reductions should be done. A final comment for future work in this area is that the search for a reducing agent which does not require such long and

harsh treatment of the resin should be continued, as the resin can not possibly have a very long use life when treated in such a manner as has been described for the LAH and silane reductions. The zinc reductions also appear to be worth spending more time on, as there was some reduction of the resin. Since the zinc reduction is done in aqueous solution, it would be a much simpler procedure if it could be optimized.

CHAPTER IV

Molecular Recognition by Polymer-Supported Reagents

Introduction

Polymer-supported reagents have been used for many years for the separation of mixtures of organic compounds using ion-exchange chromatography,⁵⁷ affinity chromatography,^{57,58} and hydrophobic interaction chromatography,⁵⁹ and the field is growing very rapidly, as a look through the current literature will indicate. There are also a large number of books and monographs on the subject of molecular absorption by polymer-supported reagents. Not all of these reagents are ion-exchange resins, some are capable only of coordination, as with the polymer bound crown ethers. Some are unfunctionalized polymers, such as the Merrifield resin. One of the better known uses for unfunctionalized polymers for separating compounds is in gel filtration chromatography, e.g., Sephadex G-10[®], which is an unfunctionalized crosslinked dextran gel⁶⁰ of 10% porosity⁶¹ used to separate molecules based strictly on their size. Because of the increasing importance of polymer-supported reagents in separations and synthesis, it is important to understand the interactions which occur between a target molecule (also called a substrate) and the polymeric reagent.

There has been much work done on inclusion complexes, size exclusion effects, and protein-substrate binding (by size, shape, and functional group charac-

teristics of the substrate), but the field is relatively void of mechanistic studies of the fundamental interactions of target compounds with polymer-supported reagents. Thus, a study of a very limited number of compounds and functional groups was done with a variety of polymer-supported reagents in order to determine the type and strength of the interaction between anilines, benzoic acids, and phenols with several polystyrene-based ion-exchange resins (cationic, anionic, mixed cationic/anionic, neutral-coordinating, and mixed neutral-coordinating/cationic).

The Hammett Equation in Molecular Recognition Studies

The aim of these studies was to determine the cause for the selectivity of ion-exchange resins towards organic compounds in solution. This information, absent of effects (e.g. structural, size, etc.) other than the fundamental interactions between the functional groups on the ion-exchange resin and the target compound functional groups, was obtained by application of the Hammett equation.

The Hammett equation was chosen as a tool for this study for several reasons, the most important being that the target compound can be varied as to acidity or basicity of the functional group while only changing the overall molecular structure minimally. The equation also allows at least some level of quantitative treatment of the data, and provides for the necessary information for graphical display of the results. For each of the classes of compounds used (i.e. aniline, benzoic acid, and phenol functionalities), the strength of the functional group can be varied due to a change in electron density at the reactive site by changing the substituents on the aromatic ring. The Hammett equation, (equation 4) is a linear free energy

relationship, and, provided that all other variables are kept constant while one is systematically varied, will provide a direct comparison of the reactivity of similar compounds (again, the only difference being in the substituent(s) on the aromatic ring).

$$\log K/K_o = \sigma \rho$$

4

In this equation, σ is the substituent constant, and ρ is the reaction constant. K and K_o are the equilibrium or rate constants for the substituted and the unsubstituted reactions, respectively. It can therefore be seen that if the reaction using the substituted reaction is faster than the unsubstituted reaction, the value for ρ will increase. Since the equation was originally devised to explain the ionization of benzoic acids in water (which is assisted by electron withdrawing groups, thereby increasing the ratio K/K_o), positive σ values denote electron withdrawing groups, while negative σ values denote electron donating groups. Because of this, positive ρ values indicate that the reaction is aided by electron withdrawing groups. By knowing σ values for the substituents used, and the ratio K/K_o , the nature of the transition state or intermediate for the reaction can be determined. It should also be noted that K and K_o themselves do not need to be determined, only their relative values. If a reaction has a positive ρ value, it is an indication that the reaction is aided by electron withdrawal (low electron density at the reaction site in the intermediate or transition state), while negative ρ values indicate the reaction is

aided by a high electron density at the reaction center. The magnitude of ρ shows the sensitivity of the reaction to changes in the electron density.

It is important to keep in mind that there are a number of assumptions made in the equation. The first is that under identical conditions, the reaction mechanism remains the same for the differently substituted compounds (the series of compounds of like functional group), while the second is that, as the name implies, the change in reactivity is linear, due to a linear change in the equilibrium or rate constants (due to activation energy) for the reaction. This means that the ratio between ΔG for the two reactions must remain constant. It also assumes that the substituent has no effect on the reaction other than through the aromatic ring (to change the electron density at the reactive site), and does not itself actually participate in the reaction. There is no attempt with the Hammett equation to separate the resonance and inductive effects of the substituent, and there is, therefore, one constant for each particular substituent. It should also be noted here that only meta and para substituents on the aromatic ring can be used, as ortho substituted compounds behave anomalously due to steric interactions between the substituent and the reaction site.

The Hammett Study Experiments

The substituents used in the experiments discussed in this chapter, along with their σ values,⁶² are given in Table 24. These substituents were chosen because they cover a fairly wide range of both electron donating and electron withdrawing ability, and do not have highly charged resonance structures, such as with, e.g., the nitro group. Table 24 also shows the effect of the substituents on the acidity of anilinium

Table 24

Substituents used in the Hammett Studies;
their σ Values, and their Effect on pK_a

Substituent(x)	p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
σ	-0.28	-0.14	-0.06	0.00	0.10	0.24	0.37
pK_a X-Ar-NH ₃ ⁺	5.34	5.10	4.72	4.60	4.23	3.98	3.52
pK_a X-Ar-CO ₂ H	4.47	4.38	4.27	4.20	4.09	3.97	3.83
pK_a X-Ar-OH	10.21	10.26	10.09	10.00	9.65	9.38	9.02

ions,⁶³ benzoic acids,⁶⁴ and phenols⁶⁵ in water at 25°C. This table shows that electron withdrawing groups do indeed increase the acidity of the compounds (by decreasing the electron density of the acidic site, thereby stabilizing the formed anion), or conversely, that electron donating groups increase the basicity of the compounds.

The experiments consisted of weighing one mequiv of resin into a bottle, pipetting one mequiv (10ml of 0.1M solution) of each of the compounds (set up non-competitively; only one compound per bottle) onto the resin, and stirring at 350rpm for 17 hours. Other than the experiments set up in order to determine the temperature effect, none of the contact studies were done with any attempt to control the temperature, and were done at ambient temperature (always between about 20°C-28°C). After the contact time was up, the solution was decanted off of the resin, centrifuged, and analyzed (by gas chromatography for the anilines and phenols, and by titration for the benzoic acids) to determine the amount of compound remaining in solution (and hence the amount absorbed by the resin).

The resins used in the experiments were: a phosphinic acid resin (both fully and partially functionalized), a VBC phosphonic acid resin, a VBC-derived carboxylic acid resin, a sulfonic acid resin (sulfonated polystyrene), a phosphonate diethyl ester resin, a phosphonate monoethyl ester resin, a tertiary (dimethyl) amine resin (both fully and partially functionalized), a (bifunctional) tertiary amine/phosphonic acid resin, a poly(ethylene glycol) resin (PEG, a pseudo-crown ether), a polyethylene imine resin (PEI, the nitrogen analogue of the PEG resin), and a (bifunctional) PEG/phosphonic acid resin, all 2% gel -40+60 mesh (except for the sulfonic acid resin, which is a 10% gel to maintain a comparable % solids with the other resins).

The synthesis of each of these resins is described in the chapter on experimental techniques. As in Chapter II, all figures can be found together at the end of the chapter for ease of comparison. Tables appear where referred to in the text.

The sulfonic acid, phosphinic acid, and carboxylic acid resins were chosen because they are, respectively, strong, moderate, and weak acid resins. The phosphonate diethyl ester resin was chosen because it is not acid at all, and should therefore provide for a "baseline" from which the other resins can be compared. The amine resin was chosen because it is the least sterically hindered of the amine tertiary amine resins (the tertiary amine group was picked because it does not contain any N-H bonds which could interact with groups on the target molecules). The PEG resin was chosen for two reasons. The PEG groups should make the resin more hydrophilic than an ester resin, but the resin is not capable of ion-exchange, only coordination. The PEG/phosphonic acid resin was chosen because of the phosphonic acid groups which have acidic protons, while the PEG groups alter the polarity of the resin. Finally, the amine/phosphonic acid resin was chosen to test the possibility of synergistic extraction by two completely different functional groups on the same resin. The resins used are presented in Table 25.

The Solvent Effect

The first problem encountered with the molecular recognition study was the choice of solvent. Since water is a good solvent for ion-exchange resins due to their hydrophilicity, it was the natural first choice. It would also allow direct comparison of the results of this study with metal ion studies. There was, however, the problem

Table 25
Resins used for Molecular Recognition

Resin Code	Table: Figure	Resin Type	tot(OH)	tot(P)	TAEC	SSAC	PEG	% Solids
BB-02-004B	26c	Dimethylamine	-	-	3.89	0.83	-	62.62
DC-01-273	36	Phosphonic Acid	8.65	4.30	-	-	-	51.57
FC-02-003	31	Trimethylamine	-	-	4.55	3.77	-	53.73
FC-02-078	31: 26c; 29d	Dimethylamine	-	-	4.88	0.46	-	54.30
GL-02-195A	27b	Phosphonic Acid	7.61	4.13	-	-	-	48.82
PK-02-156	26	Sulfonic Acid	5.16	-	-	-	-	44.57
PK-03-192	27; 29; 33; 36; 39; 27a; 28a,c; 29c; 30a; 31a,c	Phosphonic Acid	5.16	4.93	-	-	-	49.35
PK-04-021B	29; 28a	Phosphonic Acid	2.98	2.90	-	-	-	54.70
PK-04-041	29	Phosphonic Acid	0.95	1.60	0.28	-	-	73.91
PK-04-074	26; 29; 33; 39; 26b; 31b,c	Sulfonic Acid	4.18	-	-	-	-	48.50
PK-04-076A	29; 27c	Phosphonate monoester	3.33	3.64	-	-	-	50.20
PK-04-083	26a	Carboxylic Acid	4.44	-	-	-	-	50.54
PK-04-098A	27d	Phosphonate Diester	0.45	3.23	-	-	-	47.23
PK-04-154	28a	Phosphonic Acid	0.90	0.82	-	-	-	76.73
PK-04-188A	38	Ethylenediamine	-	-	5.74	0.63	-	46.73
PK-04-194A	38	Diethylenetriamine	-	-	8.74	0.91	-	41.87
PK-04-194B	38	Triethylenetetramine	-	-	8.78	0.79	-	36.73
PK-04-194C	37	Tetraethylenepentamine	-	-	8.76	0.70	-	40.67
PK-04-194D	38	Pentaethylenhexamine	-	-	7.91	0.55	-	51.78
PK-04-200	26a	Carboxylic Acid	5.61	-	-	-	-	42.90
PK-04-241	34; 29b	PEG/Phosphonic Acid	2.07	N.A.	-	-	N.A.	63.99
PK-04-268A	29; 28b	Dimethylamine	-	-	2.13	0.00	-	59.36
PK-04-268B	29; 28b	Dimethylamine	-	-	4.29	0.17	-	64.15
PK-04-268C	29; 28b; 29d; 30b	Dimethylamine	-	-	5.15	0.34	-	53.35
PK-04-276	35; 29b	Amine/Phosphonic Acid	5.30	1.10	3.17	N.A.	-	38.10
PK-04-285	34; 29a	PEG	-	-	-	-	2.27	54.48
PK-05-017	34	PEG/Phosphonic Acid	1.63	0.86	-	-	N.A.	60.60

of target compound solubility in water (for the benzoic acids), which necessitated the use of a water/methanol mixture (at least 50% (v/v) methanol). When the experiments were first done, there was a substituent effect expected for all three types of compounds (anilines, phenols, and benzoic acids). It can be seen from any of the graphs of the phosphorus based resins (e.g. figure 27, page 153) that phenol exhibits no substituent effect whatsoever, and that there is a large amount of scatter in the data. When 100% methanol was used, there was still no substituent effect observed, but there was an overall decrease in the amount of the phenols absorbed from solution. When water was used as the solvent (there is no problem of solubility of the phenols in water at the 0.1M concentration level used in these experiments), a large increase in the amount absorbed from solution was observed, but still with no substituent effect, thereby showing that there is a fairly pronounced solvent effect. Table 26 shows the results obtained for the phenols with the sulfonic acid resin in the different solvents.

The solvent effect arises from a hydrophobic interaction between the aromatic compounds and the lipophilic nature of the polymer backbone (this same effect was seen for the phosphinic acid resin with the anilines, see figure 28, page 154). This type of interaction was documented in the 1950's⁶⁶, and is the basis for the hydrophobic interaction chromatography mentioned earlier, and is also the reason that polystyrene is not commonly used as a support in affinity chromatography,⁶⁷ It arises from the preference of the relatively non-polar organic compounds for non-polar hydrocarbon environments rather than aqueous ones. Since the resins are all polystyrene-based, there is considerable hydrophobic character to the polymer

support, even though the resin overall is polar due to the functional groups. Thus, in water, the hydrophobicity of the polymer support is important, and provides a more favorable environment for the aromatic compounds than does the bulk water solution, which helps to draw the target compounds into the resin aspecifically. There is, therefore, a hydrophobic effect superimposed on the inherent extraction ability of the functional groups on the polymer.

The selectivity of the resin for the anilines will be discussed later, however the drastic effects of both water content in the methanol, and swelling (water, water/methanol) compared to non-swelling (dioxane) solvents can be seen from Table 27. When the data are graphed, it is noticed that the slope of the line decreases with increasing water content of the solvent, indicating that water also lowers the selectivity of the resin, again, because of the aspecific hydrophobic effect which is superimposed on the functional group interaction with the resin functional groups, and partially obscures the selectivity of the resin.

The hydrophobic effect can be very useful in the extraction of organic compounds from solution, but for these studies it was an unwanted complication. It became necessary, therefore, to find a solvent in which to carry out the molecular recognition studies in which there would be no interactions except between the functional groups of both the resin and the target compounds.

As has been emphasized in previous chapters, one of the most important considerations when working with polymers is the choice of solvent. If the solvent does not swell the resin, the chances for reaction to occur to any significant extent are very low, since reaction occurs only on the surface of the resin, which contains

Table 26

Absorption of Phenols by the Sulfonic Acid Resin in
Water/Methanol Mixtures

Solvent	% Absorbed/mequiv						
	p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
H ₂ O	13.28	10.12	11.96	5.69	6.16	14.63	13.11
50% MeOH	4.43	6.57	10.83	13.28	4.63	5.10	6.04
MeOH	0.00	2.19	0.00	2.86	7.13	6.26	0.00

Table 27

Absorption of Anilines by the Phosphinic Acid Resin
in Various Solvents

Solvent	% Absorbed/mequiv						
	p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
dioxane	5.95	8.99	2.88	6.73	6.64	7.37	4.57
MeOH	71.55	67.90	58.04	50.01	49.03	30.36	26.92
50% MeOH	88.11	84.25	79.05	73.84	72.89	71.90	60.75
H ₂ O	92.57	-	94.04	83.09	86.32	-	-

only a small fraction of the total number of functional groups. In order to continue the molecular absorption studies with the stated aim of determining the fundamental interactions between the target compounds and the functional groups on the resin, a solvent was required which had, as nearly as possible, identical interactions with both the resin and with the target compounds. In order to assist in choosing a solvent, the solubility parameter was used.

