

**THE ADSORPTION  
CHARACTERISTICS OF PRECIOUS  
AND BASE METALS ON FOUR  
DIFFERENT ION-EXCHANGE RESINS**

*by*

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## **DECLARATION**

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and has not been submitted previously in its entirety or in part for a degree at any University.

E.R. ELS



## ABSTRACT

Adsorption tests were conducted with four different ion-exchange resins to determine the equilibrium adsorption of a range of precious and base metals. The adsorption characteristics were determined for synthetic single metal, as well as for multi-component and base metal solutions. The effect of the  $\text{Cl}^-$  concentration on the equilibrium adsorption was established for three different HCl concentrations in the above solutions. From the ion-exchange characteristics determined, a selective adsorption sequence is proposed for the separation of precious and base metals.

Pure platinum, palladium and gold were dissolved in aqua regia and diluted to 2000 ppm (as metal) in 4M HCl. Ruthenium, rhodium and iridium were dissolved from pure salts in HCl. A 2000 ppm base metal solution was prepared by dissolving all the required components, including precious metals, to match an in-plant industrial base-metals solution composition. For each precious metal the equilibrium adsorption was determined for a couple of solution concentrations. Data points for adsorption curves were established by varying the amount of resin added to the test solution of a specific concentration. The equilibrium solution concentrations were determined by ICP analysis after 24 hours of exposure, using the bottle-roll technique.

The experimental results obtained indicate a possible process route for the separation of precious metals with ion-exchange resin. The XAD7 resin is highly selective for gold from mixed solutions containing precious and base metals. It is also evident that, with the gold removed from the solution, the A22 resin adsorbs only palladium. IR200 resin adsorbs only the base metals from the solution. With all other precious metals removed from the solution (platinum and ruthenium must be extracted by other means), iridium can be adsorbed from the solution by IRA900 resin which is highly selective for iridium over rhodium. For all of the anion resins, XAD7, IRA900, and A22, the chloride concentration of the solution did not have a big effect on the adsorption capacity. However, the adsorption of base metals on IR200 is sensitive to chloride concentration, with a rapid reduction in adsorption at higher chloride concentrations.

Statistical models were developed for the adsorption of each of the precious metals, as well as for the base metal solution. All adsorption data, obtained for a resin (typically 250 equilibrium data points), was used in the development of the model. The SPSS statistical software package was used to develop linear regression models. The interaction between all the input parameters, e.g. the interaction of gold and chloride ions, was modelled by specifying the product of the gold and the chloride concentrations as an input variable. The variables that determine the adsorption quantities were identified.

High solution concentrations of the target adsorption component increase the adsorption quantity. It has been established that a higher platinum concentration increases the adsorption quantity of gold on XAD7 resin. However, the adsorption quantity is reduced at higher ruthenium concentrations. The adsorption quantity of iridium on IRA900 is reduced with increased rhodium concentration. The adsorption quantity of palladium on A22 is increased by the presence of rhodium and decreased by larger concentrations of iridium and platinum. The adsorption of base metals on IR200 is decreased at higher acid concentrations. Higher concentrations of gold in the base metal solution also decrease the adsorption quantity of base metals. The model predicted adsorption of each component compares well with the actual measured values.

In batch adsorption tests the counter ion is not removed from the resin. The resin capacity for a specific ion concentration could therefore not be determined. As such, the adsorption models are only valid for the initial part of the ion-exchange process. The effect of kinetics on the adsorption was not determined.



## SINOPSIS

Adsorpsietoetse is gedoen met vier verskillende ionuitruilharse om die ewewig adsorpsie van edelmetale en basismetale te bepaal. Die adsorpsie karakteristieke is bepaal vir sintetiese enkelmetaal-, meermetaal-, en basismetaaloplossings. Die effek van die  $\text{Cl}^-$  konsentrasie op die ewewigadsorpsie is bepaal vir drie soutuurkonsentrasies in al die bogenoemde oplossings. 'n Prosesvloeiagram vir die selektiewe adsorpsie van edelmetale en basismetale met behulp van die vier verskillende ionuitruilharse word voorgestel.

Suiwer platinum, palladium en goud is opgelos in koningswater en verdun na 2000 dpm (uitgedruk as metaal) in 4 molaar HCl. Rutenium-, rodium- en iridiumoplossings is verkry deur die oplos van suiwer edelmetalaaloute in HCl. 'n Basismetaaloplossing van 2000 dpm is voorberei deur die individuele komponente, wat die edelmetale ingesluit het, in die regte verhouding te kombineer om die samestelling van 'n industriële basismetaaloplossing te verkry. Vir elke edelmetaal is die ewewigadsorpsie bepaal vir tipies twee konsentrasies van edelmetaaloplossings. Verskillende data punte by 'n spesifieke edelmetaal-konsentrasie is bepaal deur die hoeveelheid hars wat by die toets oplossing gevoeg word te varieer. Die oplossing-konsentrasies by ewewig is bepaal deur IGP analise na 24 uur blootstelling met die roterende botteltegniek.

Die resultate wat verkry is dui op 'n moontlike ionuitruilgebaseerde proses vir die skeiding van edelmetale. Die XAD hars is selektief vir goudadsorpsie uit gemengde oplossings wat al die edelmetale, asook basismetale bevat. Dit is ook bevind dat indien goud uit die gemengde oplossing verwyder word, die A22 hars slegs palladium adsorbeer uit die oplossing. Die IR200 hars adsorbeer slegs basismetale. Wanneer al die ander edelmetale uit die oplossing verwyder is (platinum en rutenium moet met alternatiewe prosesse verwyder word) kan iridium geadsorbeer word met IRA900 hars vanuit 'n iridium- en rodium- gemengde oplossing. Vir al drie die anioonharse wat getoets is, naamlik, XAD7, IRA900 en A22, het die chloriedkonsentrasie nie 'n groot effek op die adsorpsie gehad nie. Die hoeveelheid

basismetale wat op IR200 hars geadsorbeer word is egter baie sensitief vir die chloriedkonsentrasie, met 'n vinnige afname in adsorpsie by hoër chloriedkonsentrasies.

Statistiese modelle is ontwikkel vir elke hars en vir elk van die edelmetale, asook die basismetalaoplossing. Al die eksperimentele data wat vir elke hars verkry is, tipies 250 ewewigspunte, is gebruik in die ontwikkeling van lineêre regressie modelle vir die primêre absorberende spesie op die hars.

Hoër konsentrasies van die teiken adsorpsie komponent verhoog die adsorpsie daarvan. Hoër platinumkonsentrasies verhoog die adsorpsie van goud op XAD7, maar die teenwoordigheid van rutenium verlaag adsorpsie. Die adsorpsie van iridium op IRA900 word verlaag met hoër rodiumkonsentrasies. Die adsorpsie van palladium op A22 verhoog met die teenwoordigheid van rodium, maar neem af met hoër konsentrasies van iridium en platinum. Die adsorpsie van basismetale op IR200 neem af by hoër suurkonsentrasies. 'n Hoër goudkonsentrasie verlaag ook die adsorpsie van basismetale. Die gemodelleerde adsorpsie hoeveelhede vergelyk goed met die gemete waardes.

Aangesien die uitgeruilde ioon nie verwyder word uit die toetsoplossing nie, kon die harskapasiteit vir 'n spesifieke ioonkonsentrasie nie bepaal word nie. Die modelle is derhalwe slegs getoets vir die aanvanklike deel van die ewewigsdata en die kinetika van adsorpsie is nie in ag geneem nie.

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- B. Supplier specification sheet for XAD7 resin**
- C. Supplier specification sheet for IR200 resin**
- D. General guide for selection of ion-exchange resin**
- E. Conference presentations that originated from this research**
  - ◆ Presentation at Minerals Engineering '99 Conference in Falmouth, Cornwall, UK. September 22 – 24, 1999. “The Adsorption of Precious Metals and Base Metals on a Quaternary Ammonium Group Ion-Exchange Resin.”**
  - ◆ Presentation at IEX2000 Conference at the University of Cambridge, UK. July 16 – 21, 2000. “The Adsorption of Base Metals and Precious Metals on IR200 Ion-Exchange Resin.”**
  - ◆ Presentation at XXI International Mineral Processing Congress in Rome, Italy. July 23 – 27, 2000. “The Adsorption of Precious and Base Metals on XAD7 ion-Exchange Resin.”**



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# CHAPTER 1

## INTRODUCTION

The Bushveld Complex in South Africa has rich deposits of precious metals. The ore also contains copper and nickel. The separation and purification technologies for these metals remain a challenge to the industry, trying to cut costs and to reduce the processing time to obtain high purity metals. The current precious metal refining technology is based on separation of the chloride complexes of these metals. As stainless steel equipment is used for copper and nickel recovery, the copper and nickel must be removed first, as stainless steel is not resistant to the chlorides.

Industry is actively involved in the process of tailor-making resins by fixing the appropriate active groups onto the resin structure in order to selectively adsorb specific ionic species. Research in this area is very lucrative, owing to the possible cost savings in the simplicity of the equipment required for the process and control thereof, as well as the reduced chemical consumption. The progress in resin technology for the precious metal industry is to a large extent unknown, as the walls of confidentiality are impermeable.

The drive to obtain metal purities better than 99% (in the most cost effective way) has led the search towards ion-exchange technology and the use of active groups on a resin which can selectively extract specific species from a solution. Due to the tendency of the platinum group metals (PGM) to form anionic dissolution complexes, the focus for PGM recovery is more towards anion-exchange resins. Leaching with aqua-regia is used to dissolve the PGM metal sulphides. PGM's dissolve to form chloride complexes with the general formula  $[MCl_x]^{n-}$ . The thermodynamics and kinetics of an aqueous solution containing PGM are not always well understood and therefore remain tenaciously elusive [Dhara and Sudhir, 1993]. The study of the adsorption of PGM ions from an industrial solution, containing a variety of PGM and base metal ions, will therefore be difficult as there are many interacting species in the



solution. For this reason, single component synthetic solutions of the precious metals were used in the initial tests for this study.

Platinum, gold, and palladium were dissolved from the pure metals. Ruthenium, iridium, and rhodium were dissolved from the pure metal salts. The salts were used in instances where dissolution of the metals is very difficult. A base metal solution, which includes the PGM's, was prepared by adding all the individual components to match an industrial composition of the base metal (BM) solution.

The adsorption characteristics of a single metal were established. Further components were then added to the solution to study the effect of other ions competing for the adsorption sites on the resin.

Precious metals have always been recovered by selective chemical dissolution and precipitation, with related technologies. However, new developments in ion-exchange resin manufacture opened up new possibilities for the separation of precious metals.

By using resins which are selective for particular chemical species in solution, and in the correct sequence, high purity metals can be recovered with reduced cost for chemical consumption. This research was conducted to characterise the adsorption, loading and selectivity of four different ion-exchange resins. Only four resins were used in this study to reduce the consumption of precious metals for experimental purposes. The effects of chloride strength and solution composition on the extent of adsorption were determined. The best adsorption sequence for the separation of precious and base metals can be determined from the adsorption characteristics.

The objectives of this research are:

- i. To select four ion-exchange resins for adsorption of precious and base metals.
- ii. To determine the selectivity of the four different resins selected.
- iii. To determine the effect of the chloride concentration on the adsorption.
- iv. To determine the effect of other solution components on the adsorption.
- v. To provide models which can predict the equilibrium adsorption of a specific component on the resin.

- vi. To propose an adsorption sequence for the separation of the precious and base metals on the four different resins.

Refer to Appendix E for three papers published in International Conference Proceedings, two of which were published in International Journal Papers.



## CHAPTER 2

### LITERATURE REVIEW

The basic principle of ion-exchange employed in the separation of PGM's, the development of selective ion-exchange resins, and some successful applications of PGM recovery by ion-exchange resins, will be reviewed.

Although there is widespread interest in the separation of precious metals with ion-exchange resins, the published experimental data on the topic is limited. Due to the high market value of the pure precious metals the research findings are confined by confidentiality agreements to the specific research institution or refinery.

The platinum group metals vary considerably in their physical characteristics, melting points, specific gravity, brightness and hardness, but have common properties in that they are all noble, they remain untarnished in normal atmospheres and are resistant to corrosion by a wide variety of chemicals. They are among the best catalytic agents for accelerating various chemical reactions. Platinum is a soft ductile metal which can readily be used hot or cold and is the best known element in the group. One in five items in everyday use utilises platinum in its manufacturing process [Robinson, 1996]. Since the 1970s, platinum and PGM's have been used extensively in catalytic converters to control automobile exhaust emissions. The other metals in the platinum group alloy readily with one another and with many other metals. For instance, a small quantity of iridium or ruthenium added to platinum increases its hardness and strength, while rhodium alloyed to platinum increases its brightness.

The classical PGM refining process involves a complex cycle of smelting, electrolytic and chemical operations practised at the major refineries [Warshawsky, 1987]. The separation of the PGM from the ore is achieved by leaching with aqua regia for initial dissolution of all the components, followed by a series of precipitation and dissolution steps to selectively isolate and purify the individual

components. The modern approaches to PGM recovery and separation involve liquid-liquid extraction and more recently the search for PGM selective resins, which can by means of ion-exchange yield a viable route for PGM recovery.

The equilibria in chloride acid solutions of the PGM and Base Metals are extremely varied, and the aqueous complexes or hydration mechanisms of each metal ion are complicated. To give an example, rhodium chloride solution in aqueous system manifests itself as the minimum following member of species:

- ◆  $[\text{RhCl}_6]^{3-}$
- ◆  $[\text{RhCl}_5(\text{H}_2\text{O})]^{2-}$
- ◆ Cis- and trans-  $[\text{RhCl}_4(\text{H}_2\text{O})_2]^-$
- ◆  $[\text{RhCl}_3(\text{H}_2\text{O})_3]$
- ◆ Cis- and trans-  $[\text{RhCl}_2(\text{H}_2\text{O})_4]^+$
- ◆  $[\text{RhCl}(\text{H}_2\text{O})_5]^{2+}$
- ◆  $[\text{Rh}(\text{H}_2\text{O})_6]^{3+}$

Each complex ion of Rh will behave differently towards an ion-exchanger. The complex ionic characteristics of platinum group metals have to be dealt with in every instance of ion-exchange. For repeatability of experimental work, matched chloride concentrations and solution potentials give some assurance that the same ionic species will be present in the solution.

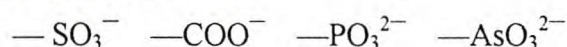
## 2.1 PGM SEPARATION BY ION-EXCHANGE

Ion-exchangers are insoluble solid materials which carry exchangeable cations or anions. These ions can be exchanged for a stoichiometrically equivalent amount of other ions of the same sign when the ion-exchanger is in contact with an electrolyte solution. Carriers of exchangeable cations are called cation-exchangers, and carriers of exchangeable anions, anion-exchangers. Ion-exchange is a reversible stoichiometric process, different to sorption in the sense that every ion removed from the solution is replaced by an equivalent amount of another ionic species of the same sign. Ion-exchangers consist of a framework which are held together by chemical



bonds or lattice energy. This framework carries a positive or negative electric surplus charge which is compensated for by ions of opposite sign, the counter ions. The counter ions are free to move within the framework and can be replaced by other ions of the same sign.

There are many types of ion-exchangers but only synthetic ion-exchange resins will be considered. The organic resin framework, or matrix, consists of an irregular, macromolecular, three-dimensional network of hydrocarbon chains. The matrix carries ionic (acid) groups such as



in cation-exchangers, and



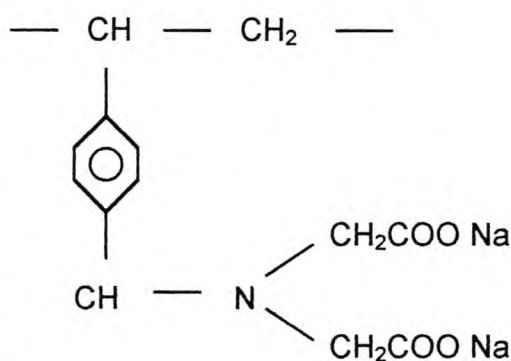
in anion (base) exchangers. The acid or base strength of the groups are important. Weak acid groups such as  $-\text{COO}^-$ , are ionised only at a high pH. At a low pH, they combine with  $\text{H}^+$ , forming undissociated  $-\text{COOH}$ , and thus no longer act as fixed charges. In contrast, strong acid groups such as  $-\text{SO}_3^-$  remain ionised even at low pH values and the resin retains its functionality at a wide range of pH values. Weak base groups such as  $-\text{NH}_3^+$ , lose a proton, forming uncharged  $-\text{NH}_2$ . When the pH is high, and strong base groups such as  $-\text{N}^+(\text{CH}_3)_3$  remain ionised even at high pH values. Because of the progressive neutralisation of fixed charges with decreasing or increasing pH, the operative capacity of weak acid and weak base resins is pH dependent [Helfferich, 1995]. The matrix of the resins is hydrophobic. However, hydrophilic components are introduced by the incorporation of ionic groups such as  $-\text{SO}_3^- \text{H}^+$ . The ion-exchange resins are insoluble due to the crosslinks which interconnect the various hydrocarbon chains. An ion-exchange resin particle is practically one single macromolecule. The ion-exchange behaviour of the resins is determined by the fixed ionic groups. The number of the groups determines the ion-exchange capacity.

In ion-exchange, water and several ions diffuse simultaneously, with different velocities. They are driven by activity, electrical and pressure gradients. The selectivity of an ion-exchange resin is the preference of the particular resin for one kind of ion over the other in the same solution. Ion-exchange resins prefer counter ions which tend to associate with the fixed ionic groups on the resin, or with



components of the resin matrix. A counter ion which forms strong complexes with, or is precipitated by, a certain reagent should thus be preferred by a resin into which this reagent has been incorporated. The behaviour of weak acid resins confirms the validity of this conclusion. Anions of weak acids tend to associate with  $H^+$  ions, forming weakly dissociated complexes or precipitates. Resins with weak acid groups have a marked preference for  $H^+$  ions [Helfferich, 1995]. The desired strong affinity for a certain counter ion is attained by introducing groups with which the counter ion tends to associate. General purpose anion-exchangers bind to the anionic complexes formed by the precious metals in chloride media. They are effective collectors of the PGM's but are ineffective as a separation media. A PGM selective resin must incorporate ligands with a definite affinity for the PGM ions.

Common chelating ion-exchangers have been prepared by interaction between chloromethylated styrene, DVB (the di-vinyl-benzene copolymer matrix), with a chelating ligand reagent. For example, the structure of iminodiacetate chelate resin in the sodium form is shown in Figure 2.1.1 [Dhara and Sudhir, 1993].

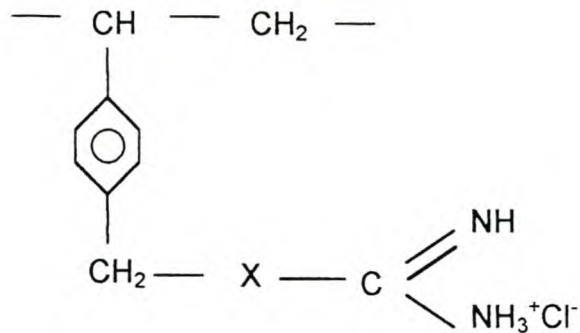


**Figure 2.1.1 Iminodiacetate chelate resin**

The presence and arrangement of the two carboxylic groups and the tertiary nitrogen results in a product which has a high selectivity for transitional metal ions. The nature of the ionizable groups attached to the hydrocarbon networks determines the chemical behaviour of a chelate ion-exchange resin. The first commercially available chelate resin was Dowex A -1. Thereafter, Schmuckler and co-workers prepared a series of chelate ion-exchange resins especially for the gold and platinum group metals separation [Schmuckler, 1970]. The method of synthesis is by interaction of



chloromethylated styrene with various chelating agents. The general formula is represented in Figure 2.1.2.



**Figure 2.1.2 General formula for chelating resin selective towards PGM**

These types of resins provide a novel and superior method for the recovery of gold and other PGM's in the presence of different base metal ions in solution. In many cases the adsorbed ion is bound so intimately that the resin must be incinerated to obtain the metal value.

The selectivity of a resin usually increases with increasing charge of the selected ion, and with the radius of the complexed or hydrated ion. The selectivity also increases with the polarisability of the ion. An undesired consequence of such an association is that the mobility of the counter ion in the resin is greatly reduced. The gain in selectivity must be paid for by a loss in the rate of ion-exchange. Resins with extreme specificity are difficult to regenerate (except when the preferred counter ion is readily displaced by H<sup>+</sup>) and may even hold chelated counter ions to the extent that ion-exchange stops. A large number of separation methods have been developed for analysis of PGM's using ion-exchange techniques [Beamish, 1967], but these have not led to industrial processes, owing mainly to the irreversibility of the binding processes. The choice of a resin for a specific application is therefore a compromise between selectivity, ease of regeneration, and rate of ion-exchange.

Superligs are the impregnated products of a mixture of macrocyclic compounds and hydrophilic solids such as silica gel. Superligs are especially effective for the separation of precious metals. These exchanger materials are capable of recovering silver, gold, platinum, palladium, rhodium, iridium and ruthenium from chloride

solutions [Dhara and Sudhir, 1993]. Superlig-1 was successfully used to separate Rh and/or Ir from the concentrated solution of precious metals containing other base metals [Bruening et. al., 1990]. The same author also reports on a novel, highly selective anion-exchanger prepared by binding  $\text{Pd}_2^+$  to an immobilised ligand [Bruening, 1991]. Because of the large equilibrium constant for the formation of the immobilised ligand-palladium complex, most anions are incapable of removing the  $\text{Pd}_2^+$  from the ligand. The palladium-ligand complex has two co-ordination sites available for binding anions. Because the complex has a 2+ charge, anions must remain with the palladium to maintain electrical neutrality. With the high selectivity facilitated by co-ordination chemistry, the selectivity for hydroxide ions over nitrate ions was determined to be in the order of  $10^8$ . Further development work is being continued in the selective separation of PGM's with Superlig reagents.