The solubility parameter is a measure of the cohesive forces between molecules, and is simply the square root of the (heat of vaporization/molar volume).⁶⁸ There are three different scales used for the solubility parameter: one for non-polar compounds, one for compounds which exhibit weak hydrogen bonding, and one for compounds with strong hydrogen bonds. Although the solubility parameter gives only an estimate of the compatibility of different molecules (strictly it is accurate only for completely non-polar compounds), it does have utility in determining whether the compounds will be miscible or not. Table 28 lists the solubility parameters for the target compounds and the solvents used in these studies.⁶⁹

It should be remembered that there are three scales for the solubility parameter, and that all of the target compounds fall into the strong hydrogen bonding category. While the solubility parameter values for dioxane and dichlorobenzene are numerically the same, they are on different scales (non-polar and polar and only weakly hydrogen bonding, respectively), and these are different than the target compound values, which are in the hydrogen bonding category. It would appear, therefore, that ethanol would be a better choice of solvent than would to

Table 28

Solubility Parameters⁶⁹

H ₂ O ^a	MeOH ^a	EtOH ^a	dioxane ^b	dichlorobenzene ^c	anilines ^{a,d}	phenols ^{a,d}	benzoic acids ^{a,d}
23.4	14.1	12.1	10.0	10.0	10.0-10.6	9.6-10.4	10.0-11.3

^a strongly hydrogen bonding compounds

^b polar, weakly hydrogen bonding compound

^c non-polar compound

^d values calculated by use of the group additivity equation:

$$\delta = d\Sigma G/M$$

where d and M are the density and molecular weight of the compound, respectively, and G is the molar attraction constant for each group present on the molecule. G values are from Hoy⁷⁰

methanol, but there is one other factor which is important, this being the amount to which the solvent swells the resins. This was used in lieu of matching the solubility parameter for the resin, as this value is not known. In determining swelling ratios (volume of the resin swelled in solvent/volume of the air-dried resin), it was found that ethanol swelled the phosphinic acid resin by a factor of 1.1, while methanol swelled it by a factor of 1.6. Therefore, in order to minimize interactions other than those between the target compound and the functional group on the polymer as well as allow for a maximum amount of swelling, methanol was chosen as the solvent for all subsequent molecular recognition studies. An unacceptable amount of scatter in

the data was found, and it was therefore necessary to solvent exchange the resin prior contact with the target solution, since the resin is used after Büchner-drying, but still contains water in its pores. It was not completely dried prior to use for fear of collapsing the polymer matrix, thereby possibly causing problems of accessibility. The solvent exchange was done by shaking the resin in four changes of methanol for 30 minutes each to displace the water in the resin. Swell ratios were determined with air dried beads, and are therefore relative to the dry resin volume. A limited number of swell ratios were also determined for the resin after Büchner-drying, but with water still in the pores. The results of both of these are given in Table 29. It can be seen that the resins which are only partially functionalized swell better in dioxane than in methanol due to their increased hydrophobic nature, although with the low level phosphinic acid resin, it appears that the presence of some water assists in the swelling, since the air dried resin does not swell as much in dioxane as does the same resin which has only been Büchner-dried (see Table 29).

A quick test was done with aniline in methanol and in dioxane to see if the low level of its extraction from dioxane by the phosphinic acid and sulfonic acid resins was due to the inability of the solvent to support formation of the anilinium ion. In this test, equivalent amounts of aniline and either phenylphosphinic acid or methanesulfonic acid were dissolved in methanol and in dioxane. The results of the test (Table 30) showed that while the compounds themselves were soluble, the salt which was formed when the compounds were mixed precipitated from solution for all but the combination of aniline and phenylphosphinic acid in methanol. Of the other three, the combination of aniline and methanesulfonic acid in dioxane could not be redissolved, while the other two could be after the addition of more solvent.

Table 29

Swell Ratios of Several Resins in Various Solvents

Resin	MeOH	EtOH	dioxane	THF	MEK
Phosphinic Acid	1.28	1.10	1.00	1.00	1.00
Low Level Phosphinic	1.20	-	1.10	-	-
Low Level Phosphinic ^a	1.00	-	1.74	-	-
Phosphonate monoester	1.10	-	-	-	-
Sulfonic Acid	1.65	-	1.68	-	-
100% Dimethylamine	1.28	-	1.33 (1.19)	-	-
80% Dimethylamine	1.48	-	1.36	-	-
40% Dimethylamine	1.40	-	1.76	-	-

^a Büchner-dried, but containing water in the pores

Table 30

Results of the Anilinium Ion Solubility Test

Compound	Methanol	Dioxane
Aniline	soluble	soluble
Phenylphosphinic Acid	soluble	soluble
Methanesulfonic Acid	soluble	soluble
Aniline + Phenylphosphinic Acid	soluble	soluble after addition of ~3 volumes dioxane
Aniline + Methanesulfonic Acid	soluble after addition of ~8 volumes methanol	insoluble

Thus, the lack of formation of the anilinium ion was shown not to be the reason for the low level absorption in dioxane.

Selectivity as a Function of Polymer/Target Interaction Strength

The selectivity of a polymer-supported reagent for one target compound over another is, in the absence of any other effects (e.g. solvent, hydrophobic, etc.), a direct result of the strength of the interaction between the target compound functional group and the functional group(s) on the polymer. Thus, when a carboxylic acid resin is contacted with the target compounds, the absorption of the phenols and benzoic acids is due only to a statistical redistribution of the compounds in the solution and in the resin (essentially just a dilution of the compound). The anilines, being basic, are extracted by the acidic resin. There is extraction of only about 25% of the anilines from solution, regardless of the substituent present. Carboxylic acids are weak acids, and thus the interaction between the carboxyl groups on the resin and the amine group of the anilines is weak. While it can be argued that the known pK values for all of the compounds used in this study were determined in water, it should also be true that any change in pK due to the different solvent should be proportional for all of the compounds, and therefore the relative pK values (and hence the relative strength of the interactions) should remain constant. This has been demonstrated by Jaffé, et al.⁷¹ with a series of phosphonic acids in water and in 50% aqueous ethanol, and is discussed by Bell⁷² for both benzoic acids and anilines in water and in methanol, and in which there is no discernable difference in the relative acidity or basicity of the series of compounds

in the different solvents. Therefore, the interaction between the anilines and the carboxylic acid resin is too weak for the substituents to exert any significant effect, as can be seen in Figure 26, page 152.

The phosphorus based resins are known to be of intermediate acidity, and it is with these resins that the highest selectivity for the anilines is seen. The basicity of the amine group is fairly well matched to the acidity of the phosphorus acid group, at least in order of magnitude, and the interaction between the resin and anilines is strong enough to allow the substituents on the anilines to influence the extraction, as shown in Figures 27a-c, page 153.

When the interaction between the amine group and the functional group of the polymer is overwhelmingly strong, any possible substituent effects are swamped out. Thus, with the sulfonic acid resin, there is no substituent effect observed with the anilines. This can be seen in Figure 26, page 152. It may also be noticed that the benzoic acids are not included in this graph. The reason is that the resin is a strong enough acid to catalyze an esterification reaction between the target compounds and the methanol solvent, as evidenced by the odor of the mixture. The presence of the ester (approximately 25% conversion after 17 hours at room temperature) was varified by GC.

It is worth noting at this time that there is very little difference in the graphs of the phosphinic acid resin (styrene-based) and the phosphonic acid resin (VBC-based). This is important in that it indicates the lack of any steric effects between the absorbed compounds and the polymer backbone. Since the VBC-based resins possess a benzylic carbon which helps remove the functional group from the polymer

backbone, a larger amount of target compound absorption would have occurred with this resin than with the polystyrene-based resins had steric (crowding) effects been present.

The foregoing statements apply to acid/base type interactions. When this type of reaction is absent, there is no selectivity displayed. Thus, for all of the acidic resins with the phenols and benzoic acids, there is only a small amount of the target compound which is absorbed from solution (see Figures 26 and 27, pages 152 and 153).

When the target compound is acidic and the resin is basic, the same conclusions apply, therefore a moderate strength amine resin shows selectivity for the substituted benzoic acids, but not for the anilines or phenols, as can be seen in Figure 26, page 152.

The amine resin, like the phosphorus resins, contains secondary crosslinks. With the phosphorus resins, these do not effect the acidity of the functional group. The amine resin is made by reacting dimethylamine with VBC copolymer to form tertiary amine functional groups. Secondary crosslinking, however, forms quaternary amine groups, which are substantially more basic than the tertiary groups (due to the hydroxide anion present on the resin). Thus, for the dimethylamine resin with the phenols, there is a slight selectivity trend exhibited by the amine resin. This is also evident for the dimethylamine resin with the anilines. To test the effect of the quaternary amine sites on the resin for selectivity with the anilines and phenols, these compounds in methanol were contacted with a quaternary amine resin (made by reacting trimethylamine with VBC instead of dimethylamine). Results for

absorption of the anilines and phenols by both tertiary and quaternary amine resins are given in Table 31. It should be noticed from Table 31 that both the anilines and phenols are absorbed as would be expected based on the substituents present. Absorption of the anilines is aided by electron releasing groups, which strengthen the interaction between the aniline lone pair of electrons and the positively charged quaternary amine site. Absorption of the phenols is aided by electron withdrawing groups, which give the phenolic proton more of a positive character, allowing for better coordination between it and the associated anion on the resin. Both of these are consistent with the presence of strong base sites on the resin, which was shown by analysis to contain 0.46 mequiv/g strong base sites out of a total of 4.88 mequiv/g of base sites, while the quaternary amine resin had a total base capacity of 4.55 mequiv/g.

Up to this point, selectivity has been alluded to, but its determination has not been described. In viewing Figures 26 and 27 (pages 152 and 153) it will be noticed that the graph is not horizontal, but has a non-zero slope. This is the ρ term from the Hammett equation. It is this slope which shows the selectivity of the resins for the compounds. Thus, a negative slope (as for the phosphorus resins with the anilines) indicates that the reaction is aided by electron donating groups on the aromatic ring of the aniline, while the numerical value of the slope is an indication of the sensitivity of the reaction to substituent effects. A very low slope (or slope=0) indicates the reaction is relatively (or completely) free of substituent effects. Thus, when the Hammett plot exhibits a fairly horizontal line, there is little to no selectivity of the resin for that class of target compounds. It also follows that selectivity (at the concentration and R_i used in these experiments) only occurs when

Table 31

The Effect of Quaternary Amine Sites on the Absorption of
Anilines and Phenols from Methanol

Resin	Compound	% Absorbed/mequiv						
		p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
Tertiary Amine	anilines	8.27	8.51	7.58	7.93	6.93	6.96	6.50
Quaternary Amine	anilines	9.82	-	-	6.78	-	-	6.68
Tertiary Amine	phenols	9.50	8.16	10.16	10.80	10.96	13.68	12.39
Quaternary Amine	phenols	1.81	-	-	6.04	-	-	8.85

there is an intermediate amount of the compound absorbed from solution. If a large amount is absorbed, as with the near quantitative absorption of the anilines by the sulfonic acid resin, the interaction between the resin and the target compound is too strong to be influenced by substituents. When only a low amount of the target compound is absorbed, the polymer/target compound interaction is too weak, and the substituents can not exert enough of an effect to significantly influence the absorption. Thus, with all of the compounds which have very low absorption levels, there is essentially no selectivity, as with the phenols with either the acidic or basic resins, the anilines with the amine resin, and the benzoic acids with the acidic resins. Again, all of these conclusions are for methanol solutions. Some ρ values are given in Table 32 for methanol solutions. When the solution itself is made a less favorable environment for the target compound than the polymer beads, as is the case for aqueous solutions, the extra driving force of the non-selective hydrophobic effect is added, decreasing the overall selectivity.

The ρ values listed in Table 32 for the dimethylamine resin contacted with the benzoic acids, and the phosphorus resins contacted with the anilines demonstrate that, while the sign of the ρ value is as one would expect, i.e., negative for the reactions which are aided by a higher electron density at the reaction site, as for the acidic resins contacted with the anilines, and positive for reactions which are aided by a lower electron density at the reaction site, as for the amine resins contacted with the benzoic acids, the magnitudes are much smaller than expected, based on published values for anilinium ions.⁷³ These published ρ values, which are based on ionization equilibria for anilinium ions in water and water/dioxane

mixtures, and are 2.767, 3.256, and 3.430 for water, 20% dioxane, and 82% dioxane, respectively, at 25°C. The much lower values obtained from the molecular absorption experiments indicates that while there is an interaction occurring, it is not as strong as an acid-base proton transfer type reaction. It is a much weaker hydrogen-bonding association of the target compounds with the polymer-supported reagents.

The Effect of Temperature on Molecular Recognition

The temperature at which the contact study is done should also give an indication as to the strength of the polymer/target compound interaction. Being acid/base type reactions, they are exothermic. Because of this, an increase in temperature should somewhat hinder selective absorption (recall that in order to show selectivity, the polymer and target compound must be fairly well matched in strength), but not the absorption of compounds which strongly interact. This is because for strong interactions, the change in temperature (the temperature range used in these experiments was 34°C; the upper and lower temperatures being 40°C and 6°C) does not provide enough of a change in energy to influence the large amount of heat released by the reaction; the temperature change only accounting for a small percentage of the total change in energy for the reaction. Very weak interactions are more or less athermal, and are therefore unaffected by external temperature changes. This is indeed shown by the experiments, as can be seen by viewing Table 33. There is no temperature effect with the sulfonic acid resin with the anilines, or with the phosphinic acid resin with the phenols, the data for both of

Table 32

Rho Values for the Absorption of Anilines
and Benzoic Acids from Methanol

Resin Type	Target Compounds	Figure	ρ	Correlation Coefficient
Carboxylic Acid	Anilines	26a	-0.129	-0.7530
Sulfonic Acid	Anilines	26b	0.003	0.1421
Phosphinic Acid	Anilines	27a	-0.701	-0.9647
Phosphonic Acid	Anilines	27b	-0.604	-0.9656
Dimethylamine	Benzoic Acids	26c	0.223	0.9786

Table 33

The Effect of Temperature on Molecular Absorption
by the Phosphinic and Sulfonic Acid Resins

Resin	Compound	Temperature	% Absorbed/mequiv						
			p-OCH ₃	p-CH ₃	m-CH ₃	H	p-OCH ₃	p-Cl	m-Cl
Sulfonic	anilines	6°C	95.71	92.40	91.18	90.80	98.61	90.54	96.80
Sulfonic	anilines	40°C	98.56	91.29	91.80	94.38	98.74	98.47	92.34
Phosphinic	anilines	6°C	81.07	-	-	65.88	-	-	37.16
Phosphinic	anilines	40°C	71.35	-	-	47.09	-	-	20.17
Phosphinic	phenols	6°C	5.54	-	-	4.59	-	-	4.93
Phosphinic	phenols	40°C	6.37	-	-	7.35	-	-	7.55

these being the same within the experimental limits of the GC analysis (one being a case of strong interactions, the other being a case of extremely weak interactions), but there is a temperature effect with the phosphinic acid resin with the anilines (intermediate interaction strength).

The Effect of Resin Partial Functionalization on Molecular Recognition

All of the resins used to this point had been fully functionalized. Experiments were done with partially functionalized phosphinic acid and partially functionalized dimethylamine resins; the level of functionalization for the phosphinic acid resin being controlled by temperature during the phosphorylation, while for the dimethylamine resin, control of the functional level was not possible, the amination being much too fast. Therefore, the partially functionalized dimethylamine resin was synthesized from a terpolymer of a mixture of styrene and VBC crosslinked with DVB (40%, 80%, and 100%, 2% crosslink level VBC copolymer was used for the amine resin syntheses).

Because methanol is not that good a swelling solvent for the partially functionalized resins, the amount of target compound absorbed from solution is significantly lower than for the fully functionalized resins (see Figure 28, page 154). Because of the accessibility problems associated with the relatively unswollen resins, selectivity is essentially lost. It can also be seen that for the intermediately functionalized phosphinic acid resin, the added hydrophobicity of the polymer support has a slight influence on the weaker anilines (those with electron withdrawing groups), helping to bring them into the resin without effecting the overall selectivity, although this effect is minor.

Synergistic Effects in Molecular Recognition

PEG and PEG/Phosphonic Acid Resins

When two different functional groups are put on the same resin, the possibility for cooperative extraction of the target compounds exists. Therefore, a PEG/phosphonic acid resin was made. A PEG resin does not display any selectivity for the target compounds used, although the amount of compound extracted from solution is higher, due simply to the larger amount of resin used for 1 mequiv of functional groups (the R_1 for this resin was based on the number of what were assumed to be penta(ethylene glycol) units on the resin), giving more resin for the target compounds to be redistributed into from the solvent (see Figure 29, page 155). The PEG/phosphonic acid resin displays some selectivity for the anilines and phenols, but not for the benzoic acids, with only a relatively low level of absorption. The selectivity seems to be influenced by a combination of both substituents present and size of the target molecule. The anilines exhibit the largest amount of compound absorbed for both of the methoxy substituted compounds, then for the methyl substituted, followed by the chloro substituted, with the order for each of these different substituents governed by its electron withdrawing ability. Crown ethers extract metal ions from solution primarily on the basis of size, and therefore this same type of behavior is not unreasonable to expect with other types of extraction.