## 2.2 APPLICATIONS OF RESIN FOR PGM RECOVERY

The carbon-in-pulp (CIP) process is a conventional technology for the extraction of gold from cyanide media and is used in many hydrometallurgical plants. The method however, still has some disadvantages. The activated carbon requires periodic thermal reactivation for the removal of adsorbed organic materials, sometimes the elution of carbon has to be carried out at high temperature and in a pressure vessel, and appreciable amounts of gold included in sulphuric ore materials are not easily leached out with alkaline cyanide solutions. There has been great interest therefore, in developing other technologies for gold recovery.

The separation of gold from the platinum group metals by Amberlite XAD-7 resin was investigated by Fritz [Fritz, 1971]. He reported that the resin is very selective for gold in hydrochloric acid solution in the presence of platinum, palladium, rhodium, iridium and ruthenium. The presence of copper, nickel and iron has no effect on the retention of gold. Experimental results obtained in this study are listed in Table 2.2.1.



**Table 2.2.1: Separation of Gold from PGM and Base Metals by XAD-7 resin**  
[Fritz, 1971]

Metal (mg)	Au	Pt	Pd	Rh	Ir
Before IX	20	65	55	30	15
After IX	0	64.5	55.5	29.8	15.2

A macroporous crosslinked polyacrylate (MET) resin series has been synthesised by the Institute of Polymer Chemistry, Nankai University, China [Chang, 1995]. It is claimed that the resins prepared were similar to XAD-7 in their functional groups, but differ from each other in their structural characteristics. From the results obtained it was concluded that gold is adsorbed by an ion-exchange mechanism on these resins. An increase in adsorption capacity with increasing HCl concentration was observed. It was postulated that the increased HCl concentration in the solution phase caused the dielectric constant of the resin phase to decrease, enhancing the stability of the ion pair,  $H^+AuCl_4^-$ , which shifts the equilibrium towards the adsorbed gold complex. All the test results presented were based on single metal gold solutions, no data as to the selective adsorption of gold from mixed solutions was given.

Successful separation of Pd(II) and Pt(II) chlorides can be achieved by using a chelate guanidine resin [Dhara and Sudhir, 1993]. The guanidine resin is uncharged and does not function as a regular cationic or anionic exchanger but adsorbed the uncharged species  $PdCl_2$  in the matrix. Complete elution of the adsorbed palladium was achieved with 3-4M hydrochloric acid.

The sorption of Pd(II) and Pt(IV) in HCl solutions has been measured on both PBI and EPBI resins [Chanda, 1989]. The preparation of the resins is described. The PBI resin contains an active  $\bar{N}H^+$  group which facilitates adsorption by ion-exchange. The EPBI resin contains an active  $\bar{N}$  and  $\bar{S}$  phase in the resin, which adsorb ions by chelating the metal ions. These two resins were tested for adsorption of the single species, from mixtures, and in the presence of a number of base metal ions. Chanda noted that the noble metals tend to form their most stable complexes with ligands containing polarizable centres. Resins with donor N, and especially S atoms in their functional groups, are thus found to be promising exchangers for selective pre-concentration and separation of noble metals. Their results indicated that the



adsorption of PGM's is not effected by HCl concentration, nor by base metal concentration, with the EPBI resin, which adsorb the PGM by chelation.

Cation-exchange methods involving PGM are primarily used to separate the base metals, such as iron, copper, nickel, lead, zinc, cobalt, rare earth's, and other alkali and alkaline earth metals from hydrochloric solution, while the precious metals pass into the effluent [Faye et al., 1964]. The separation of base metals from PGM containing solutions in chloride media are usually performed at pH values in the range of 0.5 to 2, with a reported optimum at 1 to 1.7. It was reported that Rh(III) can convert to the cationic form at low acidity, pH 2.8, in the presence of Pt, Pd, and Ir, and can be separated with cation-exchange resin Dowex 50 [McNevin and McKay, 1957]. The same authors also reported in another paper that palladium and iridium were separated from each other by passing ammoniacal solutions of palladium chloride and iridium chloride over a cation-exchange resin Amberlite IR-100. Palladium was retained in the resin as a cationic amine complex while iridium passed through the column as an anionic complex [McNevin and Crummett, 1954]. Cation-exchange separation of PGM cited was based upon different tendencies of these metals to form complexes with ammonia, pyridine, and thiourea. The adsorption of metal ions on an amine type chelating resin, MC-10, was determined at the Saga University in Japan [Inoue et al., 1990]. The resin was a polyethylene polyamine type chelating resin. The adsorption of various divalent transition metals and precious metals was investigated from HCl. The selectivity of the resin for PGM over base metals is not clearly displayed in the paper.

Anion-exchange separation of the platinum group metals has mostly been carried out using chloride solutions adsorbing on strong basic exchangers, as their anionic chloride complexes. In Table 2.2.2 some applications involving separations of anionic complexes by ion-exchange resins are shown [Dhara and Sudhir, 1993].

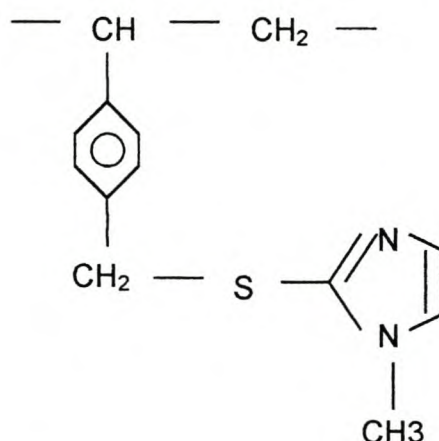


**Table 2.2.2: Anion-exchange Separations of PGM in Chloride Form [Dhara and Sudhir, 1993].**

PGM	Separated From	Resins Used
Pt, Pd	Each other	Dowex-1
Rh, Ir	Each other	Dowex-2
Rh(III)	Ir(IV)	Amberlite IR-400
Pd(II)	Ir(III)	Amberlite IR-400
Pd(II)	Rh(III)	Amberlite IR-400
Pt(IV)	Ir(III)	Dowex-1

Research work was done by Palmer at the United States Bureau of Mines on the recovery of precious metals from cyanide leach solutions with Amberlite IRA-430 resin. The results obtained indicated that strong base resins were nonselective for precious metals, but have higher loading capacities and are less affected by pH than weak-base resins. Weak-base resins were generally more selective for PGM, but have lower loading capacities [Palmer, 1986].

A crosslinked polystyrene resin bearing N-methyl-2-thioimidazole has been synthesised with a high sorption capacity and selectivity for noble metal ions [Yi-Yong Chen et al., 1990]. The structure of the resin can be seen in Figure 2.2.1.

**Figure 2.2.1: N-methyl-2-thioimidazole resin**

The functional resin was developed to recover platinum from waste firebrick in the glass fibre industry and from spent catalyst in the petroleum chemical industry. High purity platinum and a high percentage recovery were obtained. The resin was easily regenerated and re-used without an obvious decrease in sorption capacity for Au(III),

and Pd(II). Au(III) was separated quantitatively from a solution containing large amounts of  $\text{Cu}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Ni}^{2+}$ , and  $\text{Mn}^{2+}$ . It was also found that the chloride concentration has a minor effect on the bonding of the  $\text{AuCl}_4^-$  ion to the resin.

A novel weak base anion-exchange resin, which is highly selective for PGM's over base metals, was tested [Leung and Hudson, 1992]. The resin was based on poly(styrene-co-divinylbenzene) with covalently bound 1, 3, 4-thiadiazole-2-amino-5-thiol groups. The resin was selective for Pt(IV), Pd(II), Rh(III) and Ir(IV) in the presence of the base metals, e.g.  $\text{Cu}_2^+$ ,  $\text{Fe}_3^+$ ,  $\text{Co}_2^+$  and  $\text{Ni}_2^+$  in chloride media. The separation was effective from 0.5 M to 3.0 M HCl. The adsorption of PGM's was dependant on the HCl concentration as a variety of complexes are formed in solution at different conditions. With the increase in chloride concentration at higher acidities the chloride anions are in competition with the PGM anions for the ion-exchange sites on the resin with a resulting drop in adsorption capacity. The selectivity of the resin according to the adsorption maxima at 0.5 – 2 M HCl is as follows:

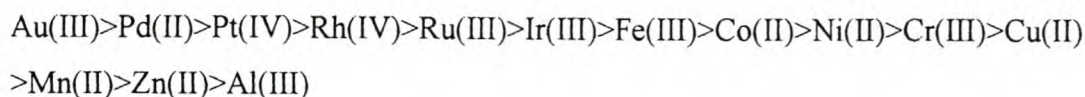
$\text{Au(III)} > \text{Pd(II)} > \text{Pt(IV)} \sim \text{Ir(IV)} > \text{Rh(III)} > \text{Fe(III)} > \text{Cu(II)} > \text{Co(II)} \sim \text{Ni(II)}$

The selectivity is explained by the relative polarisability forces between the respective anionic metallic species and the charged resin site. In addition, the selectivity may be influenced by the geometrical requirements of the metal species. In general, adsorption increases in the order of monovalent  $[\text{MCl}_4^-] >$  divalent  $[\text{MCl}_4^{2-}] >$  trivalent  $[\text{MCl}_6^{3-}]$  species, in accordance with the ease of packing around resin sites. The square planar geometry required by gold was favourable in that it was comparatively easy to accommodate the single negatively charged  $[\text{AuCl}_4^-]$ . Therefore, it is highly extracted by the resin, whereas the other PGM's having species in higher valencies, generally requiring an octahedral geometry, were extracted to a lesser degree.

Macroporous cross-linked polyacrolein-styrene chelating resins were prepared at the Central Iron and Steel Institute in China. They were highly selective for gold and platinum in aqueous acid solution [Zhang et al., 1994]. Two resins were prepared, a polyacrylic aldehyde-hydrazone and polyacrolein-phenylhydrazone resin. The



chelating properties for gold and platinum group metals were tested in the presence of base metals. The following order of affinity was found in 1.0 M HCl for both resins:



In general, the uptake of noble metal ions decreased with increasing molarity of HCl. The behaviour of the resins was therefore similar to that of resins which bind noble metal ions by ion-exchange mechanisms. The retention of the base metals was negligible in comparison with the noble metals.

The resin matrix is also an important parameter in the design of chelating resins. Although the ligand attached to the matrix has an affinity for the ion to be adsorbed the metal diffusion rates within the polymer matrix is an important parameter [Chessa et al., 1992]. Comparative studies on resins containing identical metal binding groups but differing matrices, have shown differences in their complexing behaviour. Macroporous polystyrene based resins are generally more effective as extractants than their microporous analogues. The macroporous resins proved to be more suitable for regeneration than the microporous resins. Comparative experimental studies by Chessa and co-workers were done by modification of two different macroporous polystyrenes with 2,6-bis(methylthiomethyl)-3-hydroxypyridine groups. The two resins both showed selectivity for palladium over copper and other base metals. The sorption obtained by one of the resins, XAD-2-SNS, is shown in Table 2.2.3.

**Table 2.2.3: Sorption by XAD-2-SNS from mixed solution at pH 1**

Metal	Adsorption (mmol/g)
Pd(II)	0.57
Cu(II)	0.03
Co(II)	Not detected
Ni(II)	Not detected
Zn(II)	Not detected
Fe(II)	Not detected

The results obtained from the two resins also displayed a marked difference in adsorption capacities (0.38 mmol/g Pd(II) for the other resin) due to the inaccessibility of the chelating groups in the resin.



### 2.3 MODELLING OF ADSORPTION

The equilibrium isotherms are characterised by various models presented in the literature. The biggest challenge is the prediction of multicomponent adsorption equilibria using single component isotherm data. The well known Langmuir model is the simplest and was used frequently with a good fit to experimental data [Yi-Yong Chen et al., 1990]. The disadvantage of the extended Langmuir equation is inadequate representation of the real adsorption system, because the Langmuir equation cannot fully describe single component adsorption data and / or the maximum adsorption capacity differs from species to species, causing thermodynamic inconsistencies.

The Langmuir model is:

$$q = \frac{q_s b C}{1 + b C}$$

Where  $q$  is the solute concentration in adsorbent (mmol/g dry adsorbent),  $q_s$  is the Langmuir isotherm parameter (mmol/g dry adsorbent),  $b$  is the Langmuir adsorption parameter (l/mmol), and  $C$  is the solute concentration in the fluid phase (mmol/l). The term  $q_s b$  is the Henry's law constant [Grzegorzczuk and Carta, 1996]. For each condition (temperature, solvent composition, etc.), the Langmuir parameters,  $q_s$  and  $b$ , were fitted to the data by a non-linear least-squares fitting routine. Adsorption energies can be found from the temperature dependence of the Henry's law constant,  $K = q_s b / S$ , normalised with respect to the surface area of the adsorbent.

Myers and co-workers proposed an ideal adsorbed solution theory (IAST) to resolve the thermodynamic inconsistencies suffered by the Langmuir model [Myers and Prausnitz, 1965, Myers and Novosad, 1982, and Myers and Byington, 1986]. Good results were obtained with the Myers model, using new correlation's to estimate the activity coefficients in the liquid phase, and the Wilson [Wilson, 1964] and Gilliland [Gilliland and Robinson, 1950] equations to correlate the activity coefficients in the solid phase with the composition and temperature, respectively. The equilibrium constants and Wilson binary interaction parameters were determined



by regression from experimental data. The goodness of the IAST in predicting multi-component adsorption equilibrium depends on the correct choice of the single component isotherm equations best describing experimental data. The deviations from ideal behaviour are often attributed to the non-ideality of the adsorbed phase.

There are two approaches in dealing with the non-ideality. The first attributes the non-ideality to a result from the non-unity of the activity coefficients in the solution, and it is called real adsorbed solution theory (RAST) [Costa et al., 1981; Talu and Zwiebel, 1986]. The RAST has extra parameters to be extracted from binary systems, hence it requires binary experimental data in order to predict higher-order multi-component equilibria. The other approach considers the surface energetic heterogeneity. The concept of a surface energy distribution was extended to multi-component mixtures [Hoory and Prausnitz, 1967]. This methodology assumes that IAST is applicable at a local site and the overall adsorption isotherm can be integrated over all available sites, through the use of an energy distribution. This is referred to as heterogeneous ideal adsorbed solution theory (HIAST). Since different sorbates have different energy distributions toward the solid surface, Myers, Valenzuela and co-workers used the matching of the cumulative energy of all species [Valenzuela et al., 1988].

Ideally one would like to be able to predict multi-component equilibria using only pure component data and single component isotherms. However, describing the adsorption equilibria of highly non-ideal mixtures can be very difficult even when multi-component equilibrium data is available. An alternative approach to the above models involves the use of an equation of state (EOS) to describe the adsorbed phase [Appel and Le Van, 1998]. The models, which include modifications to the IAST, were able to describe specific binary mixtures on certain adsorbents but could not generally be applied to all systems. During multi-component adsorption, competition by adsorbates for surface sites can give rise to large deviations from expected behaviour because of adsorbate – adsorbate interactions. The combined effects of all possible surface and adsorbate interactions can result in large deviations from ideal solution behaviour. In the work by Appel and Le Van, pure component isotherm models were combined with the two-dimensional virial equation with its ability to describe adsorbate – adsorbate interactions. Single component equation of state

models was substituted for the pure component terms in the two-dimensional virial EOS. The combined EOS was then used to develop multi-component adsorption isotherms. The advantage of this model was a decreased number of required coefficients. Nine coefficients were required to describe the ternary mixture of carbon dioxide, hydrogen sulphide, and propane on H-mordenite.

Multi-component adsorption can also be modelled using the law of mass action [Melis and Cao, 1995]. This model differs from the others in that it assumes that both the fluid and the solid phases behave ideally, while it acknowledges the heterogeneity of the adsorption sites. The model assumes that the effect of mixture non-idealities is smaller than that due to the resin heterogeneity and can thus be neglected. The model was tested by correlation to experimental data from the literature.

## **2.4 SUMMARY**

In this research the selectivity of four ion-exchange resins towards PGM will be assessed. The selective adsorption of base metals from a PGM solution will be also be determined.

A statistical model will be used to model the adsorption characteristics obtained. The adsorption predicted by the model will be compared to the measured values. The effect of different components, as well as chloride concentration, will be determined.



## CHAPTER 3

### EXPERIMENTAL

Noble metal chemistry will always be an area of research posing many challenges to chemists and researchers. The approach followed in this research is to experimentally determine the actual adsorption of the different precious metal ions onto the resins used and to test the factors impacting on the adsorption. The adsorption of each precious metal, and base metal, was experimentally determined on all four of the resins used. In many cases no adsorption would be expected, for example, in the adsorption of gold by a cation resin, the adsorption tests were still conducted for completeness and for the unexpected ionic species which may be present in these solutions. Furthermore, in a plant, not all of a specific PGM will be adsorbed by the selected resin in the resin column, and trace amounts of all PGM's will be present in the process streams. The objective was not to identify the actual ionic species, and the changes in composition taking place in the solution, but rather to study the adsorption of a metallic ion under various solution conditions regardless of the composition of the actual ionic compound. Care was taken to ensure that the ionic component required for adsorption by the particular resin was achieved. This was done by matching the test solution to that used in the industry where optimal pH and solution potentials were determined.

The following equilibrium adsorption tests were conducted:

- i. Single component PGM adsorption curves,
- ii. Base metal solution adsorption curve,
- iii. Effect of additional PGM's in the solution on adsorption characteristics,
- iv. Effect of different  $\text{Cl}^-$  concentrations (pH) on the adsorption from single and more component solutions.

IUPAC recommendations on ion-exchange nomenclature define "theoretical specific capacity" as the milli-equivalents of ionogenic group per gram of dry ion-exchanger [Lehto and Harjula, 1995]. The ionogenic group is the active site for ion-exchange.



For a quaternary ammonium group resin, the ionogenic group is  $-N^+(CH_3)_3$ , which holds the ions capable of exchanging for other ions in the external solution. The actual uptake will not reach the theoretical capacity, for example, if there are exchange sites to which various ions have different accessibility's. Some sites may be entirely inaccessible to larger ions. The IUPAC recommendations also include the "practical specific capacity" of an ion-exchanger. This comprises the total amount of ions expressed in milli-equivalents, taken up per gram of ion-exchanger, under specific conditions, which should always be given.

The usual way to present adsorption curves is to plot the amount of say component  $x$  adsorbed / capacity of the resin for  $x$ , against the concentration of  $x$  in the solution / total concentration of  $x$ . In this case,  $x$  will be one of the PGM's or the total base metal (BM) concentration. It is evident from the above that the practical capacity depends on the experimental conditions. All the experimental work was performed as batch adsorption tests. To determine the maximum uptake of a specific ion by the resin, that is the practical capacity, the counter ion which is displaced from the resin must be continuously removed, such as in a column. The batch equivalent should be a large number of successive batch equilibration's in series. The maximum capacity of the resin for a specific ion could therefore not be determined with the batch method used.

### 3.1 EXPERIMENTAL METHOD

To gain insight in the actual adsorption taking place and to avoid the many interactions in the actual multi-component solutions during adsorption, synthetic PGM solutions were prepared. The adsorption was firstly determined for single metal solutions. Thereafter, more PGM's were added to the solution to determine the effect of the additional ions on the adsorption. The choice of metals used in the multi-component solutions was guided by the adsorption results obtained from the single component adsorption tests. Equilibrium adsorption data points were determined for a PGM test solution by varying the amount of resin added to the specific solution concentration. The volume of test solution used for each test was either 500 or 1000 ml. The amount of resin added to a specific solution concentration ranged between 0.5ml to 100ml. The amount of resin added to the solution was varied to achieve a



low as well as a high (relative to the resin capacity) total loading on the resin. In batch experimentation, the final concentration is unknown and it is therefore difficult to predict the eventual equilibrium concentration beforehand. The test solution concentrations and resin quantities used were selected by considering the expected uptake of the resin to achieve a wide spread of adsorption data points. The resin was measured out in a small plastic measuring cylinder and tapped against the bench for settlement of the resin beads. The test solution was diluted from a 2000 ppm stock solution prepared to the required metal concentration and free acid concentration. A sample of the test solution was taken as reference before adding the resin beads. All analysis was done by inductively coupled plasma (ICP). The reference sample was also titrated to check that the targeted free HCl concentration was correct. The resin was added to the solution and rolled in bottles for 24 hours to ensure equilibrium was attained. The bottles were rolled on a roller bench to facilitate multiple simultaneous tests. After exposure, a sample of the solution was taken and analysed by ICP. The adsorption was calculated by difference to the reference sample concentration. Solution potential was measured with a platinum redox electrode with reference to Ag/AgCl. The solution potential is an important parameter to ensure optimal adsorption by the functional group of the resin. Deviation from the set potential may cause damage to the functional group, a decrease in activity and a loss in selectivity or precipitation of components. With the many species present in PGM and base metal solutions the solution potential and free acid concentration are further means of ensuring that the desired complex species are present in the solution.

## **3.2 RESINS USED**

Four resins were used, IRA900, XAD7, IR200 and A22. The resins are commercially available from the Rohm & Haas company, except for A22 which is a tailor-made resin for selective palladium adsorption. A general guide for the selection of resins is included in Appendix D.

### **3.2.1 IRA900 Resin**

The resin matrix is a styrene divinylbenzene copolymer. The active functional group is a quaternary ammonium group  $-N^+(CH_3)_3$ . The resin is a commercial type 1 strong base anion-exchange resin. The resin is frequently used for complete removal of all



anions, including weakly dissociated ones like silica. The macro-reticular structure embodies fixed large pores, presenting a sponge-like matrix. The large discrete pores mean that high molecular weight ions can be more completely removed from solution and more completely eluted from the resin on regeneration. The structure imparts superior resistance to mechanical and osmotic shock. The resin allows for fast kinetics and is also used for condensate polishing. It is also very effective as an organic scavenger when placed in front of a de-ionisation system. The resin is also suitable for colour removal from sugar syrups. The resin is supplied in the chloride form. The supplier specification sheet is included in Appendix A.

Care had to be taken in the iridium test solution preparation, see paragraph 3.4 to ensure that the required complex was attained and to avoid hydrolysis.

### **3.2.2 XAD7 Resin**

Amberlite XAD7 is a polymeric adsorbent. It is a non-ionic aliphatic acrylic polymer which derives its adsorptive properties from its patented macroreticular structure (containing both a continuous polymer phase and a continuous pore phase). The adsorption by XAD7 is therefore not ion-exchange as such. The macroreticular structure of the resin gives it excellent physical and thermal stability. Due to its aliphatic nature, the resin can adsorb non polar compounds from aqueous systems, and can also adsorb polar compounds from non-polar solvents. It has been reported that the resin is ion specific towards gold [Fritz and Millen, 1971]. The supplier specification sheet is included in Appendix B.

### **3.2.3 IR200 Resin**

The resin is a strong acid macroreticular cation-exchange resin based on sulfonic acid exchange groups, the  $\text{SO}_3^-$  functional group, on a polystyrenic matrix. It has a high degree of crosslinking which imparts superior stability to the macroreticular structure of the resin. The resin is used for demineralisation and mixed bed units, hot process softeners, chemical processing and systems involving appreciable oxidative potential or high temperatures. The supplier specification sheet is included in Appendix C.



### 3.2.4 A22 Resin

No details can be presented as to the structure or functional group of the resin due to confidentiality. A22 is used by Impala Platinum for selective palladium adsorption.

## 3.3 RESIN PREPARATION

The resin was prepared in glass columns with upward flow of solution. The solution was pumped with a variable speed peristaltic pump. The upward flow of solution through the column has to be very slow to allow displacement of the air from the resin and the connecting tubes as air pockets tend to lift the resin upwards and out of the column. Analytical grade HCl was used for all experimental work.

### 3.3.1 IRA900 Resin

The resin was firstly washed with distilled water to remove all foreign ions from the factory floor. The resin was then washed with caustic solution. The large  $\text{OH}^-$  ions force open all the small pores in the resin to free and displace foreign ions. The resin was then washed again with 2M NaCl to convert the resin back to the  $\text{Cl}^-$  form. The smaller  $\text{Cl}^-$  ions have the ability to displace the  $\text{OH}^-$  ions because of a large charge density. This was followed with a water wash and finally with 8% HCl to prepare the resin for adsorption. The resin was then taken out of the column and put into a 5-litre plastic drum from where small amounts were taken for the adsorption tests.

### 3.3.2 XAD7 Resin

The resin was supplied wetted with NaCl and  $\text{Na}_2\text{CO}_3$  salts to prevent bacterial growth. The resin was washed with 14% HCl to prepare the resin for adsorption.

### 3.3.3 IR200 Resin

The resin was supplied in the sodium ionic form. The resin was washed with 14% HCl to displace the sodium. This was followed by a rinse with 5% HCl.

### 3.3.4 A22 Resin

The resin was washed with 10.4% HCl.



### 3.4 TEST SOLUTION PREPARATION

Platinum, palladium and gold solutions were prepared by dissolution of the pure metals in aqua-regia. Ruthenium, iridium, and rhodium were dissolved from the pure salts. Metal salts were used as it is difficult to dissolve these metals. Impala Platinum Refineries in Springs, South Africa, provided the precious metals for this research. The PGM purity was better than 99.9% in all cases. Ruthenium was dissolved from the  $(\text{NH}_4)_2(\text{RuNOCl}_5)$  salt, iridium from  $(\text{NH}_4)_2(\text{IrCl}_6)$ , and rhodium from the DETA salt  $(\text{DETAH}_3)(\text{RhCl}_6)$ . DETA being the  $\text{C}_4\text{N}_3\text{H}_{10}$  chain. The mass required for a 2000 ppm stock solution was weighed off and boiled in aqua-regia until dissolved. More HCl was added and the solution was boiled further to drive off all the nitric acid which was emitted as  $\text{NO}_x$  fumes. The resulting free HCl in the solution was determined by titration. The solution was then diluted with the correct amounts of water and acid to achieve the desired final free acid and metal concentration ( $\pm 2000$  ppm, as metal). To obtain the correct ionic complex for iridium adsorption, care had to be taken in the dissolution of the iridium salt. During aqua-regia dissolution  $\text{SO}_2$  gas was bubbled through the solution to reduce the iridium from the +4 (solubility 3 g/l) to the +3 oxidation state (solubility 30g/l). The iridium is converted from the  $(\text{NH}_4)_2\text{IrCl}_6$  complex to  $(\text{NH}_4)_3\text{IrCl}_6$ . After dissolution the iridium solution was passed through a cation-exchange resin column to remove the  $\text{NH}_4^+$  ion and replace it with a proton. The IR200 resin was suitable for this, with 15% HCl. The iridium solution obtained is  $\text{H}_3\text{IrCl}_6$ . This solution was taken to high HCl concentration by slow boiling to drive off the water. Iridium in the concentrated solution was oxidised to  $\text{H}_2\text{IrCl}_6$  by bubbling  $\text{Cl}_2$  gas through the solution. The stock solution prepared was kept as such to avoid hydrolysis.

The gold solution was kept in a 25-litre glass container. The container was washed with concentrated  $\text{HNO}_3$  and rinsed with distilled water to avoid adsorption of the gold onto the glass. All other PGM solutions were kept in 25-litre polyethylene containers. From these 2000 ppm stock solutions, further dilutions to the actual test concentrations (ranging from 25 to 300 ppm and 2 to 20% HCl) were done.

A base metal solution was prepared by matching the composition of an industrial base metal solution. All the required components were added in the correct quantities for



the targeted composition. Ruthenium, rhodium and iridium were added from the already prepared pure stock solutions. The composition and reagents used for preparation of the base metal solution can be seen in Table 3.4.1.

Aqua-regia was added to dissolve all the solid components. All nitric acid was boiled off from the solution. The solution was then diluted to the required acid and 2000 ppm PGM plus base metal concentration.

A spreadsheet was used to calculate the dilution from the mother solutions prepared (2000 ppm) to the actual test solution metal and acid concentrations required, the test solution potential was adjusted to match the specification for the resin used. The solution potential was increased by adding a few drops of  $H_2O_2$ .  $Na_2SO_3$  was used for a reduction in potential. The oxidant and reductant were added drop by drop with a waiting period of 10 minutes in between drops to allow for stabilisation of the solution potential.

**Table 3.4.1: Preparation and composition of base metal solution**

	<b>Required Individual Ppm</b>	<b>Comp. Individual Gram</b>	<b>Reagent Used</b>	<b>Metal Mol.Mass</b>	<b>Reagent Mol.Mass</b>	<b>gram reagent required</b>
<b>Pt</b>	845.1	9.1	Pt metal	195.09	195.09	9.1
<b>Pd</b>	422.5	4.6	Pd metal	106.4	106.4	4.6
<b>Au</b>	28.2	0.3	Au metal	196.967	196.967	0.3
<b>Rh</b>	98.6	1.1	Use 2764ppm stock solution		ml sol used	385
<b>Ru</b>	126.8	1.4	Use 2620ppm stock solution		ml sol used	523
<b>Ir</b>	42.3	0.5	Use 7408ppm stock solution		ml sol used	62
<b>Ag</b>	70.4	0.8	$AgNO_3$	107.87	169.87	1.2
<b>Ni</b>	28.2	0.3	$Ni(NO_3)_2 \cdot 6H_2O$	58.71	290.8	1.5
<b>Cu</b>	56.3	0.6	$Cu(NO_3)_2 \cdot 3H_2O$	63.54	241.6	2.3
<b>Fe</b>	56.3	0.6	$Fe(NO_3)_3 \cdot 9H_2O$	55.847	404	4.4
<b>Pb</b>	84.5	0.9	$Pb(NO_3)_2$	207.19	331.2	1.5
<b>As</b>	14.1	0.2	$As_2O_3$	74.922	197.84	0.4
<b>Se</b>	42.3	0.5	Se	78.96	78.96	0.5
<b>Te</b>	84.5	0.9	Te	127.6	127.6	0.9
<b>Total</b>	2000.0	21.6				
<b>Non PGM</b>	436.6	4.7				

The batch equilibrium adsorption on the four resins XAD7, A22, IR200, and IRA900 were determined for each individual PGM, Au, Ir, Ru, Rh, Pd, Pt, as well as for the base metal solution. The adsorption of multi-component mixtures were then determined, omitting the target component from the solution in order to identify the next strongest bonded on the resin. A further adsorption test was then conducted to investigate the adsorption characteristics from a mixed solution containing the target metal as well as the next strongest bonded. The experimental program can be summarised as in Table 3.4.2.



**Table 3.4.2: Experimental tests conducted**

<b>Solution components</b>	<b>Resins individually tested</b>	<b>Variables</b>
Au	IRA900, XAD7, IR200, A22	Resin ml, Start ppm
Ir	IRA900, XAD7, IR200, A22	Resin ml, Start ppm
Pd	IRA900, XAD7, IR200, A22	Resin ml, Start ppm
Pt	IRA900, XAD7, IR200, A22	Resin ml, Start ppm
Rh	IRA900, XAD7, IR200, A22	Resin ml, Start ppm
Ru	IRA900, XAD7, IR200, A22	Resin ml, Start ppm
BM	IRA900, XAD7, IR200, A22	Resin ml, Start ppm
Ir, Rh	IRA900	Resin ml, Start ppm
Rh, Pt, Ru	IRA900	Resin ml, Start ppm
Rh, Pt, Ru, Au, Pd, BM	IRA900	Resin ml, Start ppm
Ir, Pd, Pt, Rh, Ru, BM	XAD7	Resin ml, Start ppm
Au, Ru	XAD7	Resin ml, Start ppm
Ir, Pt, Rh, Ru	IR200	Resin ml, Start ppm
Ir, BM	IR200	Resin ml, Start ppm
Au, Ir, Pd, Pt, Rh, Ru	IR200	Resin ml, Start ppm
Ir, Pt, Rh, Ru, BM	A22	Resin ml, Start ppm
Pd, BM	A22	Resin ml, Start ppm
Au, Ir, Pt, Rh, Ru, BM	A22	Resin ml, Start ppm
Au	IRA900, XAD7, IR200, A22	Resin ml, Start ppm, HCl
Ir	IRA900, XAD7, IR200, A22	Resin ml, Start ppm, HCl
Pd	IRA900, XAD7, IR200, A22	Resin ml, Start ppm, HCl
Pt	IRA900, XAD7, IR200, A22	Resin ml, Start ppm, HCl
Rh	IRA900, XAD7, IR200, A22	Resin ml, Start ppm, HCl
Ru	IRA900, XAD7, IR200, A22	Resin ml, Start ppm, HCl
BM	IRA900, XAD7, IR200, A22	Resin ml, Start ppm, HCl
Ir, Rh	IRA900	Resin ml, Start ppm, HCl
Rh, Pt, Ru	IRA900	Resin ml, Start ppm, HCl
Rh, Pt, Ru, Au, Pd, BM	IRA900	Resin ml, Start ppm, HCl
Ir, Pd, Pt, Rh, Ru, BM	XAD7	Resin ml, Start ppm, HCl
Au, Ru	XAD7	Resin ml, Start ppm, HCl
Ir, Pt, Rh, Ru	IR200	Resin ml, Start ppm, HCl
Ir, BM	IR200	Resin ml, Start ppm, HCl
Au, Ir, Pd, Pt, Rh, Ru	IR200	Resin ml, Start ppm, HCl
Ir, Pt, Rh, Ru, BM	A22	Resin ml, Start ppm, HCl
Pd, BM	A22	Resin ml, Start ppm, HCl
Au, Ir, Pt, Rh, Ru, BM	A22	Resin ml, Start ppm, HCl
Au, Ir, Pt, Rh, Ru, BM, Pd	A22	Resin ml, Start ppm, HCl



## *CHAPTER 4*

### **EQUILIBRIUM ADSORPTION CHARACTERISTICS**

It became evident from the experimental data analysis that effective visualisation of the quantitative adsorption data can be obtained by combining the variable parameters like solution concentration and quantity of resin used into a single ratio and to plot this ratio against the gram adsorbed per liter of resin. It is also evident that for each solution concentration the adsorption, expressed as gram/liter resin, increases as the amount of resin used decreases. This is due to the ratio of exchangeable ions in solution divided by the number of potential adsorption sites on the resin. Therefore, the ratio used for the graphs is the initial (or starting) concentration of precious metal in the solution (which determines the potential quantity of ions to be adsorbed onto the resin) divided by the ml of resin used (which determines the total amount of adsorption sites available for adsorption). The adsorption curves presented are therefore presented as such. It is evident that where the resin has a high preference for the ion to be exchanged the initial slope of the adsorption curve (that is for small ppm / ml resin) will be high. This indicates that the resin has a high affinity for the ion to be exchanged and that high loading will be attained in dilute solutions.

All solution potentials listed were measured with a platinum redox electrode with reference to Ag/AgCl. The free HCl concentrations used for all four of the resins are depicted in Table 4.1.

**Table 4.1: Free HCl concentrations for the resins**

<b>Resin</b>	<b>% Free HCl</b>
IRA900	8
XAD7	13.7
IR200	2
A22	10.4

For comparative purposes, single metal adsorption characteristics of a specific precious metal by all four resins will be presented together. For the mixed solutions, however, the adsorption of all mixed solutions by each resin is given together.



## 4.1 SINGLE METAL ADSORPTION

Adsorption data points were determined by adding different quantities of resin to each test solution concentration to construct the adsorption curves. It should be noted that inaccuracies are amplified for the very small resin volumes, that is where the ratio “start ppm / ml resin” is big. This is due to inaccuracies in the measurement of small (less than 1 ml) resin quantities.

### 4.1.1 Gold

Gold is in solution as the  $\text{AuCl}_4^-$  ion. The adsorption curve for IRA900 (Figure 4.1.1.1) was determined with a 300 ppm gold solution. The solution potential was 732 mV. It is evident from the high initial slope and adsorption quantity obtained that the resin has a high affinity for gold.

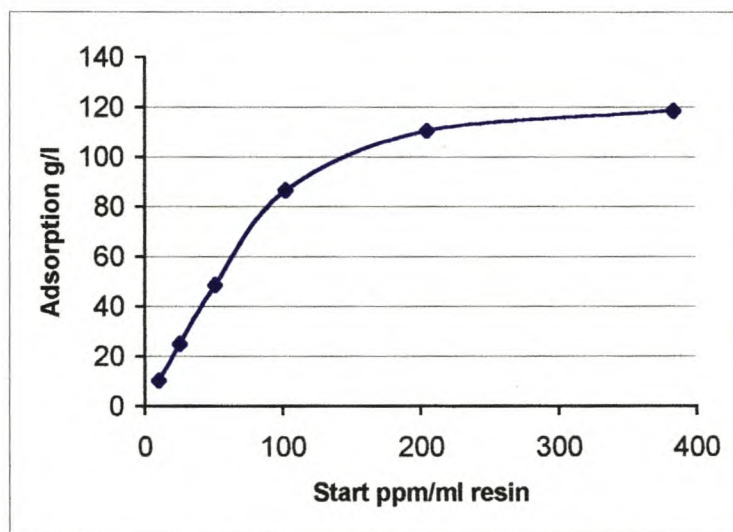
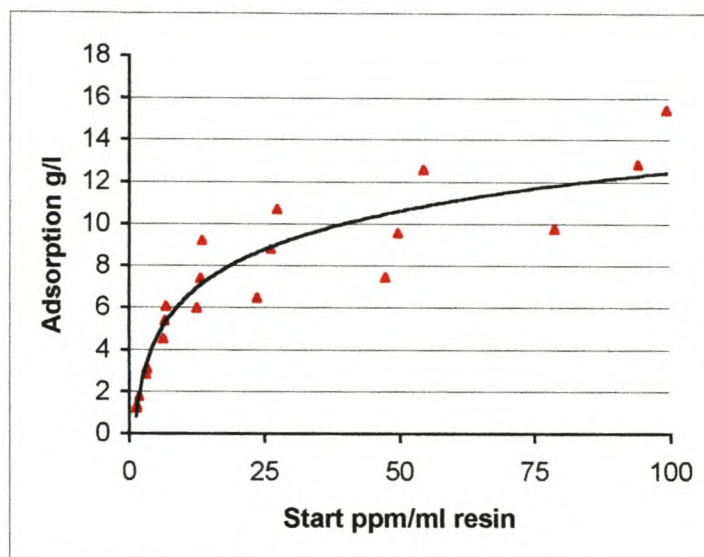


Figure 4.1.1.1: Gold adsorption on IRA900

Three different solution concentrations were evaluated for adsorption, 25, 50, and 100 ppm gold. For all three test solutions the solution potential was  $\pm 665$  mV. The adsorption of gold by XAD7 can be seen in Figure 4.1.1.2. The high initial slope indicates a high affinity for gold, but the total loading capacity became constant rapidly.

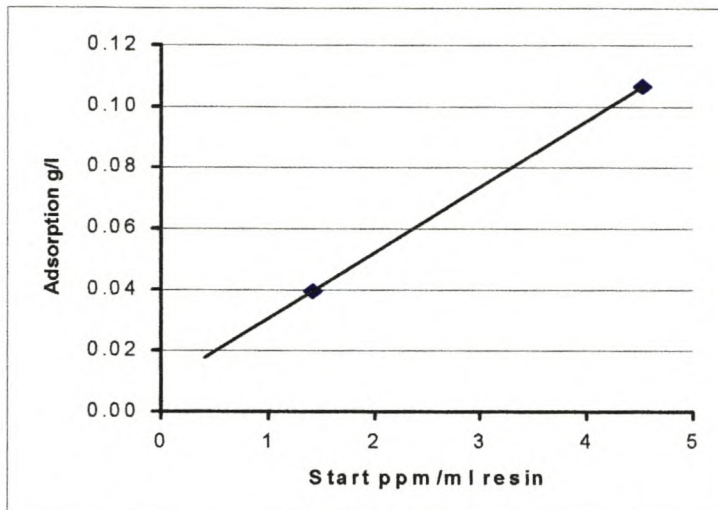


**Figure 4.1.1.2: Gold adsorption on XAD7**

Experimental data analysis suggested that for ion-exchange the adsorption from different starting solution concentrations can be shown as a single line. The data in Figure 4.1.1.2 show that the gold adsorption characteristics are on different curves for the three starting solution concentrations used. This may be explained by the fact that gold is not adsorbed by ion-exchange as such (see Section 3.2.2).

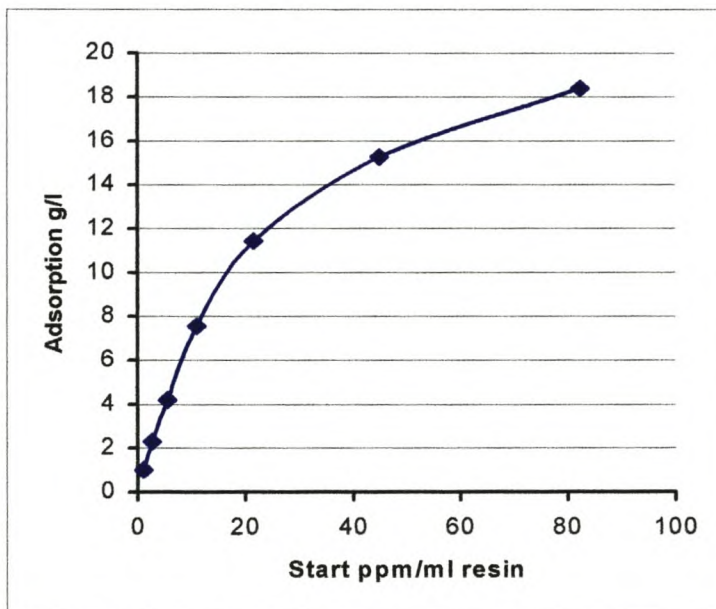
Although gold is present as the anion in the solution, the adsorption test with IR200 was done. Only two data points were determined. The solution concentration was 50 ppm and the potential 750 mV. The uptake can be seen in Figure 4.1.1.3. The gold is not adsorbed by the resin. The uptake obtained is very small and can most likely be attributed to diffusion into the resin beads.





**Figure 4.1.1.3: Gold adsorption on IR200**

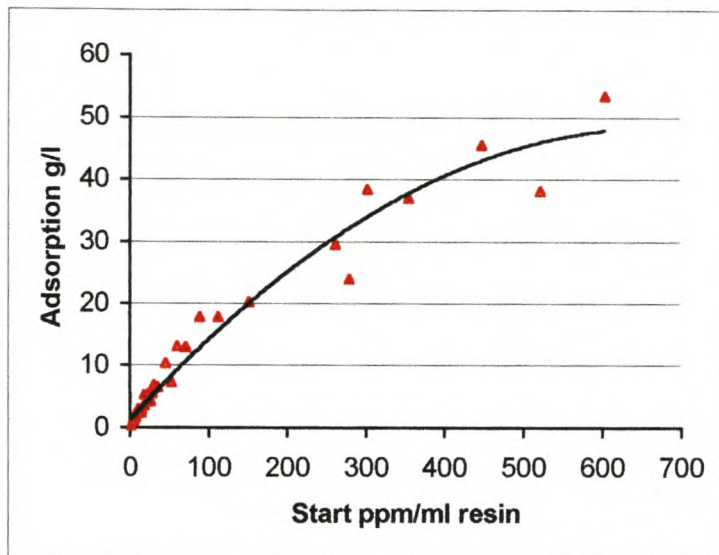
The adsorption on A22 resin was determined for a 50 ppm solution (see Figure 4.1.1.4). The solution potential was 704 mV. Gold is well adsorbed by the resin.



**Figure 4.1.1.4: Gold adsorption on A22**

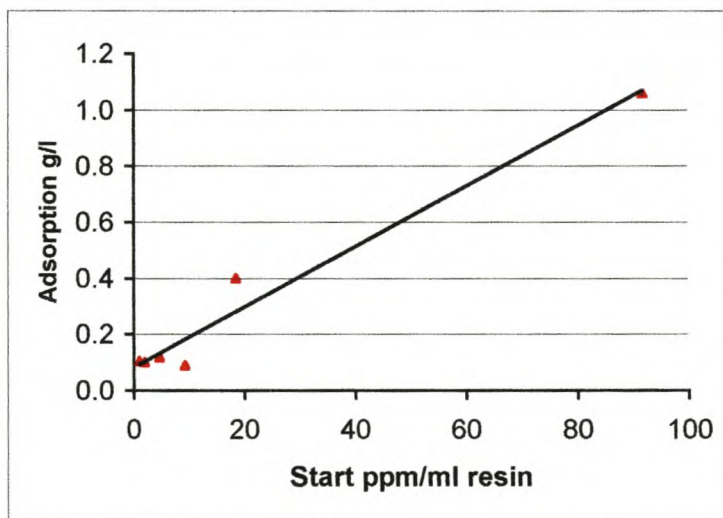
#### 4.1.2 Iridium

Five test solutions were prepared from 100 to 400 ppm iridium. The solution potentials varied from 820 to 940 mV. The duration of the bottle roll equilibration was varied from 4 to 24 hours to check for hydrolysis, but no difference in adsorption quantities was noticed. The adsorption obtained can be seen in Figure 4.1.2.1.