When different solvents are used with the PEG/phosphonic acid resin, some interesting results are obtained. As can be seen from Table 34, using dioxane as a

Table 34

The Effect of Solvent on the PEG and the
PEG/Phosphonic Acid Resins on the Hammett Studies

Resin	Compound	Solvent	% Absorbed/mequiv						
			p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
A	anilines	dioxane	28.20	-	-	18.37	-	-	6.92
A	anilines	methanol	24.32	20.34	16.72	14.93	23.73	17.11	11.83
A	anilines	water	44.24	-	-	45.79	51.29	-	-
A	phenols	dioxane	0.80	-	-	23.45	-	-	15.01
A	phenols	methanol	10.60	7.85	4.66	10.25	12.17	11.68	7.51
A	phenols	water	51.94	-	-	46.36	-	76.75	-
A	benzoic acids	dioxane	6.93	-	-	6.67	-	-	4.18
A	benzoic acids	methanol	9.10	4.55	7.97	8.41	9.58	7.91	9.61
B	anilines	dioxane	7.93	-	-	15.84	-	-	18.13
B	anilines	methanol	21.30	11.89	11.77	18.57	19.56	19.95	17.51
B	anilines	water	50.21	-	-	49.47	63.32	-	-
B	phenols	dioxane	0.00	-	-	23.40	-	-	16.68
B	phenols	methanol	19.47	16.06	12.89	10.18	17.63	18.48	17.04
B	phenols	water	73.10	-	-	68.67	-	92.43	-
B	benzoic acids	dioxane	9.96	-	-	10.76	-	-	7.92
B	benzoic acids	methanol	14.25	11.49	12.46	14.30	15.68	12.85	12.99

A PEG/Phosphonic Acid Resin

B PEG Resin

solvent had very little effect on the extraction of the anilines. There may be an slight σ effect with the phenols in methanol, but the level of scatter in the data makes it very difficult to tell. There was no difference with the benzoic acids compared to methanol. When water was used as a solvent, the amount of anilines absorbed approximately doubled. There is a mild substituent effect, with the slope being positive, rather than negative, as has been seen with all of the acid resins contacted with phenols. Upon closer inspection, it is determined that the order of extraction of the anilines by the PEG/phosphonic acid resin from water matches very well the trend of difficulty of dissolution of the compounds in water: the more difficult it was to dissolve the compound, the more was absorbed by the resin. Therefore, it would appear that the extraction is again driven by the hydrophobic effect.

The extraction of phenols from water by the PEG/phosphonic acid resin follows the same type of trend. There is a dramatic increase in the amount of compound absorbed, with the "selectivity" following the same order as the difficulty of dissolution in the water, the resin providing a much better environment for the target molecules than the bulk solution. The purely PEG resin behaved identically with the different solvents, showing that the extraction of aniline is helped only some by the presence of the phosphonic acid group, and the other compounds are not effected by it at all. It is interesting to note that the selectivity of the PEG/phosphonic acid resin with the anilines is enhanced in dioxane relative to methanol. This is most likely due to a "tighter" ion pair because of dioxane's inability to stabilize the formed ions to the extent which methanol can.

That such a high level of absorption of the phenols from water by the PEG resin is observed is a little surprising. The PEG groups apparently increase the polarity of the resin enough to increase the functional group accessibility without sacrificing the hydrophobic nature of the polymer backbone. Even though the overall polarity of the resin is increased relative to the copolymer, the PEG units also contain a fair amount of hydrophobic organic character (two methylene units/ethylene glycol repeat unit). Thus, the overall environment inside the resin is highly favorable for the phenols. Because of the very noticeable substituent effect, there is most likely extensive hydrogen bonding of the pseudo-crown ether ligands to the phenolic proton.

Although no studies have been done to show its validity, there may be dimerization of the target compounds in dioxane. It is known that carboxylic acids dimerize in solvents which do not provide for strong hydrogen bonding (this is also the reason they were analyzed by titration instead of by GC; they dimerize in the column and give misshapen and inconsistent peaks). It is well known from NMR work that this also occurs to some extent even in hydrogen bonding type solvents.⁷⁴ Thus, it may be that in dioxane, the PEG groups on the resin do not have the ability to break up the dimers, and therefore can not effectively coordinate to the molecules to extract them from solution. The phenols and anilines do not dimerize, but hydrogen bond. Therefore, they are not be as strongly held together, and the resin can extract them as individual molecules.

The Amine/Phosphonic Acid Resin

A bifunctional dimethylamine/phosphonic acid resin was also made. This resin was used in contact studies in several different forms. If acid conditioning is the final step before use (excluding, of course, a water elution of the resin to remove excess acid), then the resin is fully protonated (both the phosphonic acid and dimethylamine groups), and there is an anion associated with the amine group. If the resin is conditioned with hydroxide before use, then all of the functional groups are deprotonated, giving the free amine and the conjugate base of the acid groups. After conditioning with base, the hydroxide seemingly can not be washed out of the resin. Thus it is observed that after 15 liters of water, the pH of the eluent is still about 12, whereas the eluent from the sodium salt of a phosphonic acid resin is typically neutral after about 0.5 liters of water. The phosphonic acid group is diprotic, and therefore has two pK_a values: one being around 5, and the second one about 8 (determined from the titration of phenylphosphonic acid in water). Hydrolysis occurs with the disodium salt of the phosphonic acid resin until the functional groups have been monoprotonated. Thus, the resin is used either fully protonated, fully deprotonated (only enough water is passed through the resin to wash out the excess hydroxide after base conditioning), or with the amine protonated and the acid groups either completely deprotonated or monoprotonated. This was accomplished by elution of the fully protonated resin with either sodium acetate (for completely deprotonated acid groups) or a mixture of sodium phosphate and disodium phosphate to remove only the more acidic proton from the acid group.

The amine/phosphonic acid resin did not perform as well as was hoped. Table 35 shows the results of the studies done with this resin, all of which were done

Table 35

Results of the Hammett Studies in Methanol with the
Bifunctional Amine/Phosphonic Acid Resin

Resin	Compound	% Absorbed/mequiv						
		p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
A	phenols	10.13	-	-	2.12	-	-	-
B	phenols	6.03	-	-	5.67	-	-	6.62
B	benzoic acids	31.22	-	-	31.22	-	-	36.58
C	anilines	15.01	-	-	21.08	-	-	12.43
C	phenols	17.85	-	-	15.34	-	-	18.76
C	benzoic acids	67.99	-	-	68.12	-	-	-

A fully protonated, Cl⁻ anion on the amine

B protonated; eluted with NaOAc; NO₃⁻ anion on the amine

C protonated; eluted with NaOAc; OAc⁻ anion not exchanged

in methanol. For the sake of comparison, several monofunctional resins were also used in the deprotonated form, the results of which are given in Table 36. When the benzoic acids were contacted with the fully deprotonated amine/phosphonic acid resin, very little was absorbed from solution. The amine/phosphonic acid resin which contained the acetate anion absorbed almost all of the benzoic acids from solution. These samples, though, had the distinct smell of acetic acid. Injection of these samples in the GC showed that there was much less of the benzoic acids remaining than the titrations indicated. What had occurred, therefore, was proton transfer from the benzoic acids to the acetate anion, with the benzoate anion remaining associated with the positively charged protonated amine function in the resin. This type of extraction is also used with metal ions, and (for metals) is termed ligand-exchange extraction. No further work, however, was done with this.

The fully deprotonated phosphonic acid resin displayed the same type of behavior. In this case, however, the benzoate ion was not required to remain in the resin, since the associated ion was sodium, and the ion pair could leave the resin. Since the analysis is indiscriminate, simply being a titration for the total acidity of the sample, it showed an apparent loss of the benzoic acids from solution. There was, however, no GC analysis of these samples done because in this case the benzoate anion would not be required to remain inside the resin, being combined with sodium. The GC is not capable of showing the presence of salts.

It can be seen from Table 36 that there is still a substantial amount of the benzoic acids absorbed from solution by the salt form of the phosphinic acid and phosphonic acid resins. This is most likely due to hydrogen bonding between the

Table 36

Results of the Hammett Studies in Methanol with
the Sodium Salt Form of the
Phosphinic and Phosphonic Acid Resins

Resin	Compound	% Absorbed/mequiv						
		p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
A	benzoic acids	2.66	10.85	8.64	9.27	5.05	9.48	7.70
A	phenols	24.27	-	-	24.64	-	-	30.41
B	phenols	18.15	9.92	12.42	15.12	20.98	12.75	17.98
C	phenols	12.63	6.59	8.26	5.71	10.88	2.27	6.52
D	benzoic acids	52.50	-	-	58.54	-	-	68.68
D	phenols	11.81	-	-	14.95	-	-	15.33
E	benzoic acids	97.50	-	-	100	-	-	100
E	phenols	7.59	18.95	13.89	21.99	22.73	23.04	28.47
F	benzoic acids	0.00	-	-	0.00	-	-	1.23
F	phenols	0.00	1.25	3.16	2.60	1.02	5.83	2.49
G	benzoic acids	52.64	-	-	54.15	-	-	61.61
G	phenols	7.84	4.62	1.21	9.69	9.42	12.02	16.02

A phosphinic acid resin, sodium salt form

B phosphonate monoethyl ester, sodium salt form

C phosphonic acid resin, monosodium salt from phosphate buffer elution

D phosphonic acid resin, "disodium salt" from acetate elution, followed by 15 liters of water

E phosphonic acid resin, disodium salt from acetate elution, followed by 2 liters of water

F sulfonic acid resin, sodium salt form

G carboxylic acid resin, sodium salt form

benzoic acid proton and the phosphonate or phosphinate anion. Proton transfer is most likely not the case with the monosodium phosphonate resins, or with the sodium phosphinate resin because of the weak base properties of the deprotonated acid groups (recall that the first pK_a for the phosphonic acid, and presumably for the phosphinic acid, since titration curves of both resins start at about the same pH, is about 5). It should also be noticed that the sulfonic acid resin, being a strong acid, does not show any proton exchange with the benzoic acids. The carboxylic acid resin, on the other hand, does, since it is a weak acid. It should also be noticed that the amount of the benzoic acids missing from solution with all of the resins with relatively strong conjugate base functional groups (either by proton exchange or by legitimate absorption), follows correctly the order of the substituents present. Thus, the strongly electron withdrawing substituents increase the loss of compound from solution by stabilizing the benzoate anion after proton exchange or hydrogen bonding via the benzoic acid proton with the anion of the resin.

The phenols are also absorbed by the weaker acid resins, although there has been no attempt made to determine whether this is due to deprotonation or simply to coordination of the phenolic proton to the conjugate base of the resin. Given that there is a substantial amount absorbed by the sodium phosphinate resin (A in Table 36), the mode of absorption is most likely coordination, as the phosphinate group, based on pK_a , is too weak a base to deprotonate a phenol.

The PEI Resins

A series of poly(ethylene imine) resins (PEI) were made in order to compare a flexible coordinative functional group (the PEG resin) with one which combines

the flexibility (to allow it to conform to the shape of a molecule) with ion-exchange characteristics, the PEI resin being the nitrogen analogue of the PEG resin. These were made with the homologous series of ethylenediamine through penta(ethylene hexamine). Attempts to determine the relative amounts of primary, secondary, tertiary, and quaternary amine groups were unsuccessful. The resin was therefore only analyzed for total amine capacity (TAEC, total anion-exchange capacity). These were made in the same manner that the dimethylamine resins were made, which was reaction of VBC copolymer with the corresponding amine compound. Analysis of the resins showed that they all have approximately the same amine content, which is about double that of the dimethylamine resin, and that there is no chlorine remaining on the resin after amination (there is, therefore, 100% substitution of the polymer).

These resins were contacted with the anilines, phenols, and benzoic acids in methanol at $R_i = 1$. In order to avoid redundancy, only the results for the tetramer (the resin made with tetraethylenepentamine) will be shown, as the results for all the PEI resins are essentially the same.

The results from the contact studies with this resin, shown in Table 37, are almost identical to the results obtained with the dimethylamine resin, except that the absorption of the benzoic acids from methanol is a little less specific than for the dimethylamine resin. This is probably due to a fairly high level of secondary crosslinking of the resin by the polyamine molecules, which restricts the diffusion of the molecules in the resin. This is supported by the fact that there is a decreasing trend in the amount of the benzoic acids absorbed from methanol in going from the ethylenediamine through the pentaethylenehexamine resin, as shown in Table 38.

Table 37

Tetraethylenepentamine Resin Contacted with
Anilines, Phenols, and Benzoic Acids

Compound	Solvent	% Absorbed/mequiv						
		p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
Anilines	dioxane	10.51	5.19	4.95	3.69	8.00	12.06	6.80
Anilines	methanol	0.00	3.78	1.56	2.58	1.54	1.53	7.59
Anilines	water	10.21	-	22.29	17.25	23.30	-	-
Phenols	dioxane	6.71	10.89	9.18	25.27	5.34	22.26	22.16
Phenols	methanol	11.44	3.94	8.34	1.89	11.56	11.36	16.80
Phenols	water	42.94	56.84	55.38	44.26	52.35	77.58	-
Benzoic Acids	dioxane	29.70	40.25	33.74	30.52	38.58	35.34	50.51
Benzoic Acids	methanol	55.74	50.66	53.52	57.00	56.47	57.68	62.49

Table 38

Absorption of Benzoic Acids by the PEI resins from Methanol

Homologue	p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
Monomer ^a	55.79	-	-	58.59	-	-	68.37
Dimer ^b	63.25	56.91	61.03	65.11	67.31	65.59	68.91
Trimer ^c	56.54	54.94	54.31	57.82	60.95	62.16	65.81
Tetramer ^d	55.74	50.66	53.52	57.00	56.47	57.68	62.49
Pentamer ^e	47.95	43.12	45.37	49.82	52.80	54.28	55.12

^a ethylenediamine^b diethylenetriamine^c triethylenetetramine^d tetraethylenepentamine^e pentaethylenehexamine

The Effect of Target Compound Concentration on Molecular Recognition

The series of anilines was contacted with the phosphinic acid resin at different R_i values (1, 0.5, and 0.1) by decreasing the concentration of the target compound solution, while everything else remained the same as the $R_i=1$ studies (the solution concentrations were 0.1M, 0.05M, and 0.01M for $R_i=1$, 0.5, and 0.1, respectively). The same was done with the benzoic acids contacted with the dimethylamine resin. The results are shown in Figures 29 and 30, pages 155 and 156. It should be said first that for the $R_i=0.5$ solution, the maximum amount which can be absorbed is 0.5 mequiv/mequiv resin, and likewise, that the maximum possible absorption for the $R_i=0.1$ solution is 0.1 mequiv/mequiv resin, since the contact studies were set up with a total of 1 mequiv resin. Thus, it can be seen that the phosphinic acid resin shows nearly quantitative absorption of p-anisidine ($X=p-OCH_3$) at the two lower concentrations. Selectivity is observed at $R_i=0.5$, but not to the extent that it is at $R_i=1$. There is nearly quantitative absorption of the anilines at $R_i=0.1$ from p- OCH_3 through m- OCH_3 . This is a result of the quantity F which is commonly employed with ion-exchange resins. This quantity is the fractional conversion of the resin. At high F values, with molecules as large as the anilines, there is steric crowding, not between the polymer and the absorbed molecule, as was shown earlier not to exist by comparison of the styrene-based vs. the VBC-based resins, but by the molecules with each other. This steric effect has its origin in the absorbed molecules blocking access of adjacent functional groups on the resin because of their close proximity. This is known as a loading effect, and is the reason most ion-exchange studies are done at low concentrations. The amount of a compound (or ion) absorbed at higher

concentrations is almost never directly proportional to the amount absorbed at lower concentrations because of this effect, but rather the increase follows some type of a decay function with increasing percent loading of the resin.

At the low concentration ($R_i=0.1$), the level of benzoic acid absorption with the amine resin is not quantitative at any σ . Thus, this resin does show selectivity at the lower R_i because of the weaker interaction between the benzoic acids and the amine groups on the resin. The interaction between the anilines and the phosphinic acid groups on the resin are strong enough to cause quantitative absorption until the basicity of the anilines are reduced to the point that the amount absorbed would be above that allowed by the equilibrium constant for the reaction. Thus, it is observed that loading effects can actually enhance the selectivity of a resin, the weaker of the absorbed compounds (m-chloroaniline for the phosphinic acid resin and p-anisic acid for the amine resin) being unable to overcome the crowding as well as can the stronger of the absorbed compounds (p-anisidine for the phosphinic acid resin and m-chlorobenzoic acid for the amine resin).