**Figure 4.1.2.1: Iridium adsorption on IRA900**

The adsorption of iridium on XAD7 was determined for a 100 ppm iridium solution. The solution potential was 890 mV.

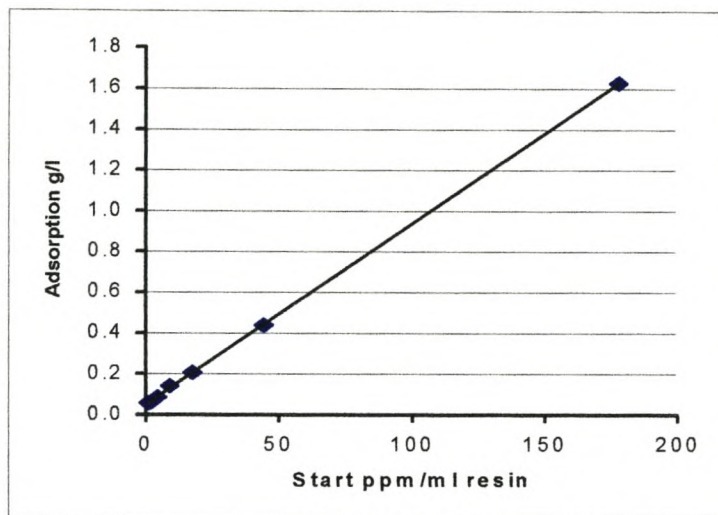


**Figure 4.1.2.2: Iridium adsorption on XAD7**

Very little iridium was adsorbed by XAD7 (see Figure 4.1.2.2). The quantity of iridium removed from the test solution was more than likely due to diffusion into the resin beads and not due to adsorption. The adsorption by IR200 was determined for a 100 ppm solution at 980 mV. It is evident from the linear adsorption characteristic (Figure 4.1.2.3) and from the small quantities of iridium removed from the solution

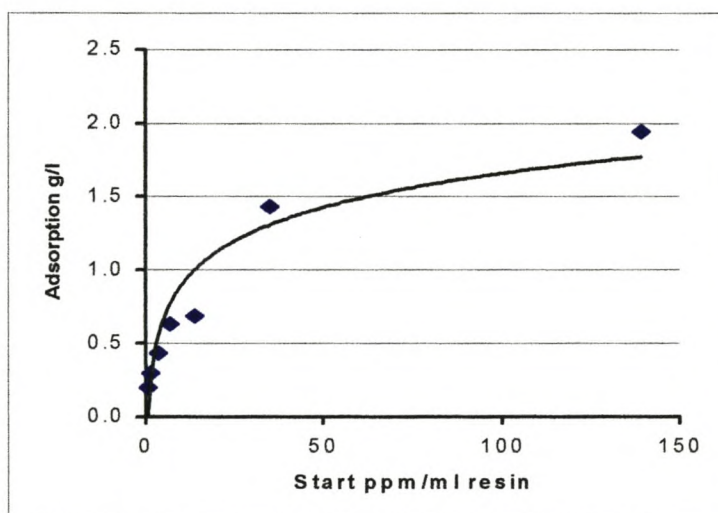


that only equilibrium diffusion occurs. This result is to be expected as IR200 is a cation resin.



**Figure 4.1.2.3: Iridium adsorption on IR200**

Iridium adsorption by A22 was determined for a 70 ppm solution. The solution potential was 700 mV.

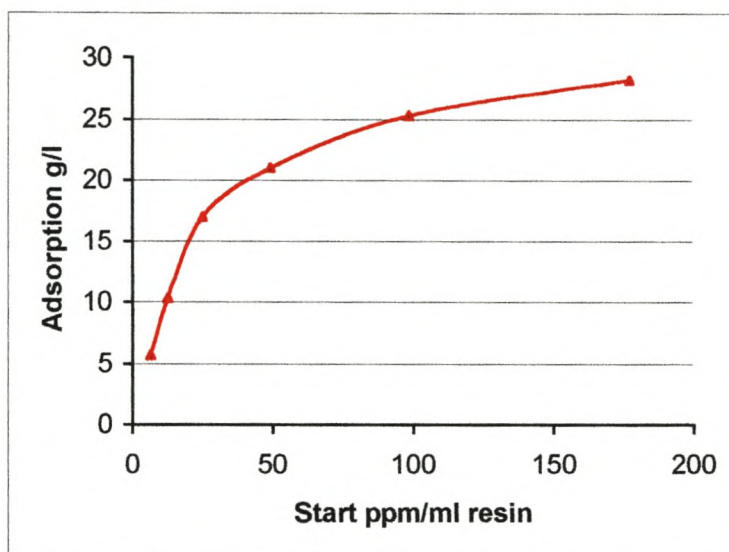


**Figure 4.1.2.4: Iridium adsorption on A22**

As can be seen in Figure 4.1.2.4, some uptake of the iridium occurs from the single metal solution, but only minor quantities.

### 4.1.3 Palladium

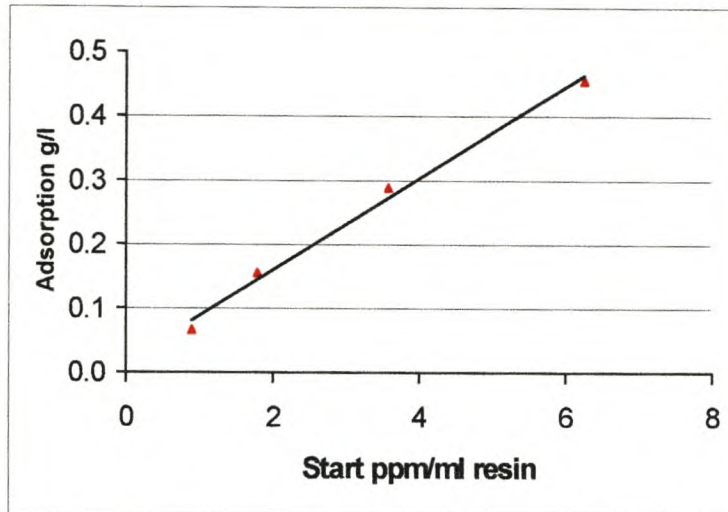
Palladium is in solution as the  $\text{PdCl}_4^{2-}$  ion. The adsorption curve for IRA900 was determined from a 270 ppm palladium solution (Figure 4.1.3.1). The solution potential was 444 mV. It is evident that palladium is adsorbed by the resin.



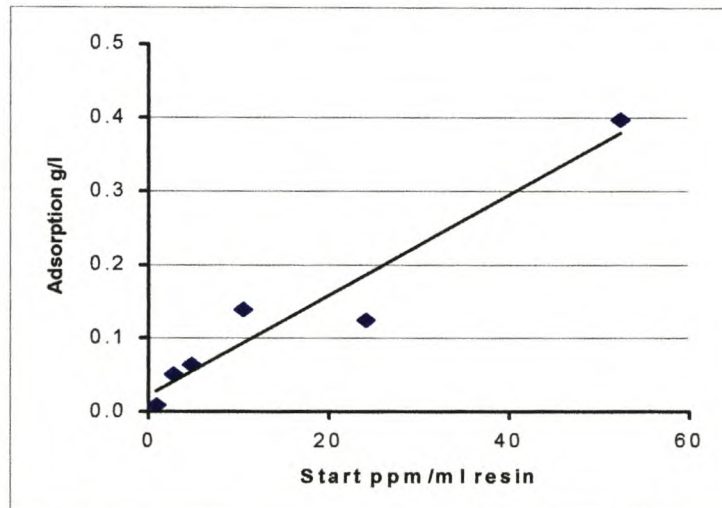
**Figure 4.1.3.1: Palladium adsorption on IRA900**

Adsorption of palladium by XAD7 resin can be seen in Figure 4.1.3.2. The solution concentration was 50 ppm, at 930 mV. It is evident from the figure that no adsorption of palladium occurs, merely diffusion into the resin for chemical equilibrium.





**Figure 4.1.3.2: Palladium adsorption on XAD7**



**Figure 4.1.3.3: Palladium adsorption on IR200**

Adsorption tests on IR200 were performed for 50 ppm and 100 ppm solutions. The solution potentials were 560 mV and 530 mV respectively. It is evident from the small uptake (Figure 4.1.3.3) that no adsorption of palladium by IR200 takes place.

The adsorption of palladium on A22 resin can be seen in Figure 4.1.3.4. Three solution concentrations were tested for adsorption, 20, 50, and 100 ppm. The solution potentials were 615, 650, and 700 mV, respectively. A logarithmic curve was fitted through the data points. It is evident that for the small resin volumes experimental inaccuracies caused some scattering in the data points. The resin has an affinity for palladium, as indicated by the steep initial slope of the adsorption curve.

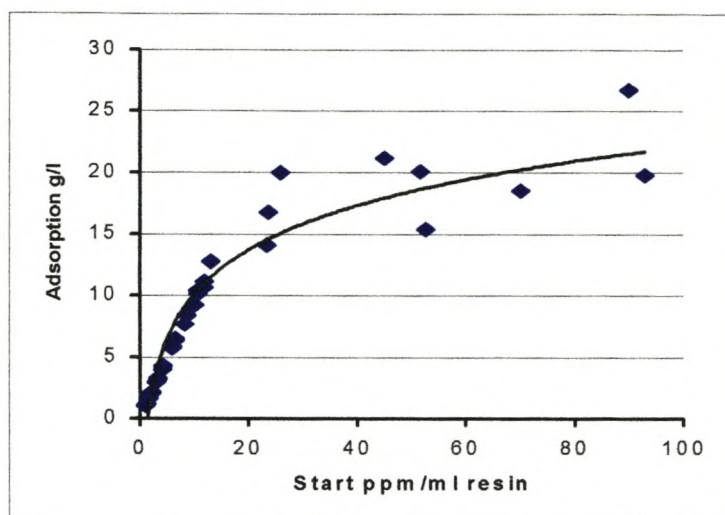


Figure 4.1.3.4: Palladium adsorption on A22

#### 4.1.4 Platinum

Platinum is in solution as the  $\text{PtCl}_6^{2-}$  ion. The adsorption curve using IRA900 (Figure 4.1.4.1) was determined by adsorption from a 305 ppm platinum solution. The solution potential was 418mV.

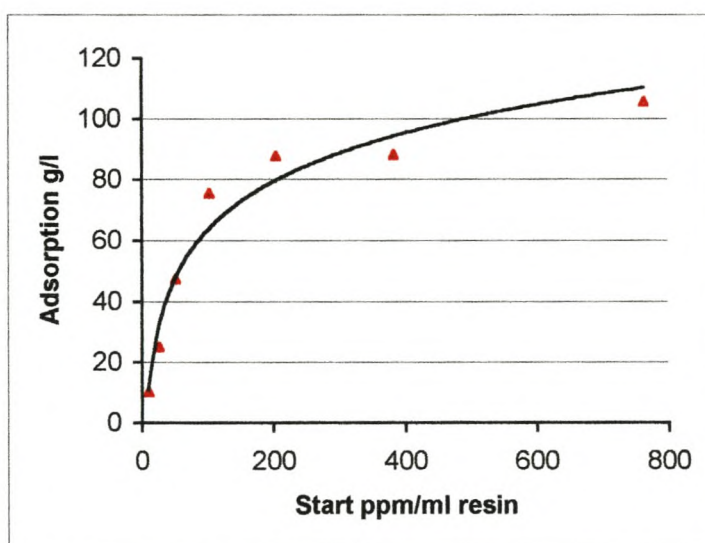
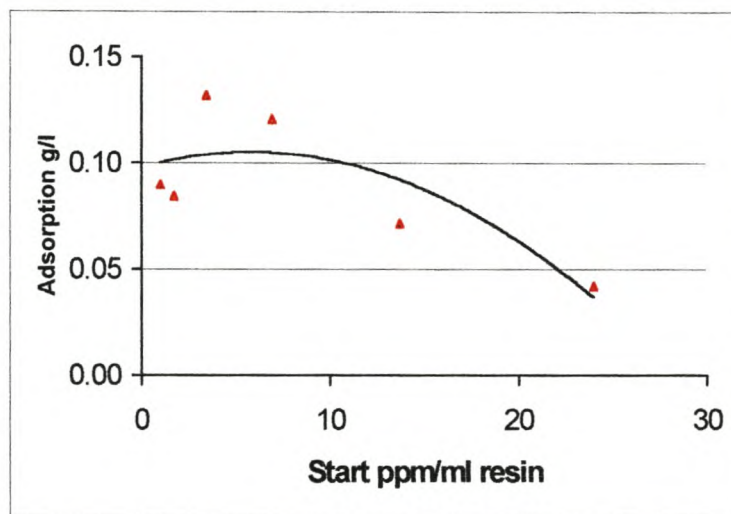


Figure 4.1.4.1: Platinum adsorption on IRA900

From the figure it is evident that the resin affinity for platinum is high and that a high column loading capacity can be expected.

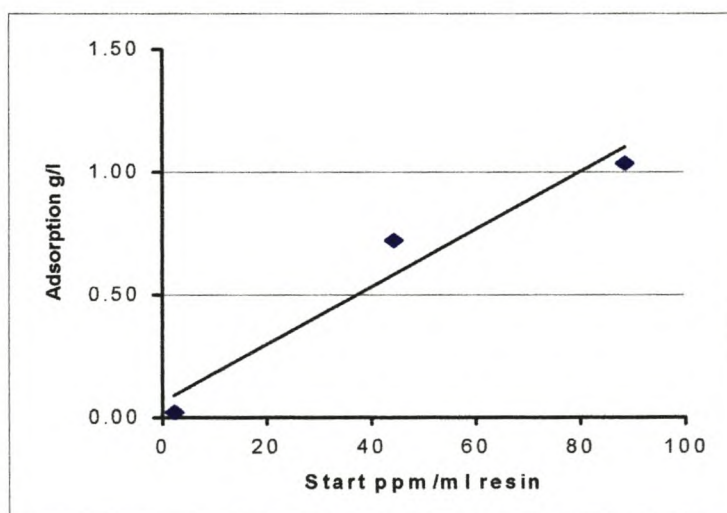


A 50 ppm platinum solution was tested for adsorption by XAD7 resin. The solution potential was 900 mV. From Figure 4.1.4.2 it is evident that there is no adsorption, and furthermore that very limited equilibrium diffusion of platinum into the resin beads occur. This may be due to the size or charge orientation of the platinum ions.



**Figure 4.1.4.2: Platinum adsorption on XAD7**

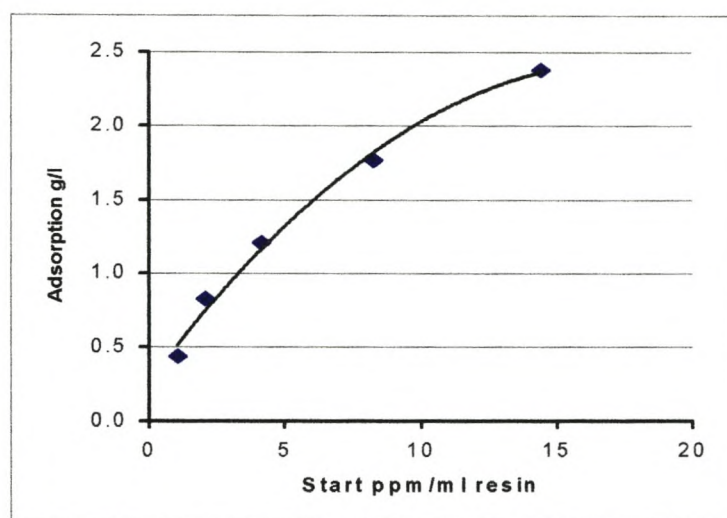
The adsorption characteristic of platinum by IR200 resin can be seen in Figure 4.1.4.3. A 50 ppm platinum solution at 450 mV was used for the tests.



**Figure 4.1.4.3: Platinum adsorption on IR200**

As to be expected there is no adsorption of platinum, which is in solution as anionic compounds. The platinum uptake by the resin is due to equilibrium diffusion.

The adsorption of platinum by A22 resin was determined for a 50 ppm platinum solution and the solution potential was 670 mV. From Figure 4.1.4.4 it can be seen that some uptake does occur from the single metal solution, but in very small quantities.

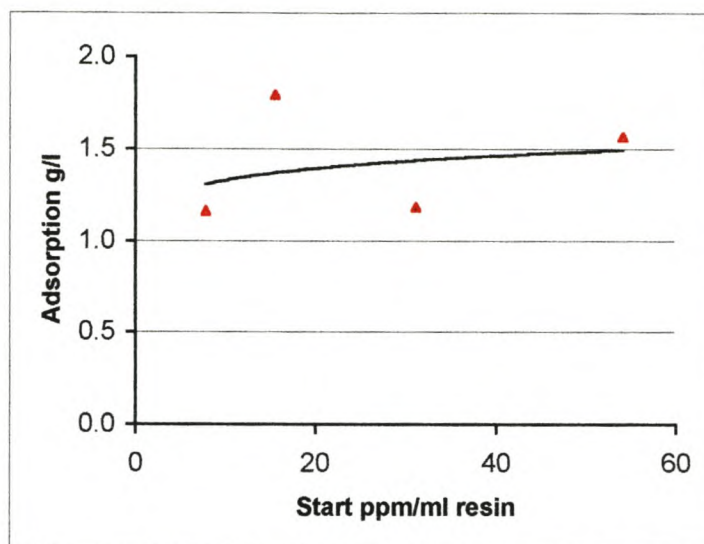


**Figure 4.1.4.4: Platinum adsorption on A22**

#### 4.1.5 Rhodium

Rhodium is in solution as one of the following chlorocomplexes [Jukka Lehto, 1995]  $\text{RhCl}_4(\text{H}_2\text{O})^-$ ,  $\text{RhCl}_5(\text{H}_2\text{O})^{2-}$ , or the  $\text{RhCl}_6^{3-}$  ion, depending on the equilibrium between these species. The adsorption of rhodium by IRA900, Figure 4.1.5.1, was determined by adsorption from a 293 ppm solution. The solution potential was 531mV.

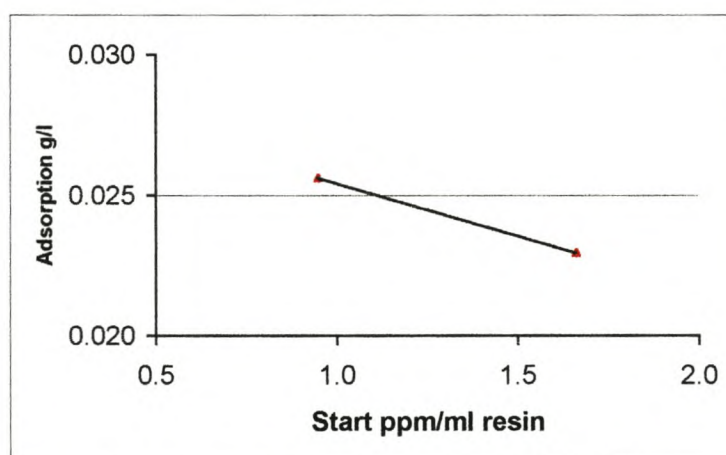




**Figure 4.1.5.1: Rhodium adsorption on IRA900**

From the figure it is evident that rhodium is not adsorbed by the resin

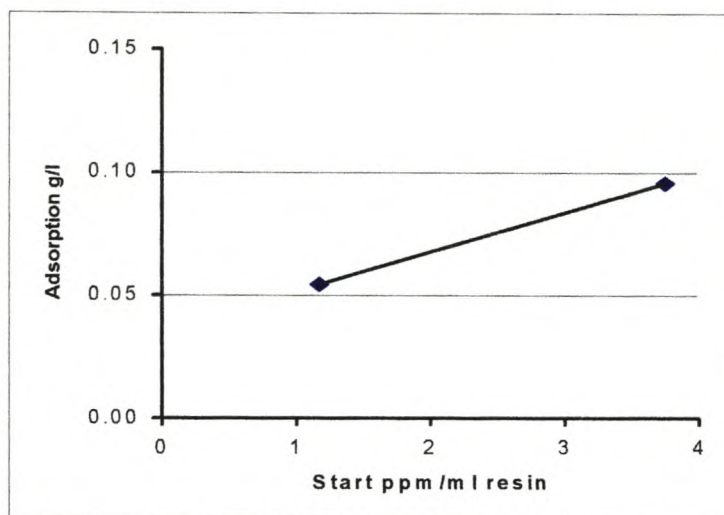
The adsorption curve for rhodium on XAD7 can be seen in Figure 4.1.5.2. Only two data points were determined as no adsorption was anticipated. It is evident that virtually no rhodium is removed from the solution, less than 0.05 g/l. The same characteristic holds true as for platinum in that no rhodium seems to enter the resin beads at all.



**Figure 4.1.5.2: Rhodium adsorption on XAD7**

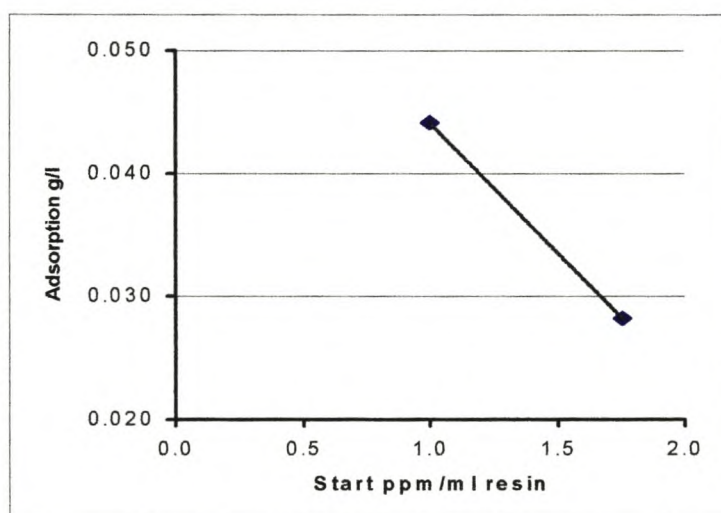
Very little rhodium was removed from the solution by IR200 (see Figure 4.1.5.3). The test solution concentration was 50 ppm rhodium at 450 mV. Some sorption by

diffusion into the resin beads is evident. The amount removed from the solution by equilibrium diffusion will increase in more concentrated solutions.



**Figure 4.1.5.3: Rhodium adsorption on IR200**

The adsorption of rhodium by the A22 resin is depicted in Figure 4.1.5.4. The test solution used was 50 ppm rhodium at 610 mV. From the figure it is evident that virtually no rhodium is removed from the solution by the resin.



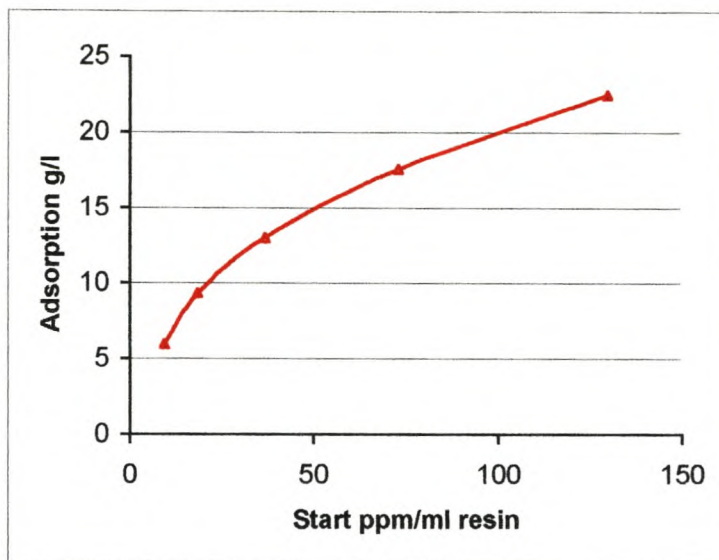
**Figure 4.1.5.4: Rhodium adsorption on A22**

#### 4.1.6 Ruthenium

Ruthenium is in solution as one of the following chlorocomplexes,  $\text{RuCl}_5(\text{H}_2\text{O})^{2-}$ , or the  $\text{RuCl}_6^{3-}$  ion [Jukka Lehto, 1995], depending on the equilibrium between these species. The adsorption curve was determined by adsorption from a 300 ppm

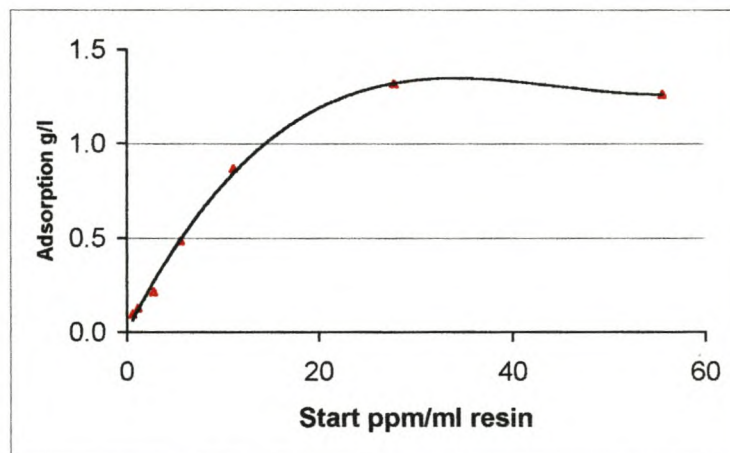


ruthenium solution. The solution potential was 834mV. From Figure 4.1.6.1 it can be seen that ruthenium is adsorbed by the resin.



**Figure 4.1.6.1: Ruthenium adsorption on IRA900**

The adsorption of ruthenium by XAD7 was determined for a 50 ppm ruthenium solution, the solution potential was 930 mV. From the adsorption curve in Figure 4.1.6.2, it appears that the resin removed some small amounts of ruthenium from the solution, less than 1.5 g/l.

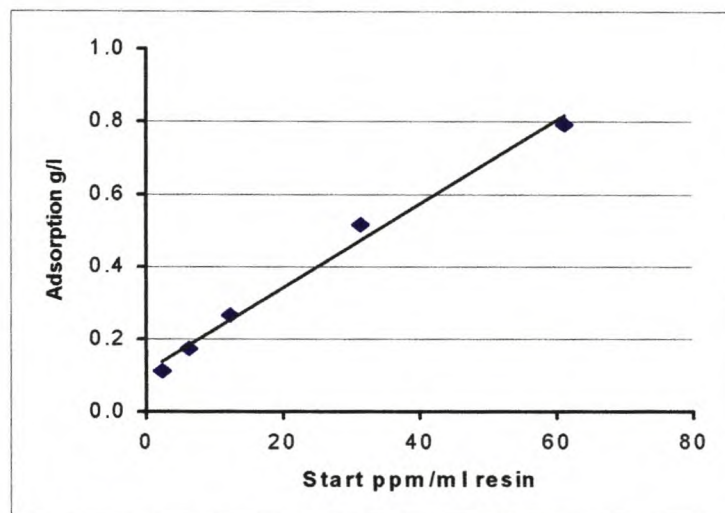


**Figure 4.1.6.2: Ruthenium adsorption on XAD7**

It is important to note that the adsorption characteristic of the resin from a mixed solution will be different, as interaction between the different ionic species in the

solution (see Chapter 5) and the kinetics of the adsorption of the different ions will determine the adsorption characteristics.

The adsorption by IR200 resin was determined for 50 ppm and 100 ppm ruthenium solutions. The solution potentials were 760 mV and 800 mV, respectively.



**Figure 4.1.6.3: Ruthenium adsorption on IR200**

From Figure 4.1.6.3 it can be seen that ruthenium is not adsorbed by IR200, which is a cation resin. Physical diffusion into the resin beads removed some of the ruthenium from the test solution.

A 50 ppm ruthenium test solution with a solution potential of 610 mV was used for the adsorption by A22. Very small negative uptake values were obtained due to analytical inaccuracies. The small values indicate that ruthenium is not adsorbed, and in fact does not seem to enter the resin beads at all.

From the adsorption results obtained with single precious metal solutions, it is evident that the PGM's are only adsorbed by the following resins;

- ◆ Gold – IRA900, XAD7, A22
- ◆ Iridium – IRA900
- ◆ Palladium – IRA900, A22
- ◆ Platinum – IRA900
- ◆ Rhodium – None



- ◆ Ruthenium – IRA900

## 4.2 BASE METAL SOLUTION ADSORPTION

The base metal stock solution composition (see Table 3.4.1) can be simplified as in Table 4.2.1. The concentration is noted as ppm of the un-complexed element.

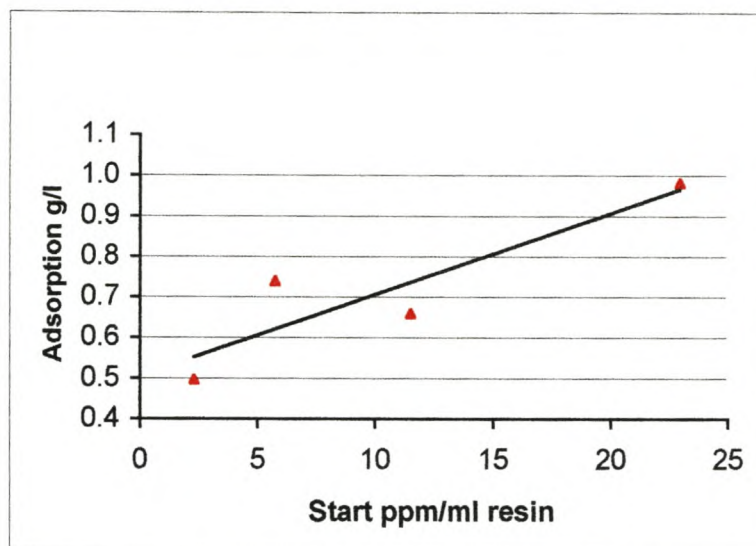
**Table 4.2.1: Base-metal solution composition**

COMP.	Pt	Pd	Au	Rh	Ru	Ir	Ag	Ni	Cu	Fe	Pb	As	Se	Te	Total	Non PGM
PPM	845	423	28	99	127	42	70	28	56	56	85	14	42	85	2000	437

Analysis, by ICP, for the base metal components was performed individually for each component. The concentration of some individual components in the diluted test solutions are very low and analytical errors can occur. Therefore, the base metal concentrations are summed up and treated as a combined base metal content. The base metals which will be present as cations in the chloride solutions should in any case not be adsorbed by the anion-exchange resins. It is important to note that the base metals solution (termed as “BM”), with an industrial composition, also contain the PGM’s and the adsorption of PGM from this mixed solution can be compared to that obtained from the single metal adsorption tests (paragraph 4.1). The adsorption of the precious metals from the base metal solution will not be shown here, but in paragraph 4.3 where the effect of additional PGM’s in the solution will be addressed.

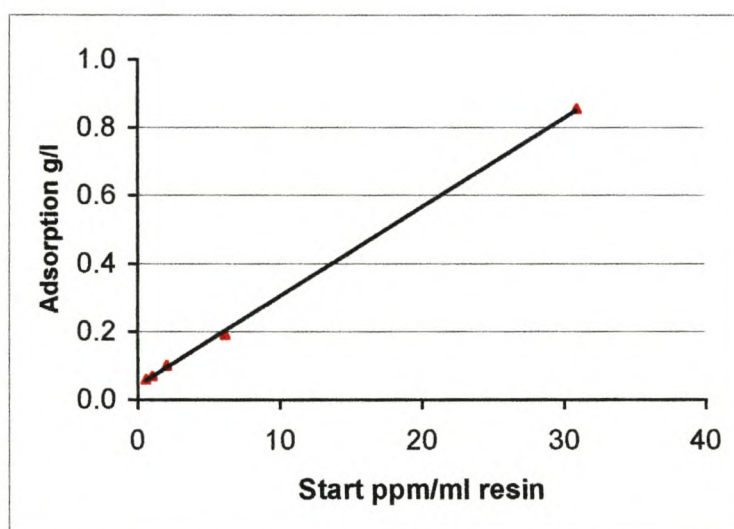
The adsorption of base metals by IRA900 can be seen in Figure 4.2.1. The adsorption was determined from a 70 ppm total base metals solution. The solution potential was 840 mV. As can be seen from the figure, that base metals are removed in minor quantities probably only due to diffusion into the resin beads. In the industrial solution the base metals are removed prior to the IRA900 resin column.





**Figure 4.2.1: Base Metals adsorption on IRA900**

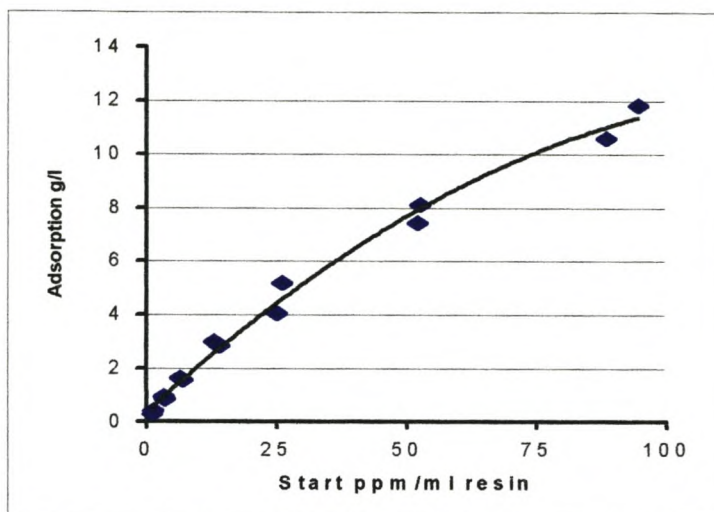
The adsorption of base metals by XAD7 (Figure 4.2.2) was determined for a 25 ppm solution with a solution potential of 900 mV.



**Figure 4.2.2: Base Metals adsorption on XAD7**

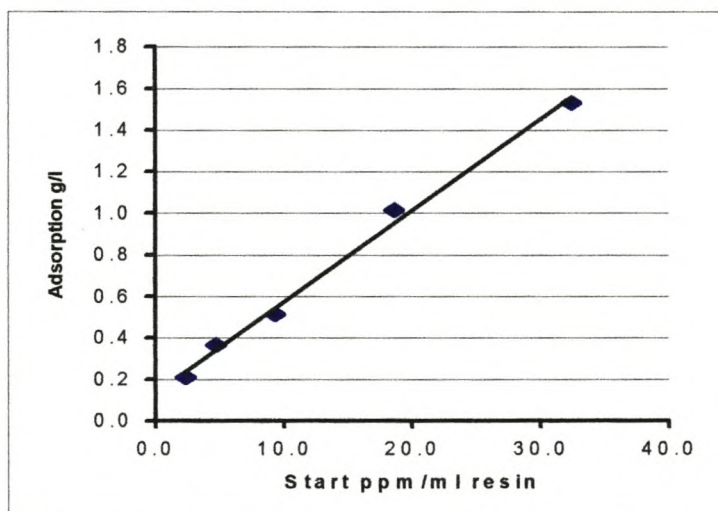
It is evident from the figure that minor quantities of base metals are removed from the solution by equilibrium diffusion.

The adsorption of base metals by IR200 was determined for 50 ppm, and for 100 ppm base metal solutions. The solution potential was 750 mV for both solutions. The adsorption characteristic can be seen in Figure 4.2.3.



**Figure 4.2.3: Base Metals adsorption on IR200**

The adsorption of base metals by A22 can be seen in Figure 4.2.4. The concentration of base metals in the test solution was 100 ppm at a solution potential of 700 mV.



**Figure 4.2.4: Base Metals adsorption on A22**

From the small uptake observed, it is evident that base metals are only removed from the solution by diffusion into the resin beads.

From the results, it is clear that the base metals are only adsorbed by IR200 resin.



### 4.3 THE EFFECT OF ADDITIONAL PGM'S IN THE TEST SOLUTION

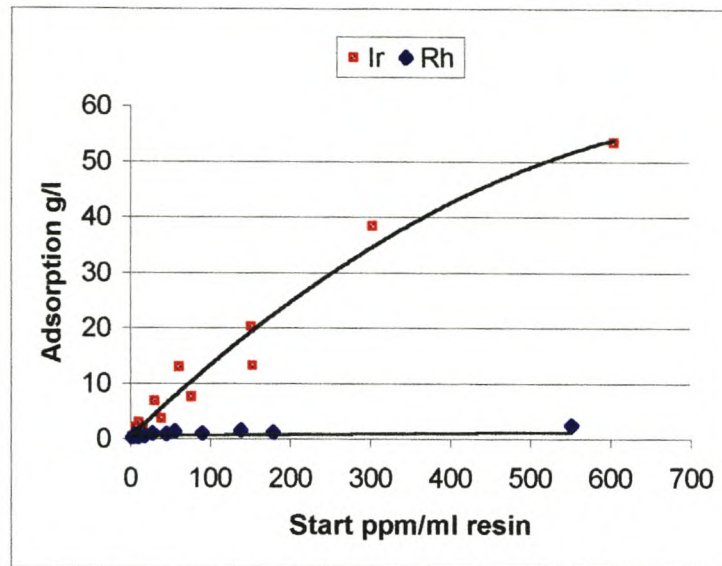
Test solutions were prepared by adding additional components to the solution. An adsorption test was done with all the PGM's in the solution to identify the most preferred PGM. For each resin an adsorption test was thereafter conducted with all the components present, but without the most preferred component. This was done with the specific purpose to identify the next strongest binder to the actual preferred PGM. A further adsorption test was then conducted with the preferred component and the next strongest binder identified to verify the selectivity. The acid concentrations used can be seen in Table 4.1. All component concentrations listed are in ppm, given as parts per million of the metal (not referring to the actual dissolved complex).

#### 4.3.1 Adsorption from mixed solutions using IRA900 resin

Single metal adsorption tests showed that rhodium is not adsorbed by any of the resins tested. Adsorption was determined from two mixed solutions containing iridium and rhodium to verify the selectivity of IRA900 for iridium over rhodium. The concentrations of the test solutions used can be seen in Table 4.3.1.1.

**Table 4.3.1.1: Ir + Rh solutions**

Test No:	Pot. (mV)	Ir	Rh
1	910	300	300
2	920	100	100



**Figure 4.3.1.1: Rh + Ir on IRA900**

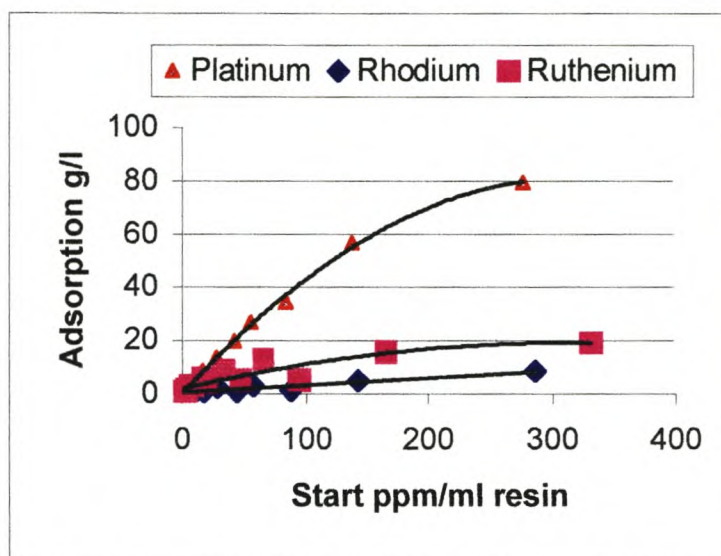
In comparison to the adsorption tests from single component iridium (Figure 4.1.2.1) and rhodium (Figure 4.1.5.1), it can be seen that the adsorption characteristics did not change much due to the combination of the two PGM's. Iridium is selectively adsorbed from the solution.

An adsorption test was conducted to establish the adsorption characteristics with platinum, ruthenium, and rhodium, but without iridium present (see Figure 4.3.1.2). Two test solutions with compositions as depicted in Table 4.3.1.2 were used for the adsorption test.

**Table 4.3.1.2: Rh + Pt +Ru solutions**

Test No:	Pot. (mV)	Pt	Rh	Ru
1	816	300	300	300
2	810	100	100	100





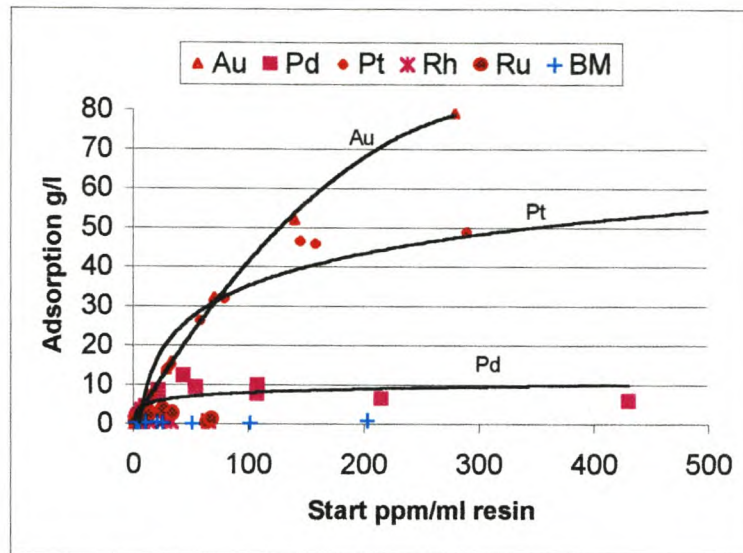
**Figure 4.3.1.2: Rh + Pt + Ru on IRA900**

From Figures 4.1.4.1, 4.1.6.1, and 4.1.5.1, respectively, it can be seen that the platinum, ruthenium, and rhodium adsorption is the same as for the single component adsorption tests.

The adsorption from a mixed solution containing all the PGM's and base metals, but excluding the target component, iridium, was determined. The test solution concentrations used for the adsorption test can be seen in Table 4.3.1.3. The addition of base metal solution to the test solution also introduced additional PGM into the solution.

**Table 4.3.1.3: Rh + Pt +Ru + Au +Pd + BM solutions**

Test No:	Pot. (mV)	Au	Pd	Pt	Rh	Ru	BM	Total
1	830	140	210	290	130	130	100	1000
2	785	65	110	160	65	70	50	520



**Figure 4.3.1.3: Rh + Pt + Ru + Au + Pd + BM on IRA900**

From Figure 4.3.1.3 it is evident by comparison to the single component adsorption characteristics (paragraph 4.1) that the amount of adsorption of gold, palladium, and platinum are much reduced. This should be attributed to the fact that the adsorption sites have to be shared. The uptake of ruthenium is greatly reduced, almost to the extent that no uptake of ruthenium occurs. Rhodium is not adsorbed. It can also be seen that the base metals are not adsorbed by the resin.

#### 4.3.2 Adsorption from mixed solutions by XAD7 resin

The adsorption was tested from two mixed solutions containing all of the PGM's and base metals, but without gold (see Table 4.3.2.1).