Competitive Absorption Studies

The statement had previously been made that the sulfonic acid resin is indiscriminate in its absorption of the anilines from methanol. While this is true under non-competitive conditions, when either the sulfonic acid or the phosphinic acid resins are contacted with a mixture of anilines in methanol, both display selectivity, although the phosphinic acid resin is still more selective than the sulfonic acid resin, as shown in figure 31, page 157.

The contact samples were set up in methanol with equivalent amounts of aniline and the particular substituted aniline for that particular point on the graph, and were at a total $R_i=2$ ($R_i=1$ for each component), and therefore the amount of compound absorbed is limited by the amount of resin, and not by the amount of compound in solution.

As can be seen from the graphs (Figure 31, page 157), the sulfonic acid resin absorbs the anilines to 100% loading, while the phosphinic acid resin reaches a maximum of approximately 83% loading (which, incidentally, is only about 8% higher than non-competitively at $R_i=1$). Thus, the total amount of compound in solution and on the resin still determines the overall equilibrium, but the ratio of aniline to substituted aniline varies with substituent. This demonstrates that competitively and non-competitively, the equilibrium remains approximately the same (this can not be stated unequivocally because there were no non-competitive studies done at $R_i=2$), but that the resin, given the choice, will preferentially absorb the compound which has the stronger interaction. If the inherent interaction between the target compound functional group and the resin is too strong, however, irregardless of the substituent, the selectivity is diminished, or even entirely lost. The ratio of the substituted aniline to aniline, the selectivity ratio, is shown in Table 39 for both the phosphinic acid resin and the sulfonic acid resins, and shows, as was stated before, that the phosphinic acid resin is more selective for the anilines than is the sulfonic acid resin.

Table 39

Selectivity Ratios of Substituted Anilines Relative to Aniline
Contacted with the Phosphinic Acid and Sulfonic Acid Resins

Resin	p-OCH ₃	p-CH ₃	m-CH ₃	H	m-OCH ₃	p-Cl	m-Cl
Phosphinic Acid	4.48	2.02	1.26	1.00	0.77	0.40	0.14
Sulfonic Acid	3.13	1.60	1.06	1.00	0.85	0.50	0.26

The Kinetics of Competitive Absorption

Two absorption studies were done using equimolar amounts of aniline and p-anisidine in methanol, one with the phosphinic acid resin, and one with the sulfonic acid resin. These were set up competitively in the same manner as the previous competitive contact studies at times from 5 minutes to 2 hours. The results are shown in Figure 31, page 157. The ratio of p-anisidine to aniline absorbed by the resin remains constant after 15 minutes with both of the resins. Since the selectivity ratio remains essentially constant, the kinetic and the thermodynamic products of the absorption (the strongly hydrogen bonded acid group/aniline molecule or the formed ion pair) are the same, indicating that selectivity is due to the interaction strength between the target compound and the functional groups on the resin.

There are two differences which can be noticed between this kinetics plot and the plots of the kinetics of ion-exchange/redox with silver from chapter two. The competitive absorptions were done in methanol, which does not swell the resin to the extent that water does, and yet the absorption is almost certainly diffusion limited, given the speed of acid/base reactions. This can be seen by comparing the time to equilibrium for the two cases. The second point is that, in spite of the resin being less swollen in methanol than in water, diffusion of the anilines into the resin is probably faster than that for ions (although this is purely conjectural) because there is no counterion, and therefore no Donnan exclusion of the compounds from the resin. The lack of the Donnan effect has been shown with alcohols with a sulfonic acid resin, and allows for a much higher concentration of molecules in an ion-exchange resin than is generally possible with ions.

Conclusion

It has been found, using a linear free energy relationship, that selectivity of polymer-supported reagents for organic compounds in solution is dependent upon a number of factors, the most important being, the interaction strength between acidic groups on the resin with basic groups on the target compound (or vice versa), and the relative polarity of the polymeric reagent and the solvent compared to the target compound. A higher level of selectivity is observed when the polarity and hydrogen bonding characteristics of the polymer-supported reagent, the solvent, and the target compound are all comparable. Selectivity is the greatest when there is a moderate interaction strength between the functional groups on the polymer-supported reagent and the target compound. Thus, the phosphorus-based resins are selective for anilines from methano solution, as are the dimethylamine resins for benzoic acids from methanol. A hydrophobic effect is observed in aqueous solvents or mixtures of solvents, which aspecifically increases the uptake of target compound by the resin. Strong interactions between the resin and target compound functional groups will also cause a high level of non-selective absorption of compound from solution under non-competitive conditions, as is observed with the sulfonic acid resin with anilines in methanol. Weak interactions, e.g., a carboxylic acid resin with anilines in methanol cause only low levels of relatively non-selective absorption. Under competitive conditions, the total amount of compound absorbed from solution is observed to be approximately the same, but in this case, selectivity is observed for resins with both strong and moderate strength interactions with the target compounds. Thus, both the sulfonic acid and phosphinic acid resins are

selective for the more basic aniline from a mixture of anilines, although the sulfonic acid resin is not as selective as the phosphonic acid resin. PEG functionalities on a phosphonic acid resin increase the polarity of the resin, causing an increase in the amount of target compound absorbed from solution, and showing a very large degree of hydrophobic extraction of phenols from water, which are absorbed only minimally by other resins because of their very low interaction strengths with the resin functional groups.

Some possible future directions for the molecular recognition project are given below. One would be to use compounds which contain two functional groups which could both interact with the functional groups on the resin. This could be especially interesting if one of these were acidic in nature, while the other was basic. Contact with a resin such as the bifunctional amine/phosphonic acid resin should then possibly show high levels of absorption. By varying the polymer support, a size exclusion effect could also enhance the selectivity for molecules (i.e. an MR bead with very large molecules as is done now with gel permeation (size exclusion) chromatography. Other types of interactions need to be investigated, some of which are: purely polar attractions (as with the PEG and the PEG/phosphonic acid resins), electrostatic attractions (i.e. high electron density compounds, especially those which are conjugated systems), and modification of the acidity or basicity of ion-exchange resins to allow their use over a very narrow pH range for the separation of proteins and amino acids without the need for many different buffer solutions. In the area of bifunctional resins, Bartsch⁷⁵ has shown that the extraction ability of crown ethers can be significantly enhanced by the addition of a functional group which will also

ion-exchange. This should work as well with molecules as it does for ions. Thus, a whole range of both ion-exchange groups (acidic and basic) and chelating or coordinating groups (e.g. crown ethers, EDTA type ligands, hydroxyoximes, etc.), or even inclusion complex forming groups such as cyclodextrins, spherands, calixarenes, cryptates, etc. could be attached to a polymer support.

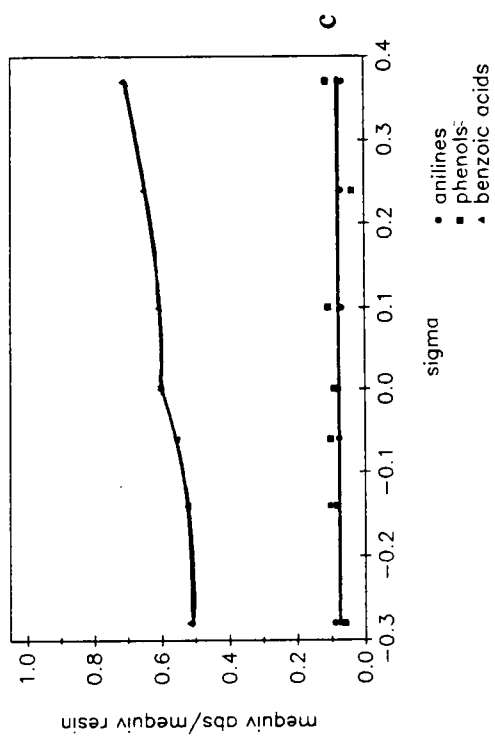
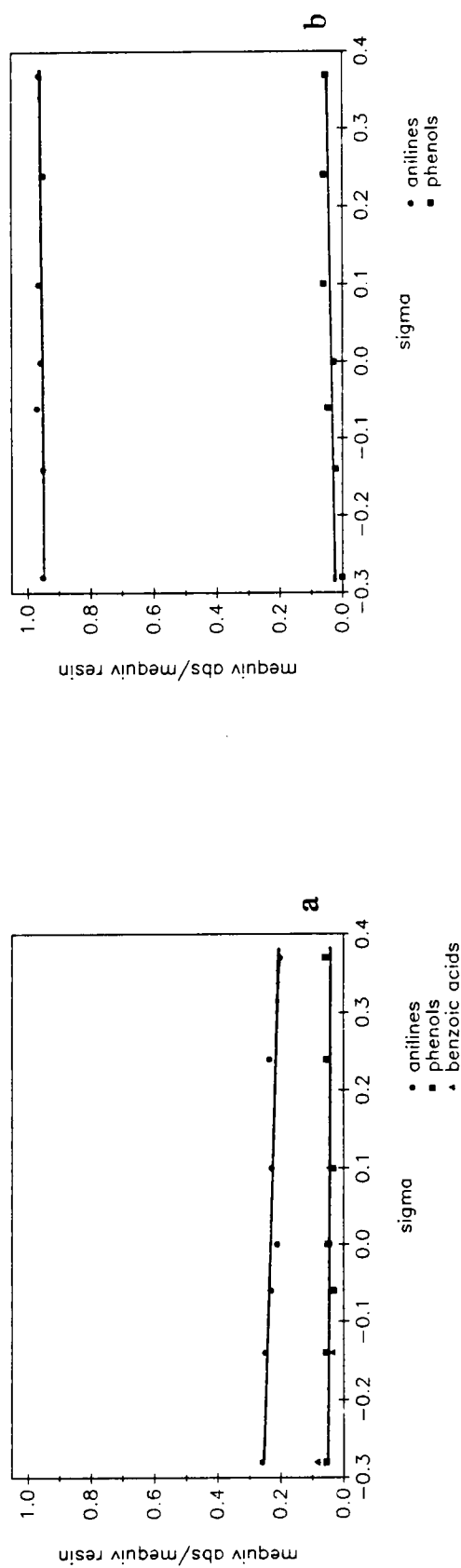


Figure 26. Absorption of Anilines, Phenols, and Benzoic Acids from Methanol by the Carboxylic Acid (a), Sulfonic Acid (b), and Dimethylamine (c) Resins

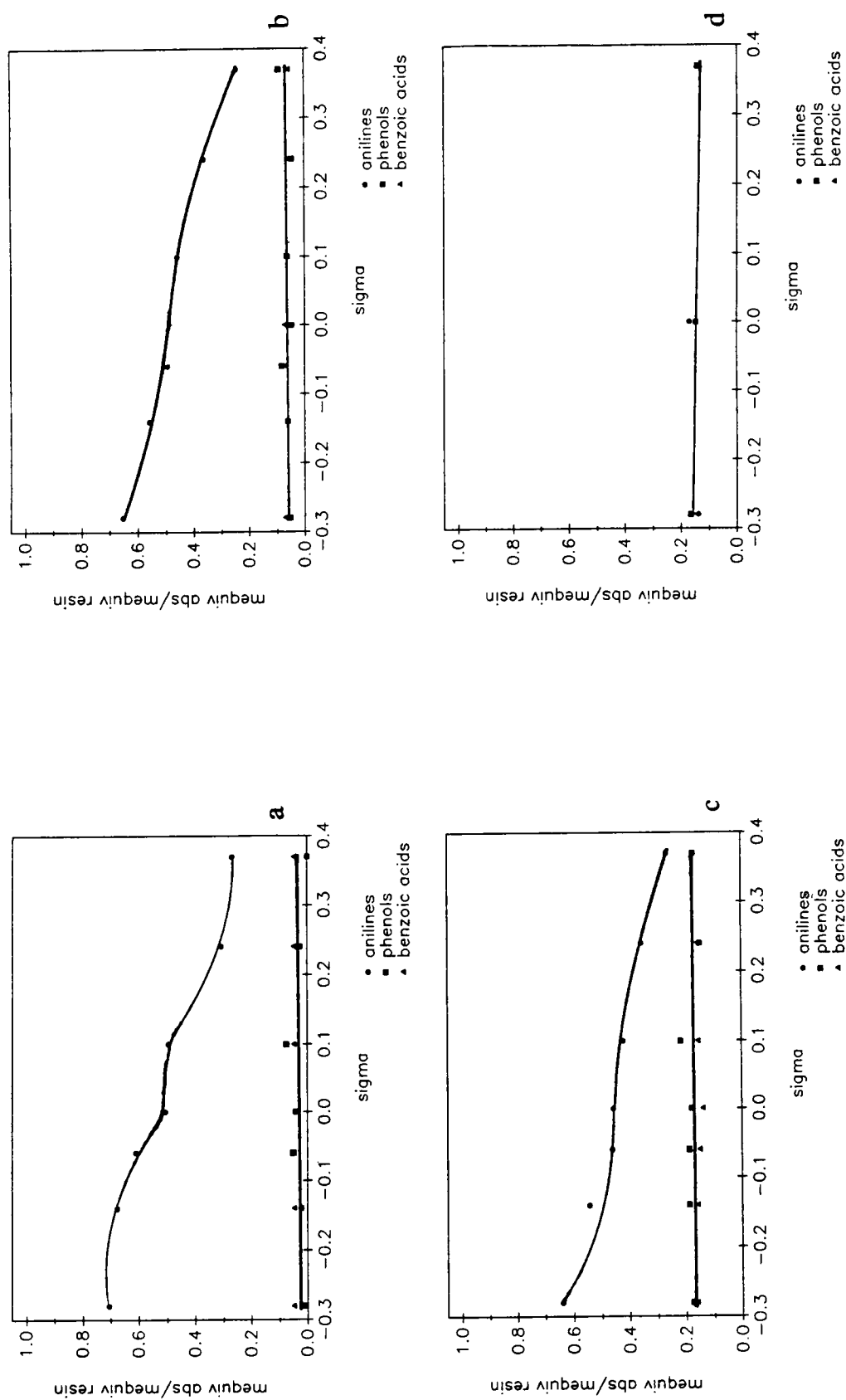


Figure 27. Absorption of Anilines, Phenols, and Benzoic Acids by the Phosphinic Acid (a), Phosphonic Acid (b), Phosphonate monoethyl Ester (c), and Phosphonate diethyl Ester (d) Resins

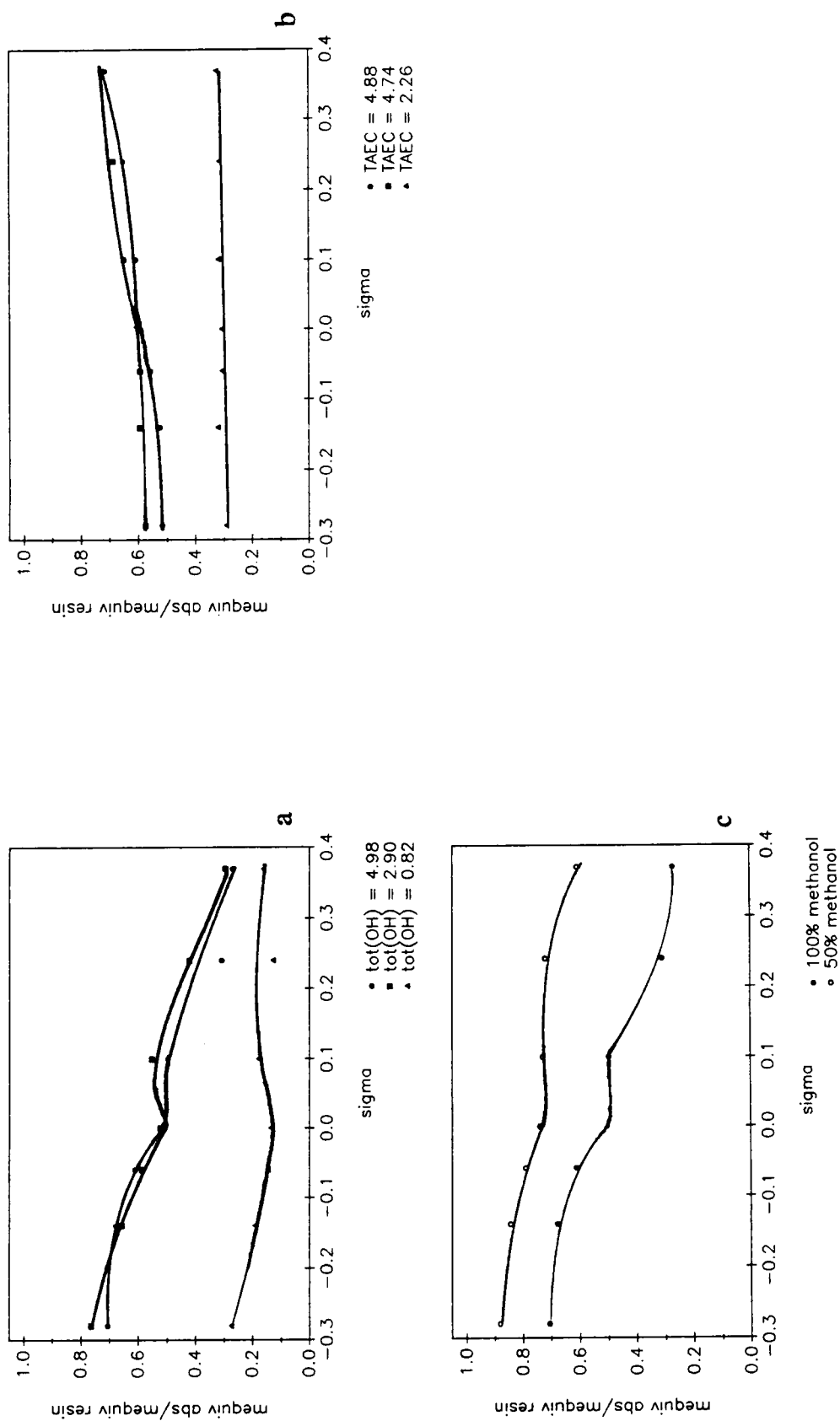


Figure 28. Phosphonic Acid Resin Functionalization Level Effect on Absorption of Anilines from Methanol (a), Dimethylamine Resin Functionalization Level Effect on Absorption of Benzoic Acids from Methanol (b), and Selectivity Dependence of Solvent on Absorption of Anilines from Methanol by the Phosphonic Acid Resin