**Table 4.3.2.1: Ir + Pd + Pt + Rh + Ru + BM solutions**

Test No:	Pot. (mV)	Ir	Pd	Pt	Rh	Ru	BM	Total
1	865	100	200	270	100	100	100	870
2	895	40	90	160	50	60	50	450



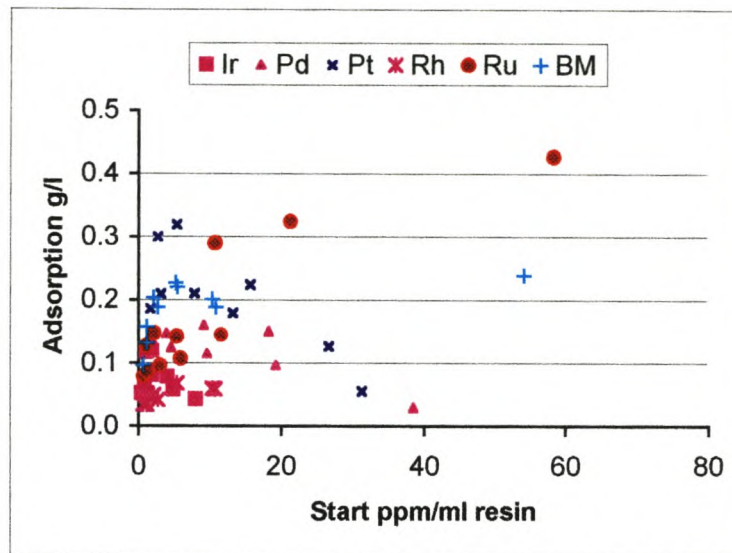


Figure 4.3.2.1: Ir + Pd + Pt + Rh + Ru + BM on XAD7

From Figure 4.3.2.1 it can be seen that in comparison to the single metal adsorption characteristics the uptake of iridium, palladium, ruthenium, and base metals is even lower than that obtained from the single component solutions. The uptake of platinum and rhodium is, as previously, negligibly small. It is noticed from the figure that only ruthenium is admitted into the resin, although the amount is very small. The adsorption from a mixed solution of gold and ruthenium was then determined (see Table 4.3.2.2).

Table 4.3.2.2: Au + Ru solutions

Test No:	Pot. (mV)	Au	Ru	Total
1	910	90	120	210
2	950	50	45	95

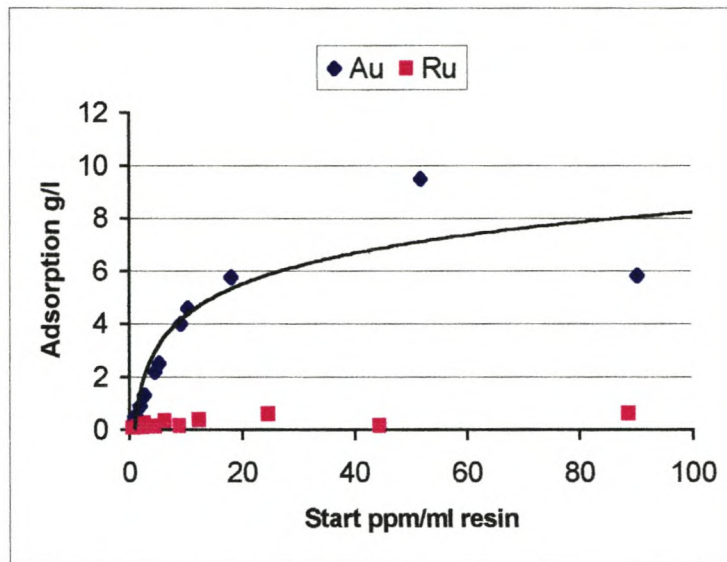


Figure 4.3.2.2: Au + Ru on XAD7

From Figure 4.3.2.2 it is evident that ruthenium is not adsorbed by the resin and it can be concluded that no component other than gold is adsorbed by XAD7.

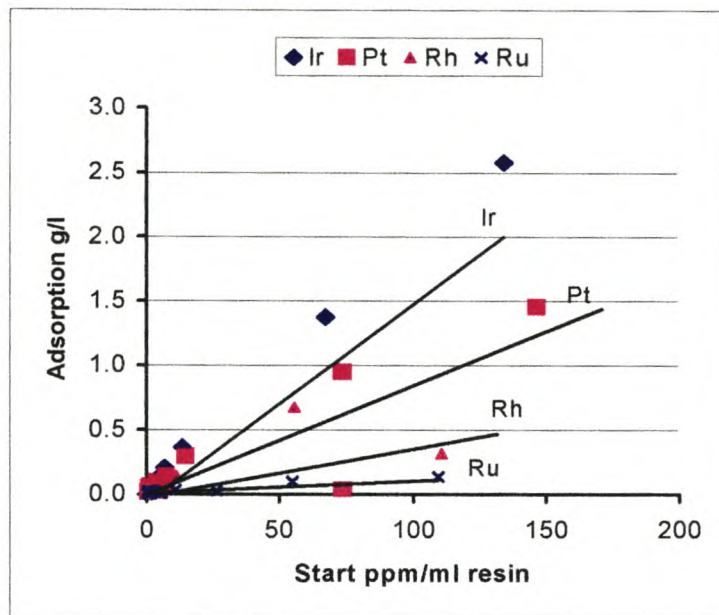
### 4.3.3 Adsorption from mixed solutions by IR200 resin

The adsorption from a mixed solution containing the same components as in the industrial process solution, platinum, rhodium, ruthenium, and iridium, but without the base metals was determined. The solution concentrations can be seen in Table 4.3.3.1.

Table 4.3.3.1: Ir + Pt + Rh + Ru solutions

Test No:	Pot. (mV)	Ir	Pt	Rh	Ru	Total
1	770	70	70	55	55	250
2	730	35	40	25	25	125





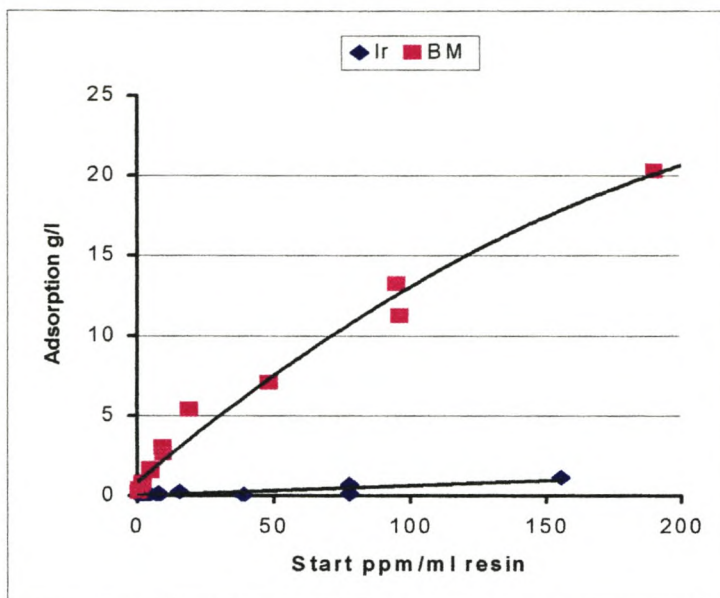
**Figure 4.3.3.1: Ir + Pt + Rh + Ru on IR200**

From the figure it can be seen that the data points at the higher values on the horizontal axis were offset from the curve fitted by the large number of data points towards the lower end of the axis. From Figure 4.3.3.1 it is evident that the uptake of iridium, platinum, and rhodium are similar to the single component characteristics obtained in paragraph 4.1. The uptake of ruthenium is less than that of ruthenium in single metal solutions. The small amounts of PGM removed from the solution indicate that there is no adsorption of PGM by the resin.

From the test the biggest uptake by the resin was iridium. An adsorption test for a mixed solution of iridium and base metals was done (Figure 4.3.3.2). The solutions used for the test are as depicted in Table 4.3.3.2.

**Table 4.3.3.2: Ir + BM solutions**

Test No:	Pot. (mV)	Ir	BM	Total
1	760	80	95	175
2	780	40	50	90



**Figure 4.3.3.2: Ir + BM on IR200**

From the figure it is evident that the adsorption of base metals are similar to that from the previous base metal adsorption test (Figure 4.2.3). Iridium is not adsorbed by the resin.

Adsorption from a solution containing all the PGM's, excluding the base metals, was determined (see Figure 4.3.3.3). The solution concentrations for the test are depicted in Table 4.3.3.3.

**Table 4.3.3.3: Au + Ir + Pd + Pt + Rh + Ru solutions**

Test No:	Pot. (mV)	Au	Ir	Pd	Pt	Rh	Ru	Total
1	800	60	40	40	50	40	40	270
2	770	30	20	20	25	20	20	135



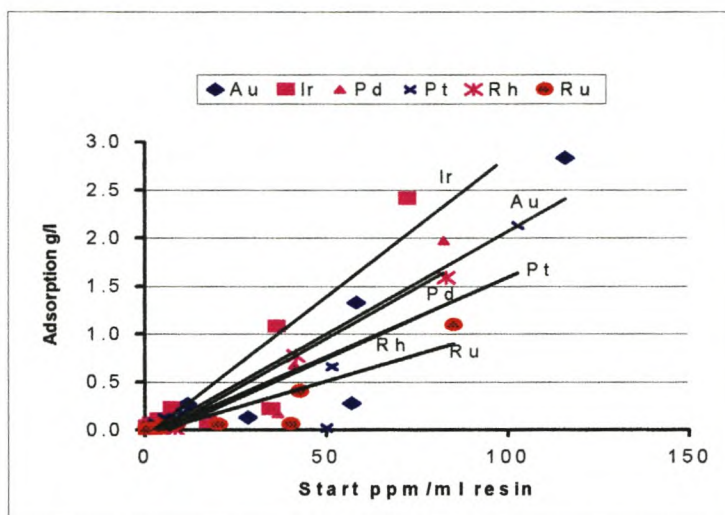


Figure 4.3.3.3: Au + Ir + Pd + Pt + Rh + Ru on IR200

It can be seen from the figure that in the absence of the base metals in the solution some uptake of PGM does occur, but in minor quantities. The uptake is most probably due to chemical diffusion into the resin beads.

#### 4.3.4 Adsorption from mixed solutions by A22 resin

A22 resin is used to selectively adsorb palladium. The equilibrium adsorption from a solution containing platinum, rhodium, ruthenium, iridium, and base metals, but without palladium was determined. The solution composition can be seen in Table 4.3.4.1.

Table 4.3.4.1: Ir + Pt + Rh + Ru + BM solutions

Test No:	Pot. (mV)	Ir	Pt	Rh	Ru	BM	Total
1	810	60	40	40	50	40	270
2	820	30	20	20	25	20	135

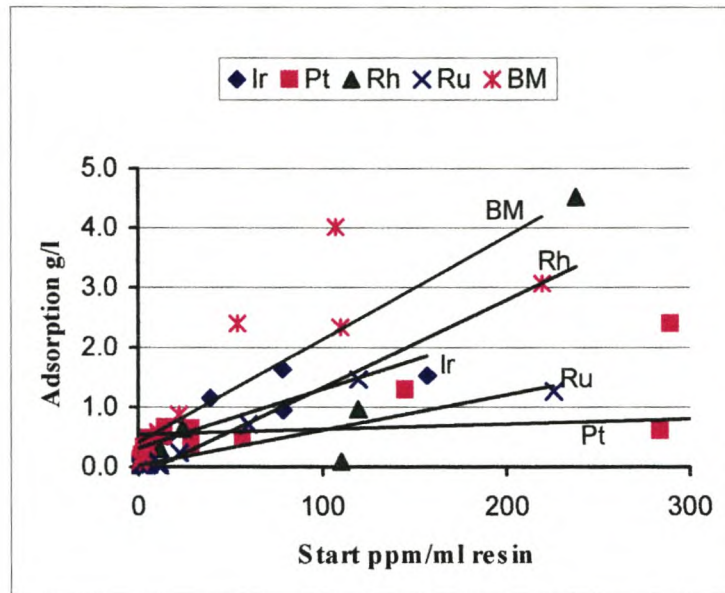


Figure 4.3.4.1: Ir + Pt + Rh + Ru + BM on A22

By comparison to the single component adsorption characteristics (Figure 4.3.4.1), the uptake of iridium, platinum, ruthenium, and base metals are similar. The uptake of rhodium is decreased. The uptake determined is very small with scattered data points indicating the absence of ion-exchange. The figure indicates that the biggest uptake is from the base metal solution. The adsorption of palladium from a mixed solution with base metals, which include all the PGM's, can be seen in Figure 4.3.4.2. The figure is a plot of adsorption by A22 of palladium from a test solution of base metals to which additional palladium was added (see Table 4.3.4.2).

Table 4.3.4.2: Pd + BM solutions

Test No:	Pot. (mV)	Pd	BM	Total
1	635	200	100	300
2	645	100	50	150



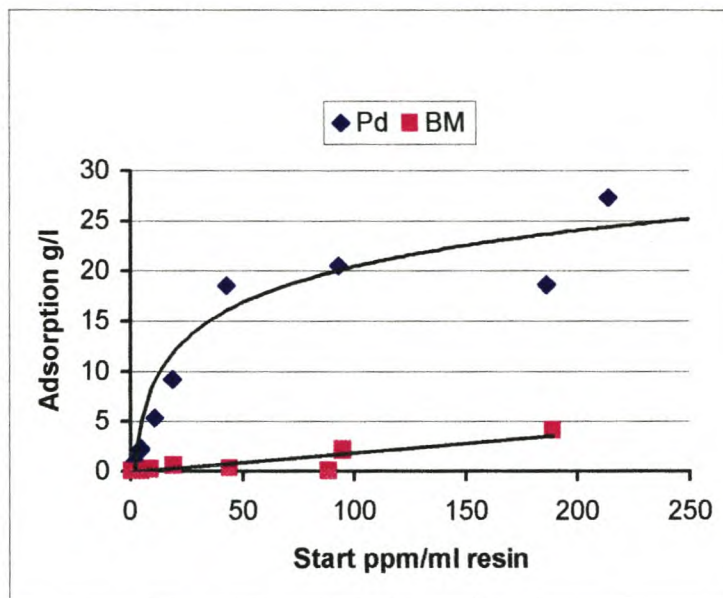


Figure 4.3.4.2: Pd + BM on A22

The adsorption of all PGM's and base metals by A22 was determined (see Figure 4.3.4.3). The individual PGM's were added to the solution in addition to the amount of PGM contained in the base metals solution (see Table 4.3.4.3).

Table 4.3.4.3: Au + Ir + Pt + Rh + Ru + BM solutions

Test No:	Pot. (mV)	Au	Ir	Pt	Rh	Ru	BM	Total
1	698	120	90	270	115	110	100	805
2	686	80	50	140	55	55	50	430

Palladium adsorption is also shown in the figure. This is the palladium contained in the base metal solution. No PGM's or base metals, other than gold and palladium, were adsorbed.

The adsorption characteristics of all the resins tested are similar to that obtained for the single metal solutions. In the case where more than one component is adsorbed by the resin, the adsorption sites are shared. It can be concluded that the additional components in the mixed solutions do not effect the adsorption characteristics drastically.

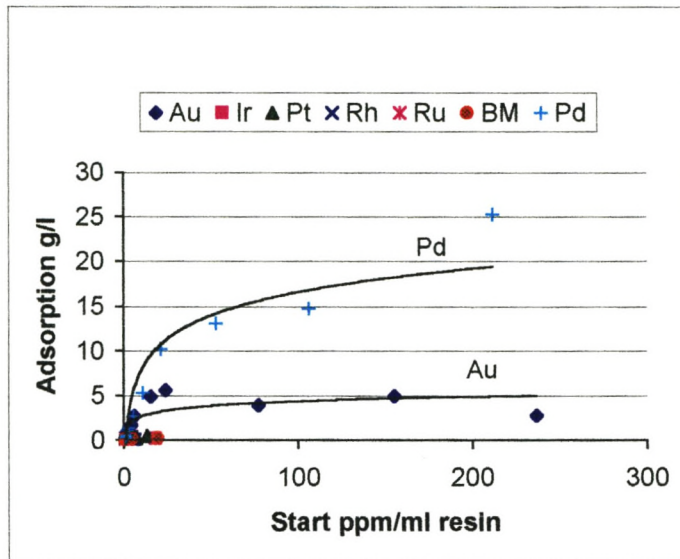


Figure 4.3.4.3: Au + Ir + Pt + Rh + Ru + BM on A22



#### 4.4. THE EFFECT OF DIFFERENT $CL^-$ CONCENTRATION ON ADSORPTION

The concentration of chloride ions and protons in the solution change the charge density of the solution. For an anionic resin the chloride ions are in competition with the other anions in the system to be adsorbed on the available adsorption sites in the resin. The same holds true for a cation resin where the protons are adsorbed by the resin. The optimal free acid concentration is determined by many factors in the system, e.g. the loading capacity of the resin, the selectivity of the functional group, and the chemical composition of the solution.

The effect of HCl concentration on the equilibrium adsorption was determined for all of the previous adsorption solutions (paragraphs 4.1 to 4.3). The adsorption was determined for three different HCl concentrations. A concentration lower than the specified, the specified concentration, and a higher concentration were used for the tests. For each of the three chloride strengths, usually two test solution strengths have been tested. For each test solution two data points were determined, the equilibrium adsorption was determined on 2ml and on 10 ml resin. The adsorption results with different acid concentrations were grouped together for each resin. The adsorption from single metal solutions is shown first, followed by the adsorption from mixed solutions at the different HCl concentrations.

##### 4.4.1 Effect of HCl concentration on adsorption by IRA900 resin

The adsorption by IRA900 resin was tested at 6, 8, and 10% HCl, respectively. The chloride concentration had no visible effect on the amount of gold adsorbed (see Figure 4.4.1.1). The gold solution concentrations used for the tests are listed in Table 4.4.1.1.

**Table 4.4.1.1: Gold test solutions**

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
6	225	740	290	740
8	285	760	190	930
10	275	880	190	905

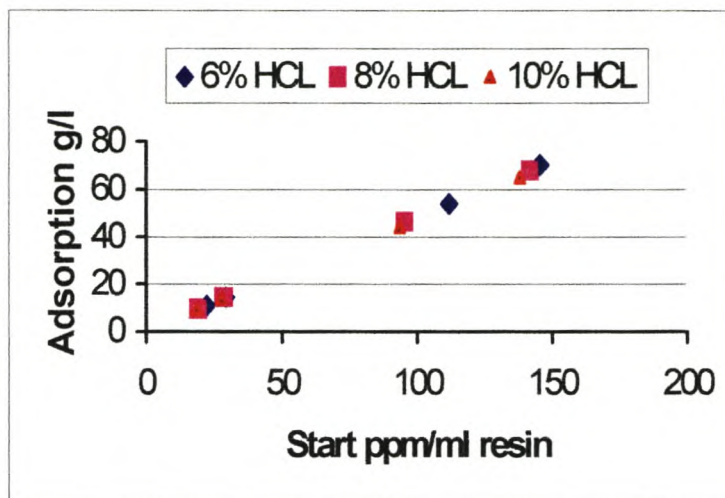


Figure 4.4.1.1: Gold adsorption on IRA900 with acidity

The chloride concentration has only a small effect on the adsorption of iridium (see Figure 4.4.1.2). No trend with regards to the amount adsorbed at different acid concentrations could be concluded from the data obtained. The iridium solution concentrations used can be seen in Table 4.4.1.2.

Table 4.4.1.2: Iridium test solutions

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
6	190	920	290	920
8	225	930	245	915
10	250	915	250	900

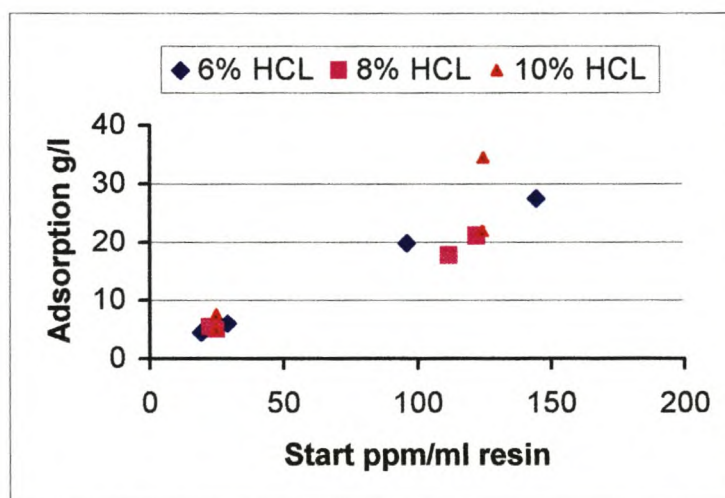


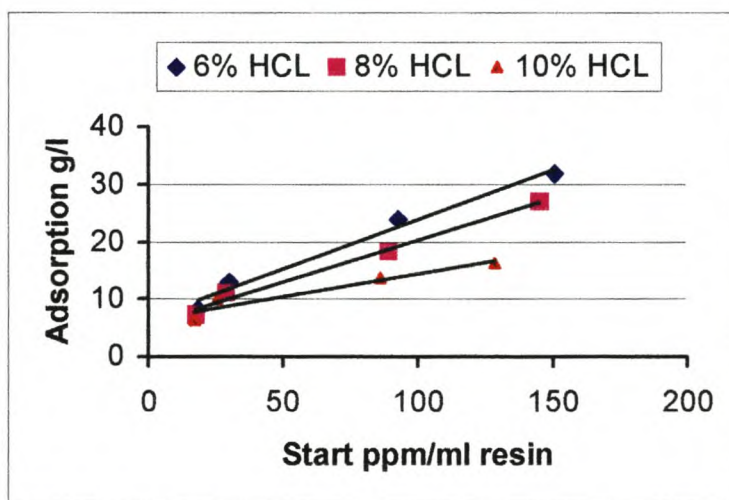
Figure 4.4.1.2: Iridium adsorption on IRA900 with acidity



The adsorption of palladium improved at lower chloride concentrations as depicted in Figure 4.4.1.3. This is to be expected as higher chloride concentrations shift the equilibrium towards higher chloride adsorptions. The palladium solution concentrations can be seen in Table 4.4.1.3.

**Table 4.4.1.3: Palladium test solutions**

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	Ppm	Pot. (mV)
6	185	920	301	920
8	178	930	290	915
10	257	915	172	900

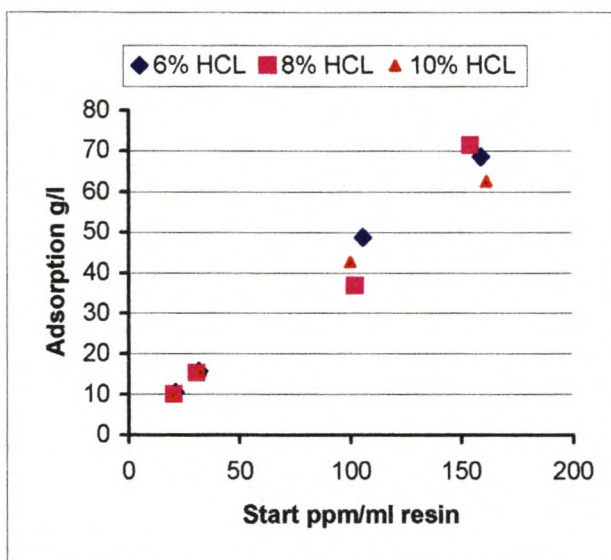


**Figure 4.4.1.3: Palladium adsorption on IRA900 with acidity**

The adsorption of platinum does not change much with acidity (see Figure 4.4.1.4). The platinum solution concentrations used can be seen in Table 4.4.1.4.