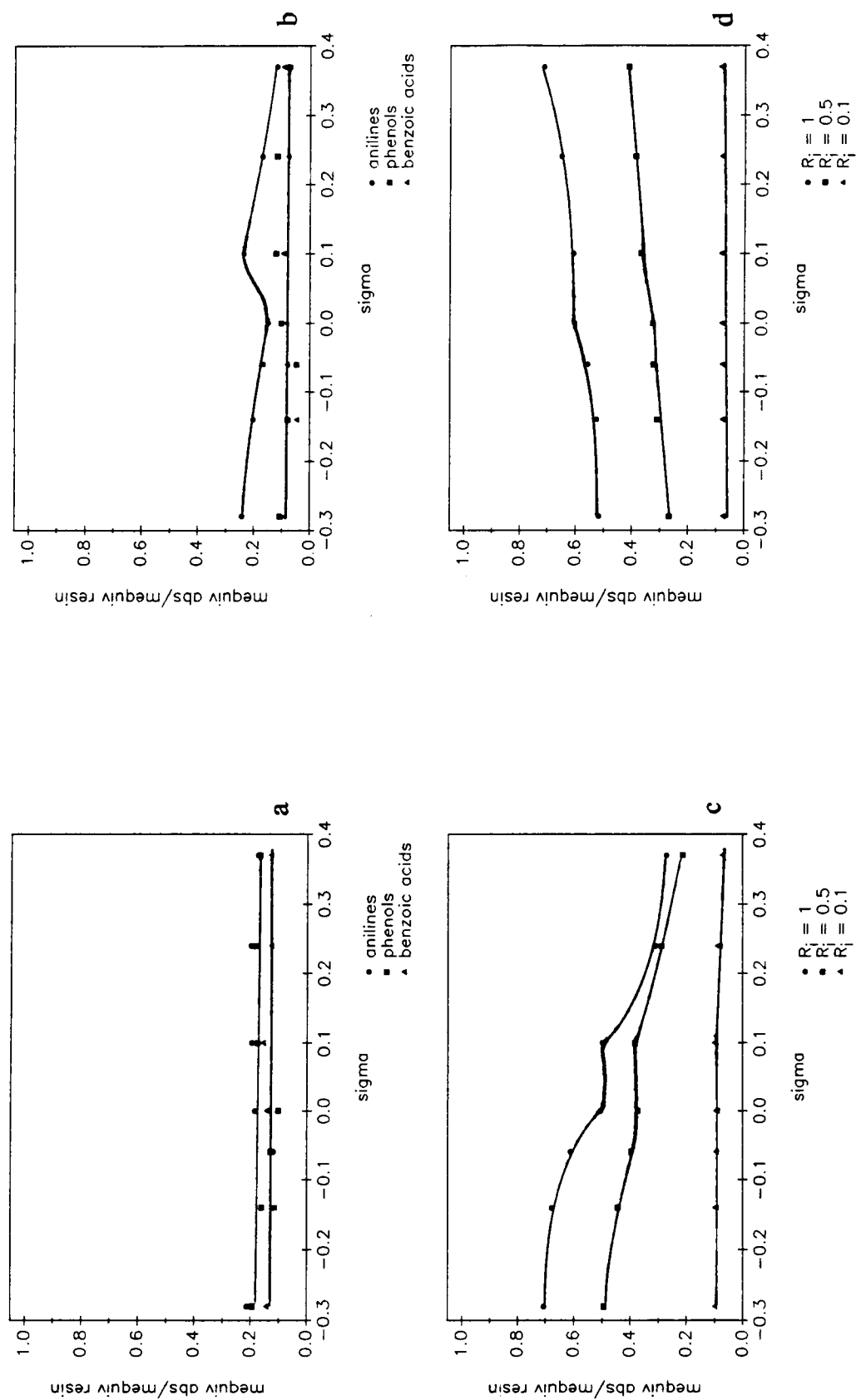


Figure 29. Absorption of Anilines, Phenols, and Benzoic Acids by the PEG (a) and PEG/Phosphonic Acid (b) Resins. The Effect of R_1 on Absorption of Anilines from Methanol by the Phosphonic Acid Resin (c), and Benzoic Acids from Methanol by the Dimethylamine Resin (d)

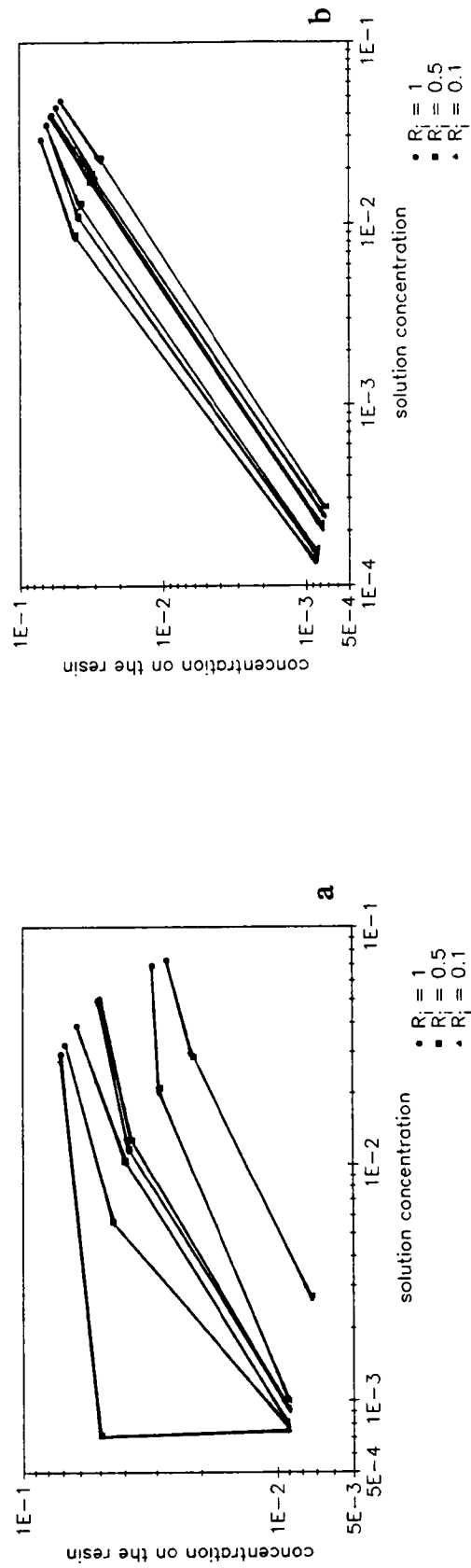


Figure 30. Isotherms for the Absorption of Anilines from Methanol by the Phosphinic Acid Resin (a) and Benzoic Acids from Methanol by the Dimethylamine Resins (b)

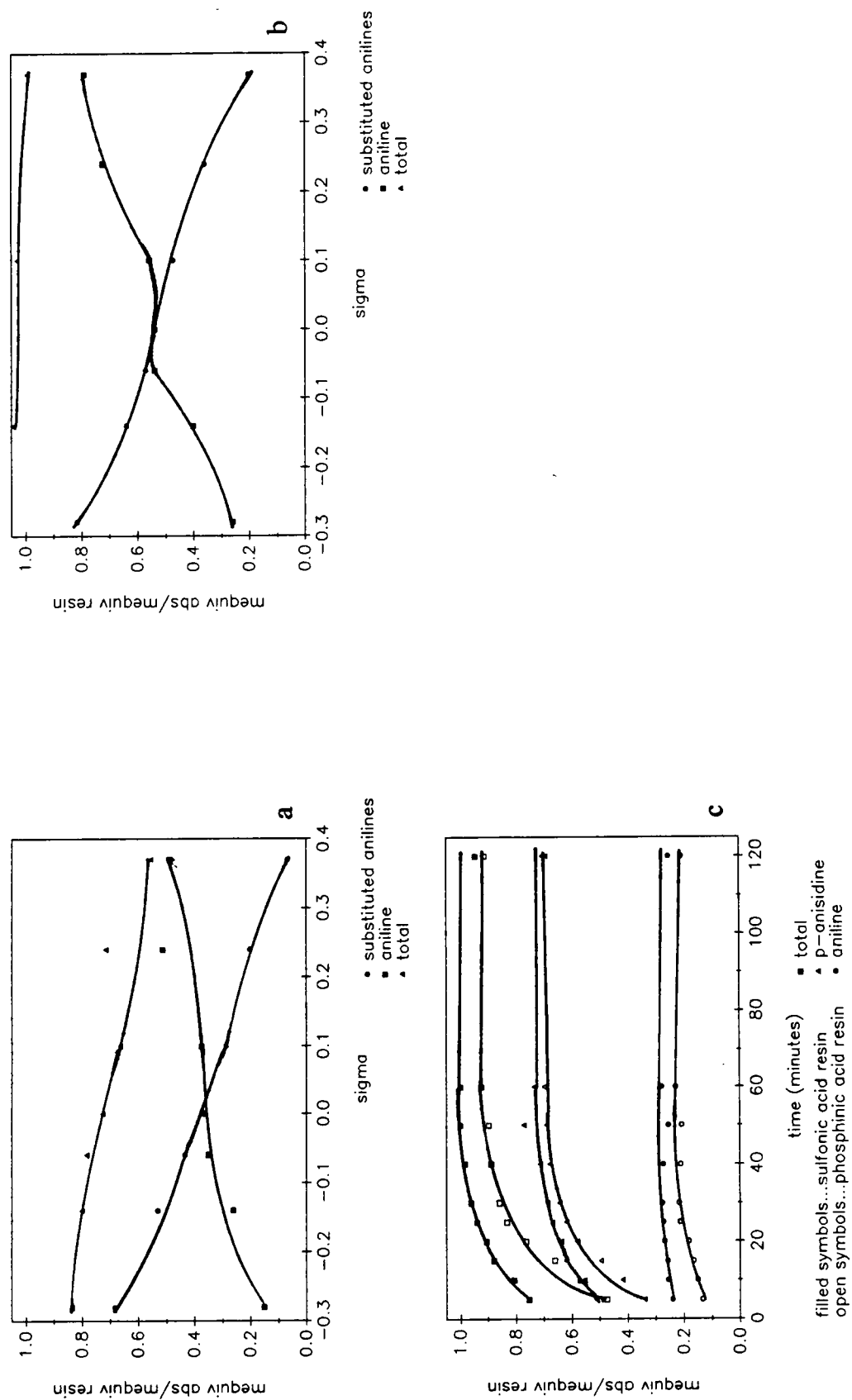


Figure 31. Competitive Selectivity of the Phosphonic Acid Resin (a) and the Sulfonic Acid Resin (b) for Anilines in Methanol, and the Comparative Rate of Aniline vs. p-Anisidine Absorption from Methanol by the Phosphonic Acid and the Sulfonic Acid Resins (c)

CHAPTER V

Experimental Procedures

Copolymer Synthesis

Polystyrene and poly(vinylbenzyl Chloride) beads were prepared by the technique of suspension polymerization. The apparatus used consisted of a 1l three-neck roundbottom flask equipped with a condenser, thermometer to which a temperature controller was attached (Thermowatch[®], I²R Co.), and a constant torque overhead stirrer (Con-Torque[®], Eberbach Co.) with a double-paddle stainless-steel stirrer. Oxygen was excluded from the system by a nitrogen purge, which was begun at least 30 minutes before addition of the solutions to the apparatus, and was continued throughout the entire reaction. The aqueous phase was composed of 0.96g gelatin (serves as a stabilizer to keep the monomer droplets from agglomerating during the polymerization) dissolved in 100.1g H₂O at 50°C. This was added to a solution containing 11.90g poly(diallyldimethylammonium chloride) (a suspending agent; it increases the viscosity of the aqueous phase) and 6.33g boric acid (buffer) dissolved in 216.5g H₂O. After combination of the two solutions, the pH was adjusted to 10.5 to prevent decomposition of the gelatin by the addition of 50% NaOH. After addition of the aqueous phase to the reaction flask, the stir motor was adjusted to 250 rpm (by the use of a Biddle dial tachometer) to give predominantly -20+40 mesh beads. For the preparation of a 2% crosslink level gel copolymer, the

organic phase consisted of 286.7g styrene (Aldrich Chemical Company) or vinylbenzyl chloride (VBC, Dow Chemical Company), 10.83g divinylbenzene (DVB, Dow Chemical Company; contained 55.4% mixture of DVB isomers, and 44.6% ethylstyrene impurity), and 3.00g benzoyl peroxide initiator (BPO, Aldrich Chemical Company). Upon addition of the organic phase to the reaction flask, the mixture was stirred for three cycles of 2 minutes stir and 1 minute settling period. The was then heated to 80°C over a two hour period with stirring, and held at this temperature for 10 hours. The reaction mixture was then heated to 100°C for an additional 2 hours to ensure complete polymerization. After cooling to room temperature, the beads were washed with pH 4 H₂O (pH adjustment was accomplished using HCl), followed by distilled H₂O. The beads were dried at 60°C overnight, and then sieved. After sieving, the poly(vinylbenzyl chloride) required soxhlet extraction with toluene to remove unreacted monomer and oligomers from the beads.

Macroporous (MR) beads were synthesized in the same manner, except that half of the monomer mixture was replaced with a phase extender or diluent. For example, 5% crosslink level MR beads were prepared using the same aqueous phase described previously, and the organic phase contained 134.95g styrene or vinylbenzyl chloride, 13.55g DVB, 1.50g BPO, and 150g 4-methyl-2-pentanol (Aldrich). The 2 hour 100°C finish off used with the gel beads was replaced with a 6 hour steam distillation to remove the alcohol. The same washing procedure was followed, but rather than oven drying as with the gel beads, the MR beads were air dried.

Resin Synthesis

Phosphinic Acid Resin Synthesis

Polystyrene beads from above (10g, 96mmoles) were placed in a 250ml three-necked roundbottom flask equipped with a condenser, thermometer, and overhead stirrer, and 80mL PCl_3 was added. The mixture was stirred for 1 hour to swell the copolymer, after which time, for a 0.77 mole ratio, 9.86g (74mmoles) AlCl_3 was added, and the mixture heated to 76°C (reflux) over 1 hour, and maintained for 4 hours at this temperature. After cooling to room temperature, the reaction was quenched by pouring into ice water saturated with NaCl . The beads were then washed with water until neutral, and then conditioned in a fritted glass funnel in the sequence (each 1 liter for 1 hour): H_2O , 4 wt% NaOH , H_2O , 4 wt% HCl , H_2O . The resin was analyzed for $\text{tot}(\text{OH})$, $\text{tot}(\text{P})$, primary acid capacity, and % solids.