**Table 4.4.1.4: Platinum test solutions**

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	Ppm	Pot. (mV)
6	317	920	211	920
8	203	930	308	915
10	200	915	322	900



**Figure 4.4.1.4: Platinum adsorption on IRA900 with acidity**

Although the adsorption of rhodium is negligible, there is however a distinct drop in uptake at a higher chloride strength, at all concentrations (see Figure 4.4.1.5). The equilibrium diffusion of rhodium into the resin beads decreased at higher chloride concentrations as more chloride enters the resin. The rhodium solution concentrations used for the tests can be seen in Table 4.4.1.5.

**Table 4.4.1.5: Rhodium test solutions**

Acidity % HCl	Test 1		Test 2	
	Ppm	Pot. (mV)	Ppm	Pot. (mV)
6	206	920	295	920
8	195	930	286	915
10	181	915	307	900



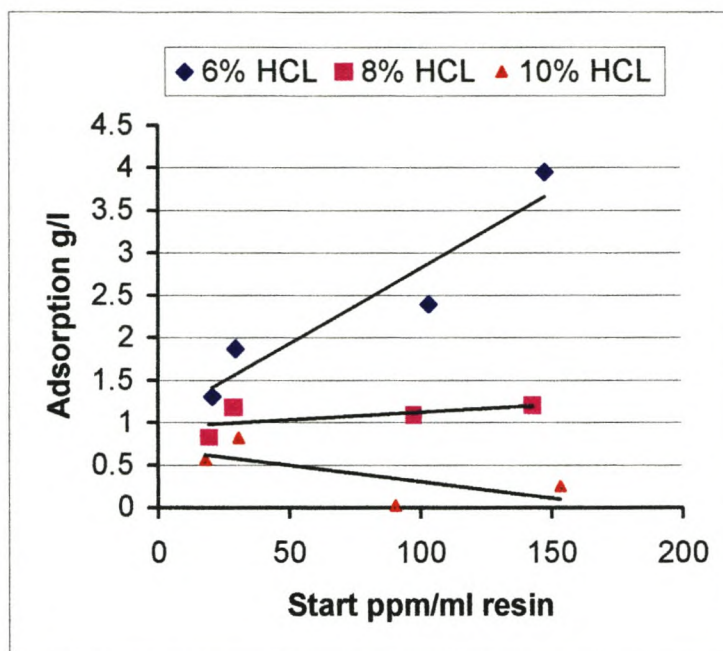


Figure 4.4.1.5: Rhodium adsorption on IRA900 with acidity

It is evident from Figure 4.4.1.6 that the ruthenium adsorption also decreased with higher chloride concentrations due to the competitive adsorption of chloride anions. The ruthenium solution concentrations used can be seen in Table 4.4.1.6.

Table 4.4.1.6: Ruthenium test solutions

Acidity	Test 1		Test 2	
	Ppm	Pot. (mV)	Ppm	Pot. (mV)
6	220	825	310	830
8	210	830	285	805
10	195	820	285	805

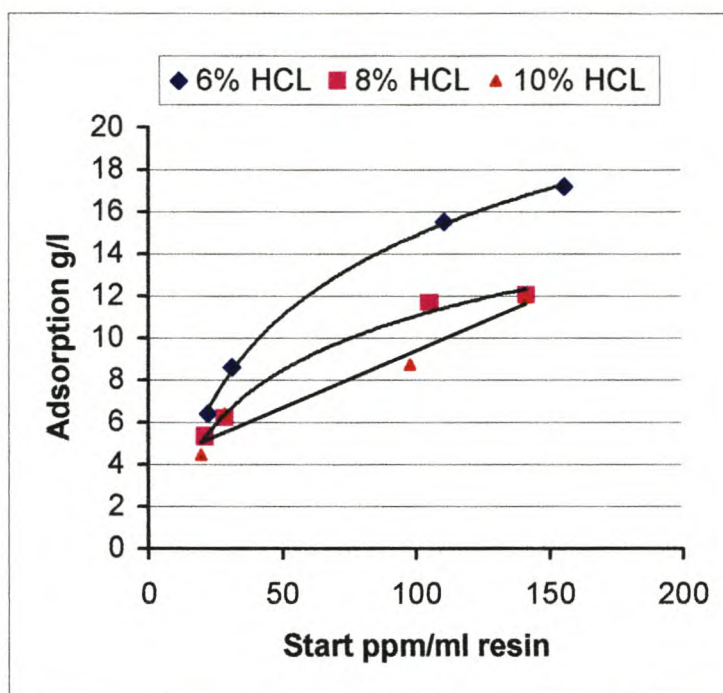


Figure 4.4.1.6: Ruthenium adsorption on IRA900 with acidity

Although the base metals are in solution primarily as cationic complexes in chloride media, some uptake does occur. It can be seen from Figure 4.4.1.7 that the data points are scattered with very little uptake by the resin. This indicates the absence of ion-exchange and reflects uptake of solution by obstructed diffusion to a more or lesser degree into the resin beads. Straight lines were fitted to the data, but due to the scattering of the data points no conclusive trends with regards to the quantity of uptake versus the solution acidity could be made. The base metals solutions tested for the effect of chloride strength are shown in Table 4.4.1.7.

Table 4.4.1.7: Base Metals test solutions

Acidity	Test 1		Test 2		Test 3	
	Ppm	Pot. (mV)	Ppm	Pot. (mV)	Ppm	Pot. (mV)
6	45	770	95	750	155	650
8	40	780	85	790	155	780
10	40	780	80	825	225	795



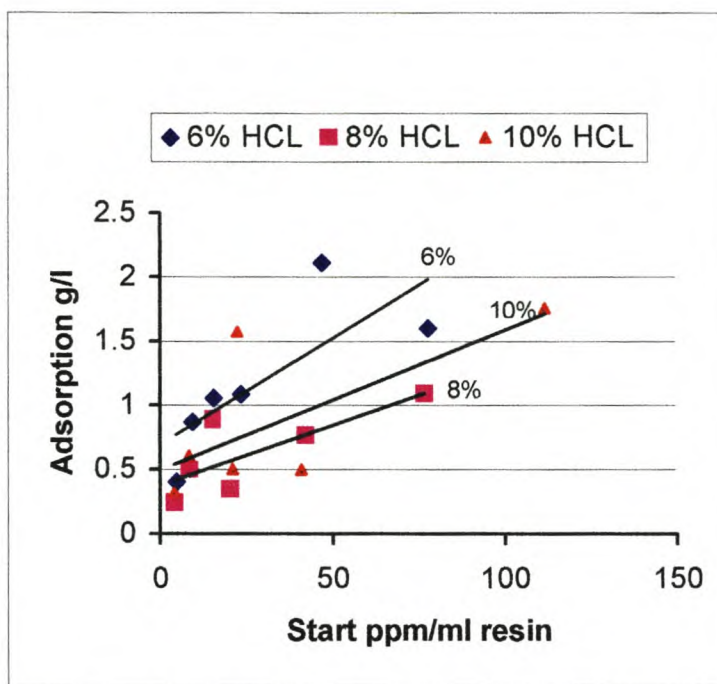


Figure 4.4.1.7: Base Metals adsorption on IRA900 with acidity

The adsorption from rhodium and iridium mixed solutions maintain the distinct preference for iridium at both 6 and 10% HCl (see Figures 4.4.1.8 and 4.4.1.9). It is to be expected that the adsorption of both rhodium and iridium decrease at higher chloride concentrations as the chlorides takes up more of the adsorption sites.

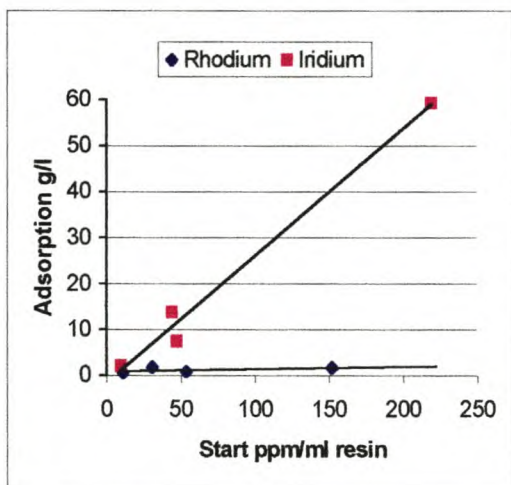


Figure 4.4.1.8: Rh + Ir on IRA900 at 6% HCl

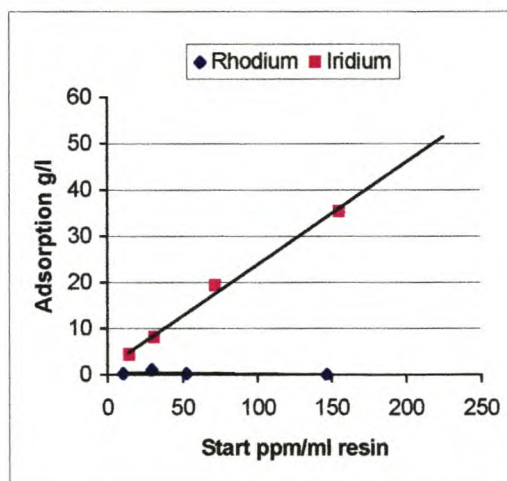


Figure 4.4.1.9: Rh + Ir on IRA900 at 10% HCl

The concentrations of the test solutions used can be seen in Table 4.4.1.8. Two solution concentrations were used for both acid concentrations, the adsorption for each test solution was determined by the uptake on 2 and on 10 ml resin.

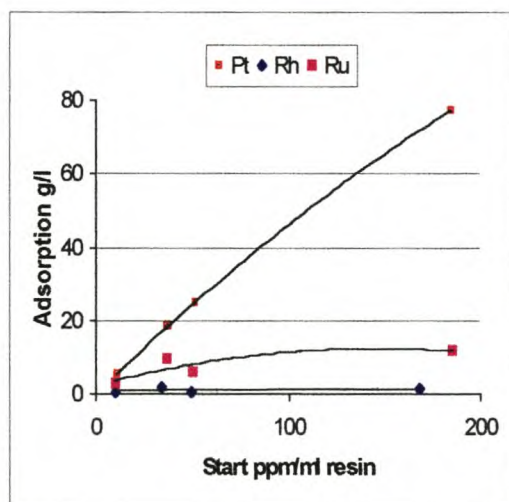
**Table 4.4.1.8: Ir + Rh solutions**

Test No:	Pot. (mV)	% HCl	Ir	Rh
1	795	6	95	110
2	835	6	440	305
3	870	10	145	105
4	840	10	310	295

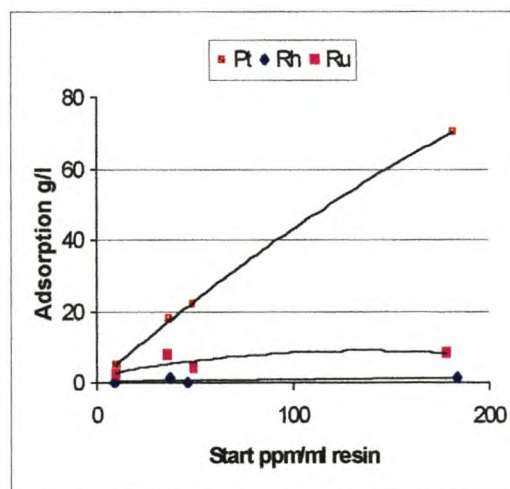
Chloride concentrations from 6 to 10% had no effect in the adsorption characteristic from the platinum, rhodium and ruthenium mixed solutions (see Figures 4.4.1.10 and 4.4.1.11). The solutions from which these adsorption test results were obtained are depicted in Table 4.4.1.9.

**Table 4.4.1.9: Pt + Rh + Ru solutions**

Test No:	Pot. (mV)	% HCl	Pt	Rh	Ru
1	800	6	100	100	100
2	805	6	370	335	370
3	785	10	100	90	100
4	840	10	360	365	355



**Figure 4.4.1.10: Pt + Rh + Ru on IRA900 at 6% HCl**



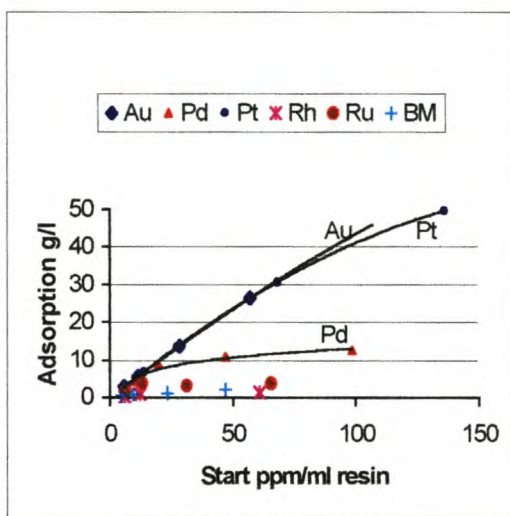
**Figure 4.4.1.11: Pt + Rh + Ru on IRA900 at 10% HCl**

Adsorption from the multi-component mixed solution which include all the PGM's, except iridium and base metals, are depicted in Figures 4.4.1.12 and 4.4.1.13. The solution composition is similar to that used for the multi-component test at 8% acid (Figure 4.3.1.3). The composition of the solutions tested are shown in Table 4.4.1.10.

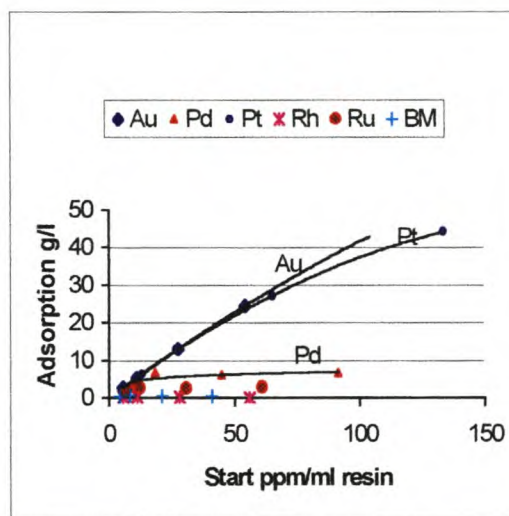


**Table 4.4.1.10: Pt + Rh + Ru + Pd + Au + BM solutions**

Test No:	Pot. (mV)	% HCl	Pt	Rh	Ru	Pd	Au	BM
1	770	6	135	55	60	95	55	45
2	750	6	270	120	130	195	115	95
3	780	10	130	55	60	90	55	40
4	825	10	265	110	120	180	110	80



**Figure 4.4.1.12: Pt + Rh + Ru + Pd + Au + BM on IRA900 at 6% HCl**



**Figure 4.4.1.13: Pt + Rh + Ru + Pd + Au + BM on IRA900 at 10% HCl**

It is evident from the figures that the effect of the chloride concentration is very small. The palladium adsorption, however, seems to be adversely effected at the higher chloride concentrations.

#### 4.4.2 Effect of HCl concentration on adsorption by XAD7 resin

The effect of HCl concentration on the adsorption by XAD7 was determined for 10.8, 13.7, and 17.2% (3, 4, and 5 Molar) free HCl in the solution. The adsorption characteristic for gold for which the resin is used with acidity variation can be seen in Figure 4.4.2.1. The test solutions used for the adsorption experiments are shown in Table 4.4.2.1.

**Table 4.4.2.1: Gold test solutions**

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
10.8	45	655	90	670
13.7	45	635	90	685
17.2	45	660	90	680

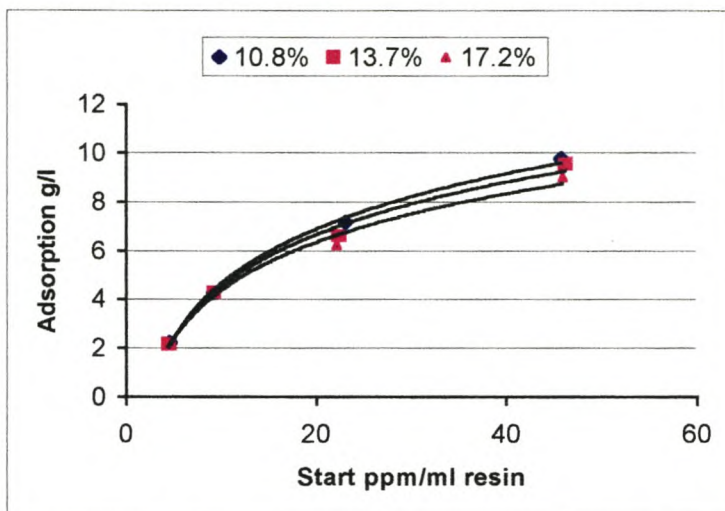


Figure 4.4.2.1: Gold adsorption with different acidity

The resin adsorbs gold effectively at all the chloride concentrations tested.

The adsorption of iridium was determined from the solutions in Table 4.4.2.2.

Table 4.4.2.2: Iridium test solutions

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
10.8	50	925	90	900
13.7	50	960	130	950
17.2	45	970	90	960

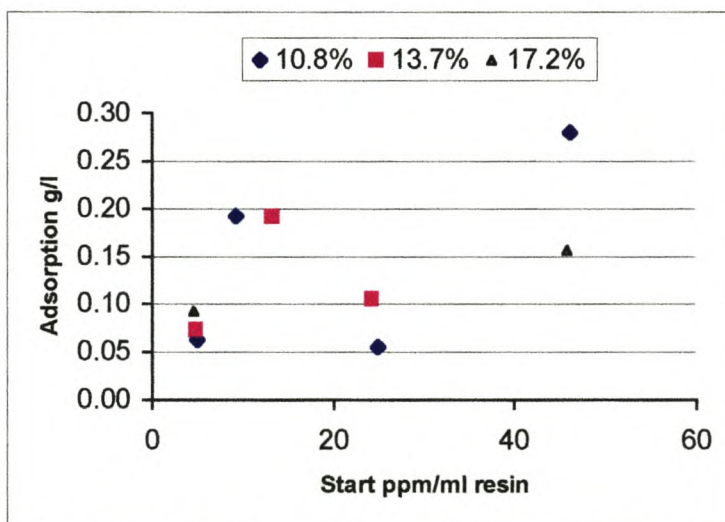


Figure 4.4.2.2: Iridium adsorption with different acidity

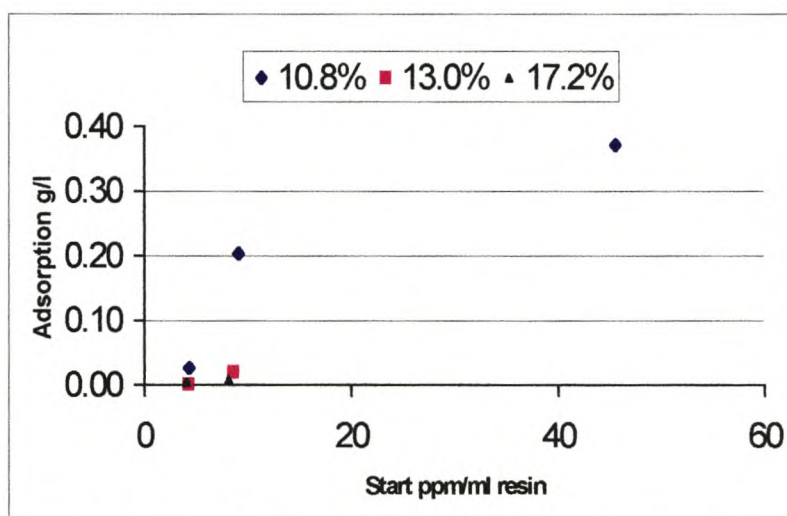


It is evident from Figure 4.4.2.2 that iridium is not adsorbed to any significant degree at any of the chloride concentrations tested.

The adsorption test results for palladium are shown in Figure 4.4.2.3. The solution concentrations used for the tests are listed in Table 4.4.2.3.

**Table 4.4.2.3: Palladium test solutions**

Acidity	Test 1		Test 2	
	Ppm	Pot. (mV)	ppm	Pot. (mV)
10.8	40	915	90	910
13.7	40	935	85	910
17.2	40	935	80	925



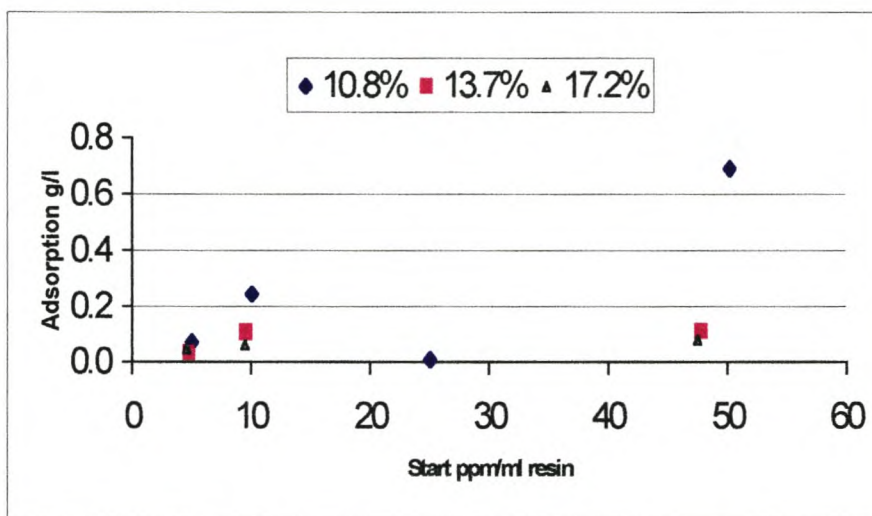
**Figure 4.4.2.3: Palladium adsorption with different acidity**

It is evident from the figure that the different chloride concentrations tested do not affect the selectivity of the resin towards palladium as no palladium was adsorbed.

Platinum was also not adsorbed at any of the chloride concentrations tested (see Figure 4.4.2.4). The solution concentrations used can be seen in Table 4.4.2.4.