Polystyrene-Based Phosphonic Acid Resin Synthesis

This synthesis was carried out as for the phosphinic acid resin, except that FeCl_3 was used in a 2 mole ratio with polystyrene beads. Thus, for 10g (96 mmoles) polystyrene beads, 15.57g (192mmoles) FeCl_3 was used. The larger amount of catalyst also required the addition of an additional 20mL PCl_3 to maintain fluidity. After conditioning, the resin was analyzed for $\text{tot}(\text{OH})$, $\text{tot}(\text{P})$, and % solids.

Poly(VBC)-Based Phosphonic Acid Resin Synthesis

This synthesis was the same as for the phosphinic acid resin synthesis, except that poly(VBC) beads were used in place of polystyrene beads, and a 1.2 mole ratio

of AlCl_3 was employed. Thus, for 10g (65.5mmoles) poly(VBC) beads, 10.5g (78.6mmoles) AlCl_3 were employed. After conditioning, the resin was then analyzed for tot(OH), tot(P), and % solids.

Poly(VBC)-based Phosphonate Diethyl Ester Resin Synthesis

This synthesis followed that for the poly(VBC)-based phosphonic acid resin, but the resulting mixture was not quenched in ice water. Instead, the beads remained in the reaction flask, and were washed free of PCl_3 using 6x200mL portions of toluene. The beads then had 50mL toluene added for fluidity, and with the reaction flask in an ice bath, an equimolar solution of ethanol and pyridine was introduced using an addition funnel, and the rate of addition was adjusted to maintain the reaction mixture between 5°C and 10°C. The mixture was stirred for 1 hour, followed by the addition of a second quench solution of the same composition the first one. The mixture was allowed to warm to room temperature, and then refluxed overnight. Conditioning was then carried out as for the phosphinic acid resin, followed by analysis for tot(OH) (both by overnight hydroxide analysis, and by a titration curve), tot(P), and % solids.

Sulfonic Acid Resin Synthesis

This resin was synthesized in the same apparatus as for the phosphinic acid resin by swelling 10g polystyrene beads with 20mL ethylene dichloride for 1 hour, followed by addition of 90g concentrated H_2SO_4 . The mixture was heated to 85°C (reflux) over a period of 1 hour, and held at this temperature for three hours.

Water washes were added, with the solution being siphoned off between washes, at a rate so as to maintain the temperature for the four washes at: 83°C-85°C, 80°C-82°C, 65°C-70°C, and 60°C, respectively. The resin was then placed in a fritted glass funnel and conditioned as per the phosphinic acid resin. The resin was then analyzed for tot(OH) and % solids.

Carboxylic Acid Resin Synthesis

Poly(VBC) beads (20g, 131mmoles) were placed in the same apparatus which was used for the phosphinic acid resin synthesis and swelled with 125mL toluene for 1 hour. A mixture of 37.5g KOH in 112.5mL ethanol was added, the mixture was heated to reflux over 1 hour, and reflux was maintained for 48 hours. After cooling, the resin was washed with 1L ethanol/1 hour, followed by three 1L/1 hour water washes. A portion of this resin was analyzed for residual chlorine and for oxidizable groups using chromic acid. The remaining portion was swelled for 1 hour in 120mL dry dioxane, followed by addition of 75mL 7% HNO₃. The mixture was heated to 80°C over 1 hour, and held at this temperature for 24 hours, after which time it was cooled to room temperature, placed in a fritted glass funnel, and washed with three 1L portions of distilled water. This resin was then placed back into the apparatus used previously, and 75mL dioxane was added, followed by 150mL 30% H₂O₂. The mixture was heated to 80°C over one hour, and held at this temperature for 24 hours. Upon cooling to room temperature, the conditioning sequence was followed (all solutions 1L for 1 hour): H₂O, 4 wt% NaOH, H₂O, 1M HNO₃, H₂O. The resin was then analyzed for tot(OH) and % solids.

Poly(ethylene glycol) Resin Synthesis

Poly(VBC) beads (10g, 65.5mmoles) were placed in the setup used for the phosphinic acid resin synthesis and swelled in 100mL dioxane for 1 hour. To this was slowly added 15.07g (thought to be penta(ethylene glycol), but later determined to most likely be the hexamer or heptamer; pentamer would be, for this weight, 63.3mmoles) and 2.7g (67.5mmoles) 60% NaH. The mixture was heated to reflux (104°C) over 1 hour, and held at this temperature for 48 hours. After cooling, the beads were placed in a fritted glass funnel and eluted with 1L dioxane, followed by 2L H₂O (1L/1 hour). The resin was then analyzed for residual chlorine content, free alcohol group content using PCl₅, chlorination followed by chlorine elemental analysis, and for (assumed) penta(ethylene glycol units by chromic acid.

Poly(ethylene glycol)/Phosphonic Acid Resin Synthesis

The multifunctional PEG/phosphonic acid resin was made by placing 20g (65.5mmoles) poly(VBC) beads in the same setup as was used for the phosphinic acid resin synthesis and stirring in a mixture of 100mL PCl₅/13.8g (85mmoles, 1.2 mole ratio) FeCl₃ for 17 hours. The temperature was then raised to 40°C, and held for 4 hours. Upon cooling to room temperature, the mixture was quenched in ice water saturated with NaCl as per the phosphinic acid resin. After being fully conditioned (see the phosphinic acid resin synthesis), the resin was analyzed for remaining chlorine, tot(OH), and tot(P). The remainder of the resin was dried by heptane azeotrope, placed back into the roundbottom flask used for the first part of the synthesis, and heated to 50°C with dioxane. The dioxane was decanted upon

cooling, dry dioxane was added, and the mixture refluxed with stirring for 24 hours. This dioxane was decanted off, dry dioxane was added until there was enough for fluidity, and to 9.84g (37.1mmoles chlorine present on the resin) partially functionalized resin was added 8.83g (assumed to be penta(ethylene glycol), in which case there would be 46.5mmoles) PEG and 3.06g (76.5mmoles) NaH. The mixture was heated to reflux over 1 hour, and the temperature maintained for 48 hours. After cooling, the beads were placed in a fritted glass funnel and washed with 1L dioxane, followed by full conditioning as per the phosphinic acid resin. The resin was then analyzed for tot(OH), tot(P), and % solids (the chromic acid analysis does not work when phosphonic acid groups are present, and the PEG content was therefore inferred from the change in tot(P) due to the change in molecular weight of the resin brought about by addition of the PEG units).

Synthesis of the Dimethylamine Resin

To the setup used for the phosphinic acid resin, with the addition of a drying tube adaptor on the end of the condenser, to which was fastened a balloon, was added 10g poly(VBC) beads, and 100mL 40% aqueous dimethylamine solution. The reaction was heated to reflux over 30 minutes, and the temperature maintained for 17 hours. Upon cooling to room temperature, the beads were put in a fritted glass funnel and conditioned using the sequence (all 1L/1 hour): H₂O, 4 wt% HCl, H₂O, 4 wt% NaOH, H₂O. The resin was then analyzed for residual chlorine, TAEC, SSAC, and % solids.

Synthesis of the Bifunctional Dimethylamine/Phosphonic Acid Resin

This resin was synthesized by partially phosphorylating poly(VBC) beads as has been described for the PEG/phosphonic acid resin synthesis, followed by amination of the unreacted benzylic chloride groups using 40% aqueous dimethylamine, which has also been previously described for the dimethylamine resin synthesis. After conditioning as per the phosphonic acid resin, the resin is analyzed for tot(OH), tot(P), chlorine content (from Cl⁻ associated with the protonated amine group), TAEC, and % solids.

Poly(ethylene imine) Resin Synthesis

To 10g (65.5mmoles) poly(VBC) beads in the setup used in the phosphonic acid resin synthesis was added 100mL dioxane, in which the beads were allowed to swell for 1 hour at room temperature. To this was then added approximately a five to tenfold excess (75mL to 190mL) of poly(ethylene imine). PEI's used were the homologues ethylenediamine through pentaethylenhexamine. The mixture was heated to reflux over 1 hour, and reflux was maintained for 44 hours, after which time the mixture was cooled to room temperature, and the resin was eluted with H₂O, followed by a full conditioning as for the dimethylamine resin. The resin was then analyzed for residual chlorine content, TAEC, SSAC, and % solids.

H₂O₂ Oxidation of the Phosphonic Acid Resin

The phosphonic acid resin was oxidized by placing 10g Büchner-dried phosphonic acid resin in the setup used for the phosphonic acid resin synthesis and

adding 150mL 20% aqueous H_2O_2 solution, and heating to reflux over a 4 hour period, and maintaining this temperature for 1 hour. The resin is then conditioned as for the phosphonic acid resin, and analyzed for tot(OH), tot(P), and % solids.

DCC Esterification of the Phosphonic Acid Resin

To 15g phosphonic acid resin in a setup such as that used for the phosphonic acid resin synthesis was added 100mL ethanol, 6g methanesulfonic acid, and 78g dicyclohexylcarbodiimide (DCC). The mixture was heated to reflux over 1 hour, and reflux maintained for 24 hours. Upon cooling to room temperature, the resulting mixture was placed in a soxhlet extraction apparatus, and extracted with ethanol for 4-7 days to remove dicyclohexylurea (DCU) and methanesulfonic acid. The resin was analyzed for tot(OH), and used without further treatment.

Azeotropic Drying of Resins

10g of resin to be dried is placed in a 250mL single-neck roundbottom flask to which is added 100-150mL heptane. The flask is equipped with a Dean-Stark water trap and condenser, and the solution is refluxed for 24 hours, with periodic removal of the water from the trap.

Ester Hydrolysis

The resin (10-20g) was placed in a 250mL single-neck roundbottom flask equipped with a condenser, approximately 125-150mL concentrated HCl was added, and the mixture was refluxed for 17 hours. After cooling to room temperature, the

mixture was poured into a fritted glass funnel and fully conditioned as in the phosphinic acid resin synthesis.

Analytical Techniques used with the Polymer-Supported Reagents

Determination of % Solids

A sample of resin was suction-dried at 40mm Hg below atmospheric pressure for 5 minutes, with the Büchner funnel covered on top with a rubber sheet held in place with a rubber band. Approximately 1g of resin was weighed into a tared scintillation vial and dried at 110°C for 16 hours. The vial was removed from the oven and placed in a desiccator to cool, upon which the vial containing the beads was reweighed, and the % solids calculated according to the equation:

$$\% \text{ solids} = \frac{\text{oven-dried resin weight}}{\text{suction-dried resin weight}} \times 100$$

Determination of Acid Capacity (tot(OH))

Approximately 0.5g-1.0g (dry weight) Büchner-dried resin was placed in a 250mL Erlenmeyer flask with a ground glass joint. Into this was pipetted 200mL standard 0.1M NaOH which was 5 wt% in NaCl. The contents were stirred for 17 hours using a magnetic stirrer, after which time a 50mL aliquot was titrated with standard 0.1M H₂SO₄. The tot(OH) analysis, which is accurate to ±0.2 mequiv/g, was calculated using the equation:

$$\text{tot(OH)} = \frac{(\text{vol NaOH})(N \text{ NaOH}) - 4(\text{vol H}_2\text{SO}_4)(N \text{ H}_2\text{SO}_4)}{\text{g resin}^a}$$

- ^a The resin is not dried prior to the tot(OH) analysis. This is, rather the dry weight equivalent of the Büchner-dried resin used for the analysis. To ensure full accessibility of the functional groups, under no circumstances is a resin ever oven or air dried before any analysis, except for the tot(P) and the chlorine analyses.

Phosphorus Elemental Analysis (tot(P))⁷⁶

Oven-dried resin (20mg) was placed in a 125mL Erlenmeyer flask, to which was added (in order) 5mL concentrated HNO₃ and 10mL 72% HClO₄. The mixture was heated until the beads were completely digested, and the solution was clear. After cooling to room temperature, the solution was quantitatively transferred to a 100mL volumetric flask, and diluted with distilled water. To 5mL of this solution in a 50mL volumetric flask was added (in order) 3.5mL 72% HClO₄, 4.5mL freshly prepared amidol solution (1g recrystallized 2,4-diaminophenol dihydrochloride (Aldrich), 10g Na₂SO₃, 2.7g concentrated H₂SO₄, and 90g H₂O), and 3.5mL ammonium molybdate solution (4.4g in 50mL H₂O). The flask was filled to the mark, and the solution was allowed to develop for 30 minutes, taking care to keep the flask away from strong or direct light. A blank solution was also prepared with all the reagents, but without any phosphorus. The absorbance of the solutions was measured at a wavelength of 700nm on a Bausch and Lomb Spectronic 21 spectrophotometer after setting the zero with the blank solution. The phosphorus

content of the samples was determined from a Beer's Law plot (slope = 131.70 mL/mg) of a series of K_2HPO_4 standard solutions. The tot(P), which is accurate to ± 0.1 mequiv/g was calculated using the equation:

$$\text{tot(P)} = \frac{(\text{absorbance})(1000\text{mL})}{(\text{g resin})(30.974 \text{ mg/mequiv})(131.7\text{mL/mg})}$$

Determination of Primary Acid Capacity by Iodine Oxidation⁷⁷

Iodine oxidation of the phosphinic acid resin was effected by placing 0.5g (dry equivalent) resin in a 250mL brown glass bottle equipped with a teflon or polyethylene-lined cap. To the resin was added 50mL 0.2N KI_3 solution (prepared at least 24 hours in advance by dissolving 25.4g I_2 and 80g KI in 1L H_2O , and standardized against a 0.1N standard $Na_2S_2O_3$ solution, which was prepared by dissolving 25g $Na_2S_2O_3$ in 1L boiled H_2O to which 0.2g Na_2CO_3 was added as a preservative, then standardized against primary standard KIO_3 , using a starch indicator) and 2mL pyridine. This was shaken for 22 hours, after which time 50mL of the 0.1N $Na_2S_2O_3$ solution was added, and the shaking was resumed until the thiosulfate had reacted with all of the iodine (as evidenced by a clear solution), or for a maximum of two hours. If the iodine color had not disappeared after 1.5 hours of shaking with the thiosulfate, 5mL toluene was added to the mixture to swell the resin (the thiosulfate is known only to have trouble getting into resins which have a low level of functionalization, and are therefore hydrophobic), and the shaking was continued for an additional 30 minutes. The entire contents of the bottle were

then quantitatively transferred to a beaker, and titrated to a starch endpoint (dark blue) for excess thiosulfate using the KI_3 solution. The primary acid capacity, was calculated with an accuracy of ± 0.2 mequiv/g using the equation:

$$1^\circ \text{ acid capacity} = \frac{(\text{vol KI}_3)(N \text{ KI}_3) - (\text{vol Na}_2\text{S}_2\text{O}_3)(N \text{ Na}_2\text{S}_2\text{O}_3)}{2(\text{g dry equivalent resin})}$$

Chlorine Elemental Analysis

Approximately 0.3g of dry resin was weighed into a 15mm X 150mm Pyrex test tube (tube #1), which was clamped onto a ring stand high enough to allow a Bunsen burner to be placed underneath it. To this tube was added approximately 2g sodium metal and 1mL xylenes. A second test tube (tube #2) containing approximately 0.5g sodium metal and 1mL xylenes was also clamped on the same stand, also high enough to allow placement of a Bunsen burner underneath it. A 7mm glass tube was bent into a U shape to act as a transfer tube for gasses to pass from test tube #1 to test tube #2. One end of this tube was mounted in a #2 single-hole rubber stopper, with the end of the tube protruding approximately 0.5 inches past the end of the stopper. The other end is made long enough to protrude completely to the bottom of test tube #2, which remains unstoppered throughout the entire sodium fusion. The rubber stopper containing the transfer tube is placed securely into test tube #1, and the other end of the transfer tube is placed in the molten sodium metal in test tube #2, which is heated strongly by placing a Bunsen burner beneath it until the end of the sodium fusion. Test tube #1 is then slowly

heated, first to drive off the xylenes (to ensure before the beads began to char that the transfer tube was not plugged with sodium), then to melt the sodium. This is accomplished by a slow waving of the Bunsen burner flame above the sodium at first, slowly working down towards the beads in the bottom of the test tube. The heating is continued, working towards the resin sample with stronger heating to slowly char the beads over a 3 to 4 minute time period. When the beads are completely charred, the Bunsen burner is placed underneath test tube #1, and both tube are allowed to remain in the Bunsen burner flames for 15 minutes. After cooling to room temperature, the transfer tube and the two test tubes were broken using pliers into a 250mL beaker containing 100mL-150mL dry methanol. After the sodium had all reacted, the methanol was evaporated using a hot plate. The remaining solid was dissolved with distilled water and quantitatively filtered into a 250mL volumetric flask. A 50mL aliquot of this was acidified with concentrated HNO_3 to a methyl orange endpoint (the indicator turned from yellow to red), and was then neutralized using 0.3M NaOH just until the solution turned yellow again. The sample was then titrated for chloride using the Mohr method, which uses standard AgNO_3 (0.05M, 8.494g in 1L distilled H_2O) as the titrant, and 5 wt% $\text{K}_2\text{Cr}_2\text{O}_7$ (2mL) as the indicator. The endpoint is detected when the first permanent brick red color is observed. If the beads contained nitrogen, it is necessary to boil the sample for 5 minutes after acidification to remove CN^- , which is an interference in the method. The chlorine content was calculated with an accuracy of ± 0.2 mequiv/g using the equation:

$$\text{chlorine capacity} = \frac{5(\text{vol AgNO}_3)(N \text{ AgNO}_3)}{\text{g resin}}$$

Chromic Acid Oxidation of the PEG Resin

Into a 125mL Erlenmeyer flask with a ground glass joint was weighed approximately 0.5g resin. To this was pipetted 100mL 0.6N standard chromic acid solution (prepared by dissolving 29.4g dried $\text{K}_2\text{Cr}_2\text{O}_7$ and 300mL concentrated H_2SO_4 in 1L H_2O), the stopper was greased, and the mixture was stirred with a magnetic stirrer for five days. A 10mL aliquot was then titrated (millivolt titration) with standard 0.1N FeSO_4 solution (prepared by dissolving 41.6g $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ and 20mL concentrated H_2SO_4 in 1L H_2O , followed by standardization against the dichromate solution) using a Corning model 130 pH meter and a combination silver/silver chloride and platinum redox electrode. The PEG capacity of the resin was calculated with an accuracy of ± 0.2 mequiv/g using the equation:

$$\text{PEG capacity} = \frac{60 - 10(\text{vol FeSO}_4)(N \text{ FeSO}_4)}{52(\text{g dry equivalent resin})}$$

In this equation, 60 is the total number of electrons in the chromic acid, 10 is the total equivalence of the iron solution, and 52 is an experimentally determined number,³⁶ which was originally thought to be for penta(ethylene glycol) units. It has

since been determined that the hexamer or the heptamer were actually used in this work.

Chlorination using PCl₅

The PEG resin was chlorinated with PCl₅ in order to determine the number of free hydroxyl groups via chlorine elemental analysis. This was accomplished by shaking 2g dried resin with 1g pyridine and 2.5g PCl₅ in 50 mL dry dioxane for 48 hours. The solution was then decanted, and the beads shaken for 1 hour with each (in order): dry dioxane, 80% aqueous dioxane, 0.5M KOH in 50% aqueous dioxane, 80% aqueous dioxane, 0.5M HNO₃ in 80% aqueous dioxane, and 80% aqueous dioxane. The resin was then placed in a fritted glass funnel and eluted with 1L distilled water.

Determination of the Total Anion Exchange Capacity (TAEC)

A 5-10g (dry equivalent) sample of resin containing the amine function was converted to the chloride form by elution with HCl, placed in a fritted glass funnel, and eluted with 1L 4 wt% NaNO₃ for 1 hour, the effluent being collected in a 1L volumetric flask. A 100mL aliquot was titrated for chloride content using the Mohr titration described earlier. The TAEC was calculated with an accuracy of ± 0.2 mequiv/g using the equation:

$$\text{TAEC} = \frac{10(\text{vol AgNO}_3)(N \text{ AgNO}_3)}{\text{g dry equivalent resin}}$$

Determination of the Salt Splitting Anion Exchange Capacity (SSAC)

The resin sample used in the TAEC determination was left in the fritted glass funnel and eluted with 1L 4 wt% NaOH for 1 hour to give the free amine, and OH⁻ as the associated counterion to the quaternary amine sites. After eluting with water to remove excess hydroxide, the sample was eluted with 1L 4 wt% NaNO₃ for 1 hour. The eluent was collected in a 1L volumetric flask, and a 100mL aliquot was titrated with standard 0.1M H₂SO₄ for hydroxide ion. The SSAC was calculated with an accuracy of ± 0.2 mequiv/g using the equation:

$$\text{SSAC} = \frac{10(\text{vol H}_2\text{SO}_4)(N \text{ H}_2\text{SO}_4)}{\text{g dry equivalent resin}}$$

Determination of Ag⁺ and Hg²⁺ Absorbed by the Phosphinic Acid Resin

To 10mequiv resin was added in a brown glass bottle with a teflon-lined cap 50mL 0.2N AgNO₃ or Hg(NO₃)₂ at the appropriate temperature, and stirred at 350rpm for the appropriate amount of time. The contents were then poured into a fritted glass funnel, the metal solution kept for analysis, and the resin washed quickly with approximately 100mL water, then eluted with 1L for 1 hour each 4.2M HNO₃, followed by water. The resin was then analyzed for tot(OH), and the amount absorbed by redox was calculated with an accuracy of $\pm 3\%$ using the equation:

$$\% \text{ absorbed by redox} = \frac{2(\text{g dry equivalent resin})(\text{tot}(\text{OH})_i - \text{tot}(\text{OH})_f)}{10}$$

The total amount of metal absorbed from solution was determined by Volhard⁷⁸ titration of 25mL of the metal solution using standard 0.1N NH_4SCN (standardized against standard AgNO_3 solution) with 5mL ferric ammonium sulfate (10g $\text{Fe}(\text{NH}_4)(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ dissolved in 100mL 6M HNO_3) indicator, with a permanent brick red color indicating the endpoint. The total amount of metal absorbed from solution was calculated using the equation:

$$\% \text{ absorbed} = \frac{10 - 2(\text{vol } \text{NH}_4\text{SCN})(N \text{ NH}_4\text{SCN})}{10}$$

The amount of metal absorbed by ion-exchange is taken to be the difference between the amount absorbed by redox and the total amount absorbed.

Reduction of the Phosphonic Acid Resin

NaBH_4 Reduction of the Phosphonic Acid Resin

To 25g Büchner-dried resin in the sodium salt form in a 250mL brown glass bottle with a teflon-lined cap in 45mL H_2O and 5mL 1M NaOH was added 1.20g NaBH_4 . The solution was shaken (using a Burrell wrist-action shaker) for 44 hours,

after which time it was placed in a fritted glass funnel and conditioned as for the phosphinic acid resin, and analyzed for tot(OH).

NaH and LAH Reduction of the Phosphonic Acid Resin

To 15g heptane azeotroped resin (diethyl ester or acid) in the sodium salt form in the setup used for the phosphinic acid resin synthesis in 100mL dry dioxane was added 2.50g LAH. The mixture was heated to reflux over 1 hour with stirring, and maintained at reflux for the appropriate amount of time. The thermometer was replaced with an addition funnel, and approximately 100mL 0.1M HCl was slowly added. The resin was then placed in a fritted glass funnel, conditioned as for the phosphinic acid resin, and analyzed for tot(OH). For the ester resins, hydrolysis of the ester function was performed before conditioning.

Sodium Metal Reduction of the Phosphonic Acid Resin

To 100mL THF and 65ml toluene in a setup such as that used for the phosphinic acid resin synthesis was added 15g sodium metal. The solution was heated to reflux with rapid stirring to form a fine sodium "sand". The stirring was continued after the heat was removed and the mixture cooled to below the melting point of sodium (98°C). To this was then added 5g dry (azeotropically dried, or eluted with ethanol) resin (either the diethyl ester or the acid) converted to the sodium salt by elution with 1L 4 wt% NaOH before drying, and (in some procedures) 30g naphthalene. The mixture was brought back to reflux over 30 minutes, and held at this temperature for the appropriate amount of time. After cooling, the

reaction was quenched by slowly adding through an addition funnel approximately 100mL 0.1M HCl. The resin was then fully conditioned and analyzed for tot(OH). If an ester resin was used, hydrolysis of the ester function was performed before conditioning.

Zinc Metal Reduction of the Phosphonic Acid Resin

To 2.06 grams of phosphonic acid resin and 100mL H₂O in a 250mL single neck roundbottom flask equipped with an overhead stirrer was added 20g NaOH and 12.26g powdered zinc metal. The mixture was stirred for 48 hours, after which time the resin was placed in a fritted glass funnel and conditioned as for the phosphonic acid synthesis. The resin was then analyzed for tot(OH) and % solids.

Trichlorosilane Reduction of the Phosphonic Acid Resin

To a 250mL three-neck roundbottom flask was added 5.5g heptane azeotroped resin (diethyl ester or acid), 90mL benzene, 3mL HSiCl₃, and 3.7mL N,N-dimethylaniline. The mixture was heated to reflux over 30 minutes, and maintained at this temperature for the appropriate amount of time, after which the mixture was cooled to room temperature, and 30% aqueous NaOH was slowly added. The resin, if the ester, was hydrolyzed and fully conditioned after eluting with 1L ethanol to remove benzene and the aniline.

Molecular Absorption Studies

In a 50mL glass bottle was placed 1mequiv resin (which had been solvent exchanged by shaking each resin sample four times for 15 minutes in the solvent to

be used for the study and decanting the after each shake period) and a 1 inch spinbar. To this was pipetted 10mL of a 0.1M solution of the target compound in the appropriate solvent, and the solution stirred for 17 hours at 350rpm. The solution was then centrifuged for 15 minutes, and for the anilines and phenols, a 5mL aliquot was pipetted into a 13mm X 100mm test tube, 50 μ L of internal standard compound was added (n-hexanol for dioxane and alcohol solvents, dioxane for water), and the samples were analyzed by gas chromatography (see the Appendix for details). For the benzoic acids, a 5mL aliquot was titrated with standard 0.1M NaOH to a phenolphthalein endpoint.

LIST OF REFERENCES

1. The Works of Aristotle, *Meteorologica* II. 3, 359^a (B. C. 330).
2. Thompson, H. S. *J. Roy. Agric. Soc.*, 1850, 11, 68.
3. Way, J. T. *ibid.*, 313.
4. Way, J. T. *J. Roy. Agric. Soc.* 1852, 13, 123.
5. Eichorn, H. *Progg. Ann. Phys. Chem.* 1858, 105, 126.
6. Kitchener, J. A. *Ion-Exchange Resins*; John Wiley and Sons: New York, 1961, pp. 7-8.
7. Kitchener, J. A. *ibid.*, p. 3.
8. Inczédy, J. *Analytical Applications of Ion Exchangers*; Pergamon Press: New York, 1966, p. 2.
9. Adams, B. A.; Holmes, E. L. *J. Soc. Chem. Ind. (London)*, 1935, 54, 1T.
10. D'Alelio, G., *U. S. Patents* 2,366,007 (December 26, 1944); 2,336,008 (December 26, 1944).
11. Brenes Balbuena, M.; Garrido Fernandez, A. *Grasas Aceites (Seville)* 1988, 39, 22.
12. Osborn, G. H. *Synthetic Ion-Exchangers*; MacMillan: New York, 1956, pp. 89-191.
13. Dow Chemical Company *Dowex: Ion Exchange*; R. R. Donnelley and Sons: Chicago, 1958.
14. Gel type copolymer is synthesized by polymerization of a mixture of monomers, which in this case are either styrene or vinylbenzyl chloride with divinylbenzene as a crosslinking agent. Macroreticular type copolymer is produced by substitution of half of the monomer mixture with a compound (in this case 4-methyl-2-pentanol) which is a good solvent for the monomer mixture, but not for the polymer. When the alcohol is removed from the copolymer beads, large, rigid channels are present. There is a third type of copolymer which can be made, known as a xerogel. This produced by the addition of a compound such as toluene, which is a good solvent for both the monomer mixture and the polymer. This type of copolymer has a greater distance between the polymer chains, but does not have rigid or enforced macropores.
15. Alexandratos, S.D.; Strand, M.A.; Quillen, D.R.; Walder, A.J. *Macromolecules* 1985, 18, 829.

16. Olah, G. A.; Kobayashi, S.; Tashiro, M. *J. Am. Chem. Soc.* **1972**, *94*, 7448.
17. Segi, M.; Nakajima, T.; Suga, S. *Bul. Chem. Soc. Jpn.* **1980**, *53*, 1466.
18. It has since been found that 0.1M KOH in 80% dioxane gives good results for the tot(OH) analysis of low functional level resins due to better swelling. The tot(OH) and the tot(P) agree very well when this technique is used. See Walder, A. J. Ph.D. Dissertation, The University of Tennessee, Knoxville, August, 1989.
19. Kosolapoff, G. M.; Huber, W. F. *J. Am. Chem. Soc.* **1947**, *69*, 2020.
20. Streitwieser, A., Jr.; Heathcock, C. H. *Introduction to Organic Chemistry*, 2nd ed.; Macmillan Publishing Company: New York, 1981, pp. 701-702.
21. Frank, A. W. *J. Org. Chem.* **1959**, *24*, 966.
22. Jacobelli, H.; Bartholin, M.; Guyot, A. *Angew. Makromol. Chem.* **1979**, *80*, 31.
23. Wilson, D.L. Masters Thesis, University of Tennessee, Knoxville, May, 1985.
24. Alexandratos, S. D.; Wilson, D. L.; Kaiser, P. T.; McDowell, W. J. *Reactive Polymers* **1987**, *5*, 23.
25. *Handbook of Chemistry and Physics*, 60th ed.; Weast, R. C., Ed.; CRC Press: Boca Raton, 1980; D-155.
26. *Lange's Handbook of Chemistry*, 13th ed.; Dean, J.A., Ed.; McGraw-Hill Book Company: New York, 1985; 6-34.
27. Boyd, G. E.; Soldano, B. A. *J. Am. Chem. Soc.* **1954**, *75*, 6091.
28. Helfferich, F. *J. Phys. Chem.* **1965**, *69*, 1178.
29. Nativ, M.; Goldstein, S.; Schmuckler, G. *J. Inorg. Nucl. Chem.* **1975**, *37*, 1951.
30. Helfferich, F. G. In *Mass Transfer and Kinetics of Ion Exchange*; Liberti, L.; Helfferich, F. G., Eds.; Martinus Nijhoff: The Hague, 1983; Chapter 5.
31. Helfferich, F. G.; Liberti, L.; Petruzzelli, D.; Passino, R. *Isr. J. Chem.*, **1985**, *26*, chapter 2.
32. Quillen, D.R. Ph.D. Dissertation, The University of Tennessee, Knoxville, December, 1989.
33. Alexandratos, S. D.; Quillen, D. R.; Kaiser, P. T.; Bates, M. E.; Liang, G. *Polym. Prepr. Am. Chem. Soc. Div. Polym. Chem.* **1988**, *29*, 414.

34. Recollections of work done by A. J. Walder, in which he had considerable difficulty performing sodium fusions on HNO_3 contacted beads. Upon holding the flame of a Bunsen burner close to a small amount of dried resin on a watch glass, all of the beads ignited almost immediately. Polystyrene beads (or the copolymer itself does not behave in such a manner, but only very slowly chars.
35. Itsuno, S.; Ito, K. *J. Org. Chem.* **1990**, *55*, 3950.
36. Streitwieser, A., Jr.; Heathcock, C. H. *Introduction to Organic Chemistry*, 2nd ed.; Macmillan Publishing Company: New York, 1981, pp. 401-403.
37. March, J. *Advanced Organic Chemistry*, 3rd ed.; Wiley-Interscience: New York, 1985, p. 1101.
38. Perman, C. A. *Talanta* **1979**, *26*, 603.
39. Imamoto, T.; Kusumoto, T.; Suzuki, N.; Sato, K. *J. Am Chem. Soc.* **1985**, *107*, 5301.
40. Streitwieser, A., Jr.; Heathcock, C. H. *Introduction to Organic Chemistry*, 2nd ed.; Macmillan Publishing Company: New York, 1981, p. 516.
41. Streitwieser, A., Jr.; Heathcock, C. H. *ibid*, p. 516.
42. House, H. O. *Modern Synthetic Reactions*, 2nd ed.; Benjamin Cummings Publishing Company: Menlo Park, 1972, pp. 146-7.
43. Benkeser, R.A. *Acc. Chem. Res.* **1971**, *4*, 94.
44. Benkeser, R.A.; Dunny, S.; Jones, P.R. *J. Organometal. Chem.* **1965**, *4*, 338.
45. Kursanov, D.N.; Parnes, Z.N.; Loim, N.M. *Synthesis* **1974**, 633.
46. Bernard, M.; Ford, W.T. *J. Org. Chem.* **1983**, *48*, 326.
47. Quin, L.D.; Caster, K.C.; Kisalus, J.C. *Phosphorus and Sulfur* **1983**, *18*, 105.
48. Fritzsche, H.; Hasserodt, U.; Korte, F. *Chem. Ber.* **1965**, *98*, 171.
49. Regen, S.L.; Lee, D.P. *J. Org. Chem.* **1975**, *40*, 1669.
50. Horner, L.; Balzer, W.D. *Tetrahedron Lett.* **1965**, *17*, 1157.
51. Collins, D.J.; Drygala, P.F.; Swan, J.M. *Aust. J. Chem.* **1984**, *37*, 1349.
52. Frizsche, H.; Hasserodt, U.; Korte, F. *Chem. Ber.* **1965**, *98*, 1681.

53. Hudlicky, M. *Reductions in Organic Chemistry*; Halstead Press: Chichester, 1984, p. 139.
54. Quin, L.D.; Bernhardt, F.C. *J. Org. Chem.* **1986**, *51*, 3235.
55. Sheehen, J. C.; Hess, G. P. *J. Am. Chem. Soc.* **1955**, *77*, 1067.
56. Walder, A. J. Ph.D. Dissertation, University of Tennessee, Knoxville, August, 1989.
57. Stryer, L. *Biochemistry*, 2nd ed.; W. H. Freeman and Company: San Francisco, 1981, pp. 19-22.
58. Zubay, G. *Biochemistry*; Addison-Wesley Publishing Company: Reading, 1984, p. 60.
59. Zubay, G. *ibid.*, p. 590.
60. Porath, J.; Flodin, P. *Nature* **1959**, *183*, 1657.
61. *Aldrich Catalogue, Handbook of Fine Chemicals* Aldrich Chemical Company: Milwaukee, 1990, pp. 1147-1148.
62. Hansch, C.; Leo, A.; Unger, S. H.; Kim, K. H.; Nikaitani, D.; Lien, E. J. *J. Med. Chem.* **1973**, *16*, 1207.
63. Streitwieser, A., Jr.; Heathcock, C. H. *Introduction to Organic Chemistry*, 2nd ed.; Macmillan Publishing Company: New York, 1981, p. 969.
64. Streitwieser, A., Jr.; Heathcock, C. H. *ibid.*, p. 945.
65. Streitwieser, A., Jr.; Heathcock, C. H. *ibid.*, p. 1003.
66. Reichenberg, D. in *Ion Exchangers in Organic and Biochemistry*; Calmon, C.; Kressman, T. R. E., Eds.; Interscience Publishers, Inc.: New York, 1957, pp. 78-84.
67. Jervis, L. in *Synthesis and Separations using Functional Polymers*; Hodge, P.; Sherrington, D. C., Eds.; John Wiley and Sons: New York, 1988; pp. 275-277.
68. Billmeyer, F. W., Jr. *Textbook of Polymer Science*, 3rd ed.; John Wiley and Sons: New York, 1984, pp.152-154.
69. *Polymer Handbook*, 2nd ed.; Brandrup, J.; Immergut, E. H., Ed.; John Wiley and Sons: New York, 1975, pp. IV-337-IV-344.
70. Hoy, K.L. *J. Paint Technol.* **1970**, *42*, 76.

71. Jaffé, H.H.; Freedman, L.D.; Doak, G.O. *J. Am. Chem. Soc.*, **1953**, *75*, 2209.
72. Bell, R.P. *The Proton in Chemistry*, 2nd ed.; Cornell University Press: Ithica, New York, 1973, chapter 2.
73. Leffler, J.E.; Grunwald, E. *Rates and Equilibria of Organic Reactions*; John Wiley and Sons: New York, 1963; p.178.
74. Silverstein, R. M.; Bassler, G. C.; Morrill, T. C. *Spectrometric Identification of Organic Compounds*, 4th ed.; John Wiley and Sons: New York, 1981, p. 197.
75. Koszuk, J. F.; Czech, B. P.; Walkowiak, W.; Babb, D. A.; Bartsch, R. A. *J. Chem. Soc., Chem. Commun.* **1984**, 1504.
76. Arcus, C. L.; Matthews, R. J. S. *J. Chem. Soc.* **1956**, Part IV, 4207.
77. Blake, C. A.; Brown, K. B.; Coleman, C. F. Report 1964; Oak Ridge National Laboratory: Oak Ridge, TN, 1955.
78. Skoog, D. A.; West, D. M. *Analytical Chemistry*, 3rd ed.; Saunders: Philadelphia, 1980; p. 581.

APPENDIX

Care and Feeding of the GC

The gas chromatograph is an absolutely essential instrument in work such as that involving the molecular recognition project. The quantitative analysis of mixtures using the GC is not as trivial a procedure as it may appear. There were many symptoms encountered in its use, which I have endeavored to list here, along with the causes of the problems and suggested solutions.

The GC used was a Hewlett-Packard model 5890 equipped with two injection ports, one for use with packed columns, but adapted to 530 μ id "capillary" columns (capillary in parentheses because these are not true capillary columns; only at id's less than about 300 μ do open tubular columns truly behave in a capillary fashion), the other being a split/splitless port for capillary columns. As already alluded to, the column was a 530 μ fused silica open tubular column (three were used: one was a Hewlett-Packard 5m x 530 μ x 1.5 μ column, one was an Alltech 10m x 530 μ x 1.5 μ column, and one was a JW 15m x 530 μ x 1.5 μ column, all of which had an internal coating of crosslinked poly (dimethylsiloxane)). The GC also had two detectors: a thermal conductivity detector and a flame ionization detector. There were two carrier gasses used: the first was nitrogen, then later helium was used exclusively as the carrier gas. Nitrogen was used as a makeup gas for the FID with both carrier gasses. Recording and integration of peaks was performed by a Hewlett-Packard model 3353A recording integrator. The injection port was set at 275°C, the oven programmed to go from 60°C to 150°C at 15°C per minute, the detector temperature was set at 325°C, and the flow rate was set to a head pressure of 70 kpasal. Sample injection was accomplished with a Hamilton 1000 series 1 μ l positive displacement syringe, with 0.1 μ l injections of 0.1M (maximum concentration injected) solutions.

Some general comments regarding the GC, which if adhered to will allow it to give excellent results. Only if kept in absolutely prime condition will the GC perform properly. Two of the most important areas of interest are cleanliness and airtightness. The entire flow path of the analytes must be kept scrupulously clean. This includes the injection port, the detector, and the column. As for airtightness, the entire gas flow system, from the pressure regulator at the supply tanks through to the detector must be free of leaks.

The Injection Ports

The first component of the GC to which the analyte is exposed is the injection port. The studies were begun using the packed column injector, the maintenance of which is quite simple. There are only two areas with which one must be concerned with this injector: the liner and the septum. The liner is a removable glass piece which is designed to be disposable. It can also be cleaned with organic solvents and with acids, so long as any traces of material are removed before its reinstallation in the GC. It is especially important that if chromic acid, or other solutions containing metals are used, that the metal ions are completely removed from the glass, or interactions with the analyte are almost sure to happen. Problems with the septum should be obvious to anyone who has done gas chromatography. The septum will begin leaking after a certain number of injections. Therefore, regular replacement is necessary. The number of injections on a septum before replacement was standardized at about 25 to alleviate problems with leaking, and therefore inconsistent relative peak areas between multiple injections.

The slit/splitless injection port was installed on the GC during the course of the molecular recognition project, with the switch made to helium as the carrier gas at the same time. This injection port provides much greater flexibility of use, but also has more potential problem areas. The main reason for using a split injection port is that it is very easy to overload the capillary columns. Thus, with a split injection port, only a portion of the solution injected reaches the column, the rest being diverted and released into the air (safety dictating the use of a trap if there are toxic components in the sample). The split injection port also has a septum purge which can be programmed to turn on or off during a run. The solenoid valve used with this can develop leaks, as can the flow manifold blocks for either injection port, all three of which use replaceable rubber O-rings for seals. It is usually not too difficult to tell if the seals in the flow block are leaking. If a temperature programmed run is used, the head pressure should increase as the temperature increases. If the pressure decreases, or if the baseline of the chromatogram decreases with increasing temperature (it should slightly increase), then the flow block should be inspected. The solenoid valve can be easily checked by attaching a flow meter to the split outlet port. With all of the gasses turned on and at operating pressure, the septum purge is turned off. There should be no flow at the outlet (time must be allowed for the pressure inside the small id tubing to drop, so this test should be done a few minutes after turning off the purge). There are no typical symptoms of a leaking solenoid valve for which one can watch. The overall peak areas will be lower, and there may be less of the lower boiling components of the mixture which reach the detector.

The Column

There is not too much to be said of the column itself. It should be obvious that all of the fittings on the column (where it enters the injection port and the detector) must be free of leaks. Capillary columns are broken off at the end when installed so that the end portions of the column do not contain graphite particles (from installing the Vespel ferrules on the column). To help ensure that graphite particles do not fall into the column, it should be held with the opening facing down during installation of the ferrules. These columns are also very oxygen sensitive, due to the extremely thin coating of stationary phase material. Thus, air should be excluded from the column at all times. This is done by the use of oxygen traps on the carrier gas supply, and by ensuring that there is a positive carrier gas pressure on the column at all times, even when the GC is not in use. If the column is removed from the instrument, silicone rubber endcaps are placed over the column ends to keep out air. Column bleed is common with all columns, and is no cause for concern unless it becomes excessive, at which time the column should be removed and backflushed with solvent. The treatment of the column is very important, as improper solvent removal will destroy the column. The solvent almost always swells the coating (recall that it is a crosslinked polymer). After backflushing the column, it should be reinstalled onto the cold injection port, and the carrier gas turned on. After allowing the gas to flow for at least 30 minutes to 1 hour, the oven temperature is programmed to go from room temperature to whatever higher temperature will be used during chromatographic runs at a slow rate, about 1°C to 2°C a minute. After this, the column is then reinstalled onto the detector, being

inserted all the way up into the FID jet, then backed off about 1mm. It should, incidentally, be inserted approximately 5mm to 6mm past the end of the Vespel ferrule into the injection port.

Of course, the proper column should be chosen for the analysis being performed. Each different column has a maximum use temperature (MAOT: Maximum Allowable Oven Temperature) which should never be exceeded, or depolymerization of the coating will occur. The "oven max" on the GC should be set to correspond to this value to ensure that the oven temperature is not inadvertently raised above the safe operating temperature of the column installed. The more polar columns generally have a lower MAOT.

The Detector

The detector has two mechanical problem areas (electronic problems are not covered at all, and should be referred to those more knowledgeable about them). Other than the obvious problem of leaks, these areas are cleanliness of the collector, and clogging of the jet. If the detector is not kept clean, a loss of sensitivity will result. It has therefore been adopted as standard policy that the detector be cleaned once a month. This is accomplished by removing the collector, and cleaning with the cleaning brush in water, followed by organic solvents to remove silicon dioxide buildup. Under no circumstances should any type of soap ever be used for cleaning any GC components, as it is nearly impossible to remove all of it. The jet is cleaned simply by inserting a cleaning wire into the orifice to dislodge any solids, followed by washing through with water or an organic solvent to remove the dislodged

particles. The components are dried in a 60°C oven for 30 minutes to 1 hour, and then reinstalled, and the temperature turned back on. It should be noted here that the heated zones (the injection port and the detector) are HOT, and the temperature should be turned off well in advance to any maintenance, or the pieces should at least be handled very cautiously (and quickly until they have had time to cool).

Technique

The idea in making an injection on the GC is to have all of the components of the mixture enter the column at the same moment, and then condense. From here, partitioning of the compounds between the stationary and the mobile phases occurs to effect separation. As was mentioned earlier, the injection port was set at 275°C (it should always be set at least 20°C higher than the boiling point of the highest boiling component of the mixture) so as to flash vaporize the sample. If, however, a slow injection is made, or if the syringe is allowed to remain in the injection port for a time before the injection is made, then the sample will not all start flowing through the column at the same time. For qualitative work, this simply means that the peaks will have an excessive amount of tailing, and that small peaks may altogether disappear. For quantitative work, it is a disaster. The tailing makes integration of the peak areas very inaccurate, and if the syringe remains in the injection port for different times, then the relative peak areas in repeat injections can be quite different. It should be mentioned here that the condition of the syringe is critical to consistent results. Although not actually a part of the GC itself, the

syringe, if leaking, will make it impossible for the GC to yield reliable, i.e., repeatable results. Thus it is important to assure that the teflon ferrule in the syringe forms a good seal against the plunger wire.

Treatment of the Data

Raw peak areas are too inaccurate to use for quantitative analysis of compounds due to inability to inject exactly the same amount of sample each time, and the variations of syringe residence time in the injection port for repeat injections. Because of this, peak area percent was used, comparing the compound of interest to the internal standard (n-hexanol for all but water solutions, for which dioxane was used). At no time were peak areas used, except for recalculating the area percent when other peaks were present (most of these, by setting the area reject to a high enough value, were not included in the area percent printout). It should be noticed that these were not done in the usual way of making a standard curve of concentration vs. peak area (or area percent), much the same way as a spectrophotometer is standardized. Because of the many different compounds used in the study, all available time would have been spent standardizing and restandardizing the GC with this method. Therefore, the data treatment basically involved a normalization procedure against an internal standard. A sample calculation should suffice to show how the calculations were done. When there were impurity peaks which were not ignored by the integrator, such as with the $R_i=0.1$ studies where the analyte concentration was low, or where there was more than one analyte peak, as with the competitive studies, new area percent values were calculated by adding the

one peak area of interest to the internal standard peak area, and dividing by one of these two, the other simply derived from subtracting the obtained number from 100. This must be done separately for each component in the mixture.

Table 40

Sample Numbers for the Calculation of % Absorbed from GC Data

Standard Solution ^a		Contacted Sample Solution ^a			
Compound	Internal Standard	Internal Standard	Ratio ^b	Compound ^c	% Absorbed ^d
73.463	26.537	37.860	70.092	43.555	40.71

^a all data, with the exception of the final % Absorbed, is in area percent

^b (standard solution internal standard/contacted solution internal standard) X 100

^c ratio^a minus the standard internal standard

^d 1 - (compound^b/the standard compound)

Reclamation of Silver

Because of the quantity of AgNO_3 used for the project on the kinetics of the ion-exchange/redox reaction, it was necessary to reclaim the silver in order to keep the cost of the project to a reasonable level. The procedure for reclaiming silver was used more or less as given in the article in which it was found.³⁸ In this procedure, all of the silver to be reclaimed is converted to the chloride using HCl (the acid helped keep chromium and iron from Mohr and Volhard titrations in solution, these titration solutions also having been added to the reclaiming jug). The AgCl was then filtered and washed with copious amounts of water to remove any soluble compounds. The washed AgCl was then dissolved in NH_4OH , this was quickly filtered to remove insoluble particles (beads, pieces of glass, spinbars, etc.), and reduced to silver metal by the addition of sodium ascorbate. Since explosive fulminates are known to form in this solution, it is important that the silver not remain dissolved in the NH_4OH any longer than is necessary. The silver metal is then filtered from the liquid, dissolved with a slow drip of 10M HNO_3 , and evaporated to dryness on a rotary evaporator at 60°C . The resulting crystals were redissolved in water and evaporated to dryness three more times to rid them of remaining traces of HNO_3 .

VITA

Paul Timothy Kaiser was born on February 14, 1958 in Birmingham, Alabama, and attended elementary schools in Old Saybrook, Connecticut, and Hancock and Peterborough, New Hampshire. Junior high and high school were attended in Keene, New Hampshire. Upon graduation from high school, he attended Keene State College for two years before leaving to work in a scissor manufacturing firm, where he was promoted to department manager and company trainer. He returned to Keene State College in 1980, and was awarded the B.S. degree in Chemistry/Biology in May 1983. He moved his family to Tennessee in August, 1983 to begin graduate studies at the University of Tennessee, Knoxville in polymer chemistry under Dr. S. D. Alexandratos. He was awarded the Ph.D. degree in August 1990, and will be working in polymer research with the Army Material Command at the Belvoir Research, Development and Engineering Center, Ft. Belvoir, Virginia.