**Table 4.4.2.4: Platinum test solutions**

Acidity	Test 1		Test 2	
% HCl	Ppm	Pot. (mV)	ppm	Pot. (mV)
10.8	50	875	100	835
13.7	45	845	95	810
17.2	45	920	95	915



**Figure 4.4.2.4: Platinum adsorption with different acidity**

The rhodium test results can be seen in Figure 4.4.2.5. Only data points for the 10.8% HCl solution can be seen as the adsorption loadings obtained for the 13.7% and 17.2% HCl were zero. It is evident that the resin retained its selectivity against adsorbing rhodium, when the acid concentration is changed. Table 4.4.2.5 depict the solutions used in the tests.

**Table 4.4.2.5: Rhodium test solutions**

Acidity	Test 1		Test 2	
% HCl	ppm	Pot. (mV)	ppm	Pot. (mV)
10.8	45	905	100	910
13.7	45	955	90	890
17.2	40	910	90	945



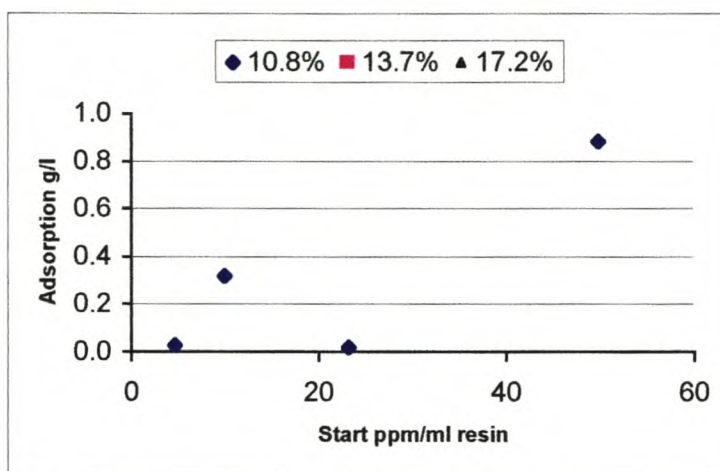


Figure 4.4.2.5: Rhodium adsorption with different acidity

No ruthenium is adsorbed by the resin at either of the chloride concentrations tested (Figure 4.4.2.6). The values of the data points for the 17.2% HCl test solutions were zero. The compositions of the test solutions used are shown in Table 4.4.2.6.

Table 4.4.2.6: Ruthenium test solutions

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
10.8	50	910	115	880
13.7	50	955	110	940
17.2	50	930	100	960

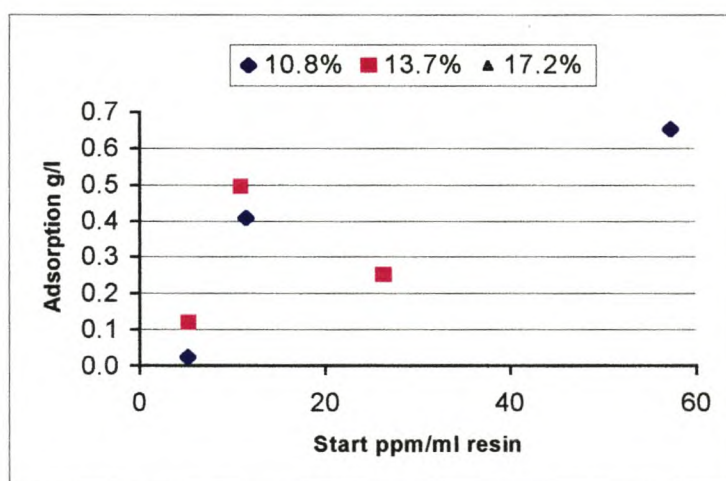


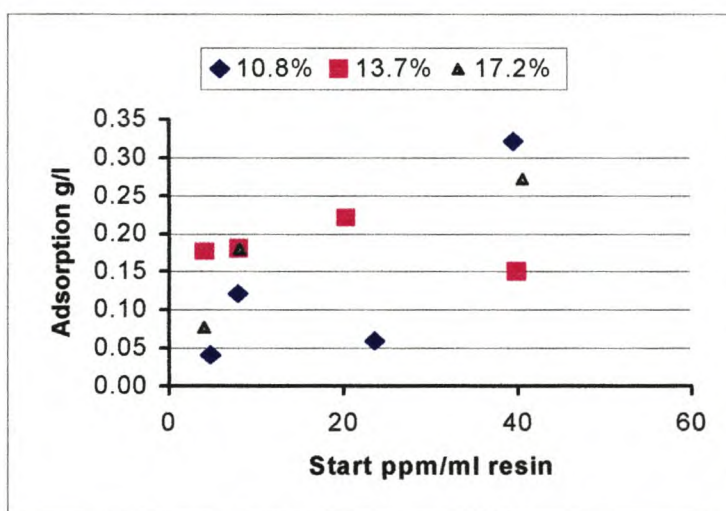
Figure 4.4.2.6: Ruthenium adsorption with different acidity

The solutions used to determine the effect of chloride concentration on the adsorption of base metals by XAD7 can be seen in Table 4.4.2.7. The scattered data points and

low uptake values obtained (Figure 4.4.2.7) show that the base metals are not adsorbed by the resin at any of the chloride concentrations tested.

**Table 4.4.2.7: Base Metals test solutions**

Acidity	Test 1		Test 2	
% HCl	Ppm	Pot. (mV)	Ppm	Pot. (mV)
6	45	910	80	910
8	40	910	80	895
10	40	930	80	910



**Figure 4.4.2.7: Base Metals adsorption with different acidity**

The effect of chloride strength on the adsorption from mixed solutions was determined from the mixed solutions depicted in Table 4.4.2.8. The solution composition is similar to the composition of the test solution used for the test done at 13.7% HCl (Table 4.3.2.1). Gold was not added to this mixed solution, but is present as one of the components in the base metal solution.

**Table 4.4.2.8: Ir + Pd + Pt + Rh + Ru + BM solutions**

Test No:	Pot. (mV)	% HCl	Ir	Pd	Pt	Rh	Ru	BM	Au
1	415	10.8	55	95	130	60	60	40	5
2	430	10.8	185	205	275	120	130	85	9
3	445	17.2	50	85	130	55	60	40	4
4	440	17.2	130	180	270	110	120	100	9



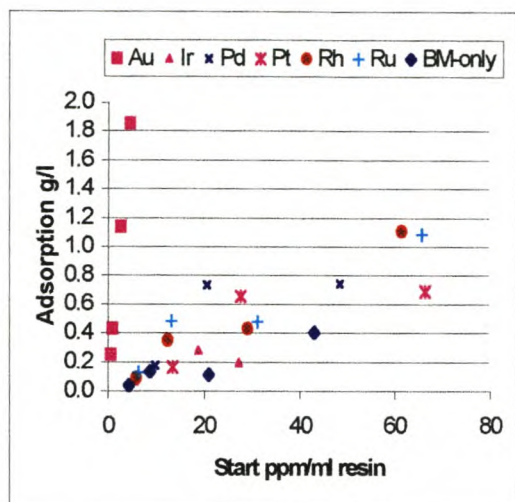


Figure 4.4.2.8: Ir + Pd + Pt + Rh + Ru + BM on XAD7 at 10.8% HCl

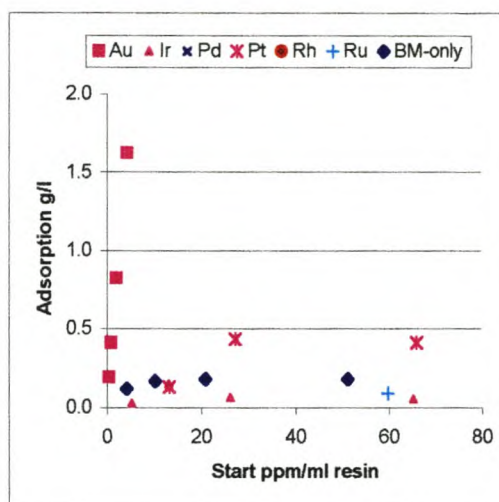


Figure 4.4.2.9: Ir + Pd + Pt + Rh + Ru + BM on XAD7 at 17.2% HCl

It can be seen from Figures 4.4.2.8 and 4.4.2.9 that although the gold concentration is less than 10 ppm, the resin has a distinct preference for gold. The uptake of all other ions is very small and decreases with higher acidity.

Ruthenium was selected as the next strongest bonded ion in paragraph 4.3.2. The adsorption of gold and ruthenium from mixed solutions with different acidities can be seen in Figures 4.4.2.10 and 4.4.2.11. The solution compositions are listed in Table 4.4.2.9.

Table 4.4.2.9: Au + Ru solutions

Test No:	Pot. (mV)	% HCl	Au	Ru
1	425	10.8	50	50
2	430	10.8	90	95
3	450	17.2	45	45
4	440	17.2	85	90

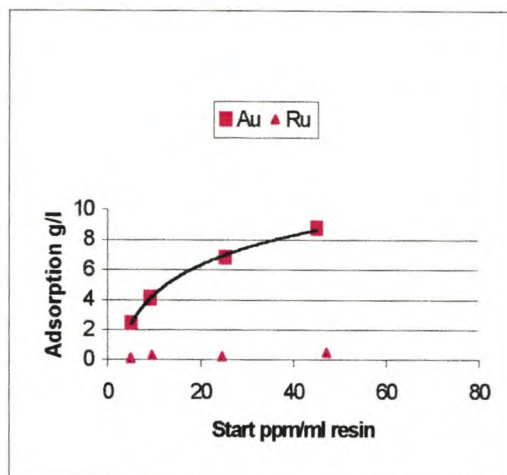


Figure 4.4.2.10: Au + Ru on XAD7 at 10.8% HCl

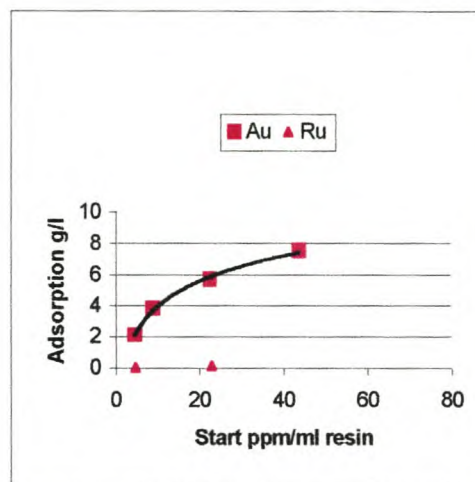


Figure 4.4.2.11: Au + Ru on XAD7 at 17.2% HCl

It is evident that there is no ruthenium uptake by the resin at the chloride concentrations tested. By comparing of the above figures, the equilibrium uptake of gold is reduced by higher chloride concentrations.

#### 4.4.3 Effect of HCl concentration on adsorption by IR200 resin

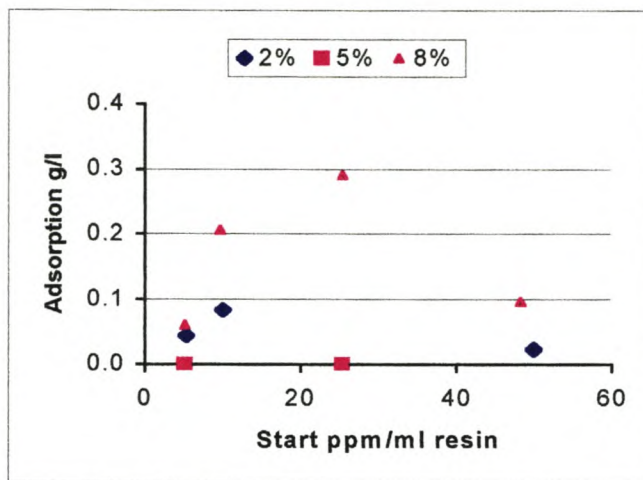
The effect of HCl concentration on the adsorption by IR200 was determined for 2, 5, and 8% free HCl in the solution. The chloride concentration of the solution could not be decreased to below 2% as some of the base metals started precipitating from the solution. The acidity was therefore varied by testing the adsorption at two higher concentrations.

The adsorption characteristic of gold with acidity can be seen in Figure 4.4.3.1. The test solutions used for the adsorption experiments are shown in Table 4.4.3.1.

Table 4.4.3.1: Gold test solutions

Acidity	Test 1		Test 2	
	% HCl	Ppm	Pot. (mV)	ppm
2	50	750	100	765
5	50	770	-----	-----
8	50	725	95	725





**Figure 4.4.3.1: Gold adsorption on IR200 with acidity**

It is evident from the figure that gold is not adsorbed by the resin, also not at higher chloride concentrations. This result is to be expected as gold is in solution as an anion, and IR200 is a cation resin.

It can be seen from Figure 4.4.3.2 that there is no adsorption of iridium at higher acid concentrations. The test solution concentrations are shown in Table 4.4.3.2. The uptake of iridium is reduced with higher acid concentrations as more protons fill up the resin beads, reducing the iridium ion concentration in the resin.

**Table 4.4.3.2: Iridium test solutions**

Acidity	Test 1		Test 2	
	Ppm	Pot. (mV)	ppm	Pot. (mV)
2	50	940	160	940
5	45	900	65	900
8	40	930	100	930

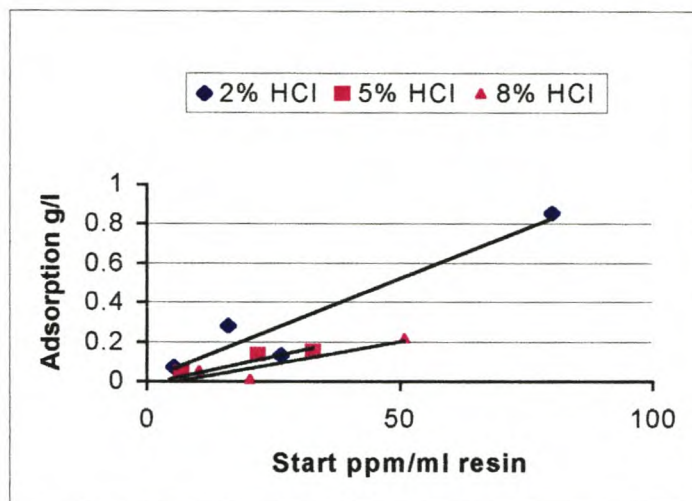


Figure 4.4.3.2: Iridium adsorption on IR200 with acidity

The adsorption of palladium at higher acid concentrations is depicted in Figure 4.4.3.3 from solutions listed in Table 4.4.3.3. There is no real adsorption of palladium, as expected, as IR200 is a cation resin. As for iridium, the palladium uptake by the resin is reduced at higher chloride concentrations. The reduction is very small and in this case a higher uptake was found from 8% HCl than from the 5% acid solutions.

Table 4.4.3.3: Palladium test solutions

Acidity	Test 1		Test 2	
	% HCl	ppm	Ppm	Pot. (mV)
2	50	470	105	530
5	45	455	95	450
8	45	440	90	450

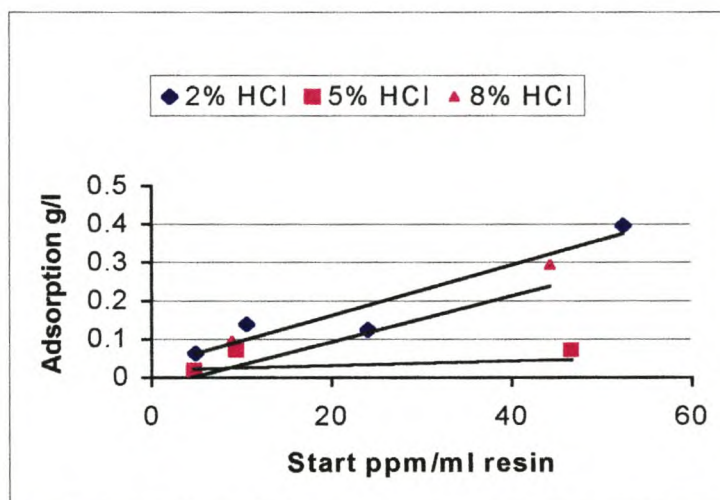


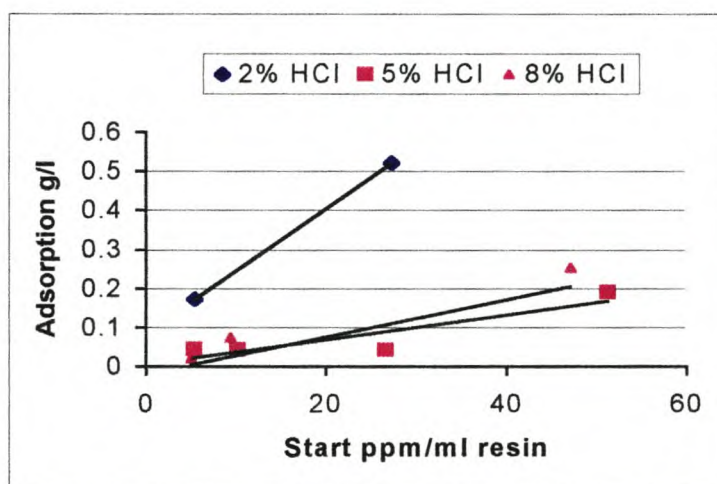
Figure 4.4.3.3: Palladium adsorption on IR200 with acidity



The adsorption test for platinum at higher acid concentrations was done from the solutions shown in Table 4.4.3.4. The adsorption test results is shown in Figure 4.4.3.4.

**Table 4.4.3.4: Platinum test solutions**

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	Ppm	Pot. (mV)
2	55	420	-----	-----
5	55	395	100	470
8	50	395	95	420



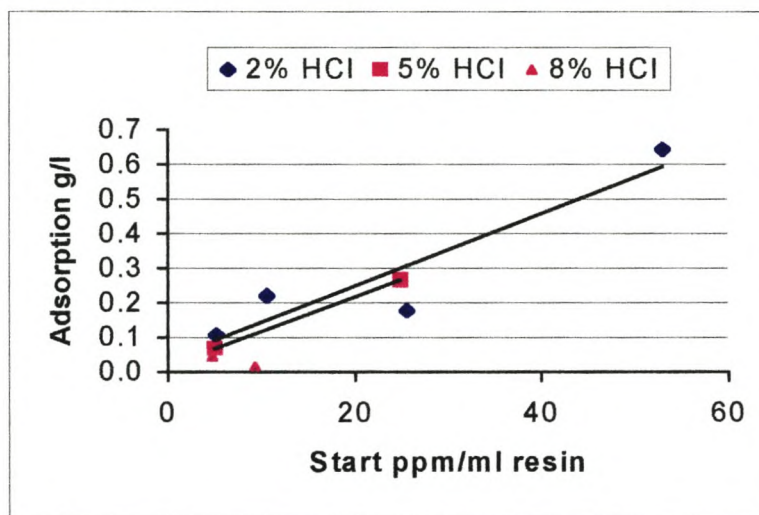
**Figure 4.4.3.4: Platinum adsorption on IR200 with acidity**

It is evident from the figure that platinum uptake is further decreased at higher acid concentrations and that there is no real adsorption of platinum by the resin.

Table 4.4.3.5 shows the test solutions for the rhodium adsorption with acidity test. It is evident from Figure 4.4.3.5 that rhodium is not adsorbed by the resin at either of the chloride concentrations tested. By comparison to the adsorption curve obtained at 2% HCl (Figure 4.1.5.3), it can be seen that the values on the horizontal axis are much higher as the acidity tests were conducted with only 2 and 10 ml resin. The test at 2% HCl in paragraph 4.1.5 was done for 12.5 ml and 40 ml resin. It is also evident from the figure that the uptake is reduced by higher HCl concentrations.

**Table 4.4.3.5: Rhodium test solutions**

Acidity % HCl	Test 1		Test 2	
	Ppm	Pot. (mV)	ppm	Pot. (mV)
2	50	390	105	460
5	50	410	-----	-----
8	45	410	90	450

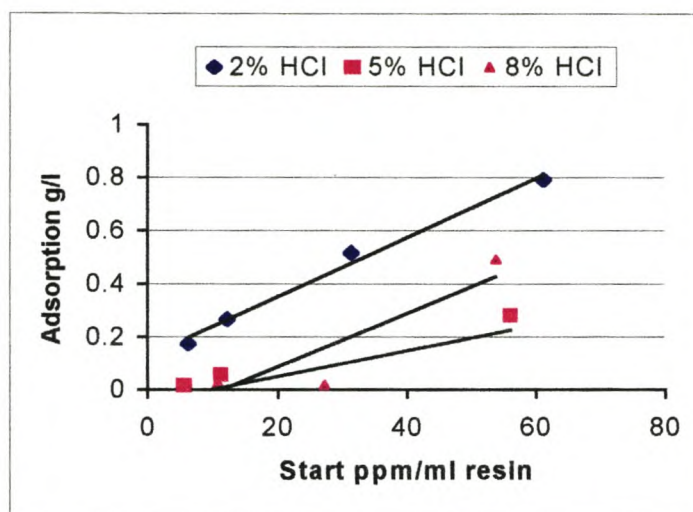
**Figure 4.4.3.5: Rhodium adsorption on IR200 with acidity**

The adsorption test for ruthenium with acidity can be seen in Figure 4.4.3.6. The test solutions used are listed in Table 4.4.3.6.

**Table 4.4.3.6: Ruthenium test solutions**

Acidity % HCl	Test 1		Test 2	
	Ppm	Pot. (mV)	ppm	Pot. (mV)
2	60	760	120	800
5	55	780	110	785
8	55	755	105	800





**Figure 4.4.3.6: Ruthenium adsorption on IR200 with acidity**

From the figure it is evident that ruthenium is not adsorbed by the resin, with a decrease in ruthenium uptake at higher chloride concentrations. Ruthenium is present in solution as an anion and is not adsorbed by the IR200 cation resin.

From Figure 4.4.3.7, and Table 4.4.3.7, it can be seen that the resin do not adsorb the base metals at higher acid concentrations. This is attributed to the equilibrium between the base metal cations and the proton concentration in the solution.

**Table 4.4.3.7: Base Metals test solutions**

Acidity	Test 1		Test 2	
	Ppm	Pot. (mV)	ppm	Pot. (mV)
2	85	775	-----	-----
5	50	755	80	795
8	40	745	80	775

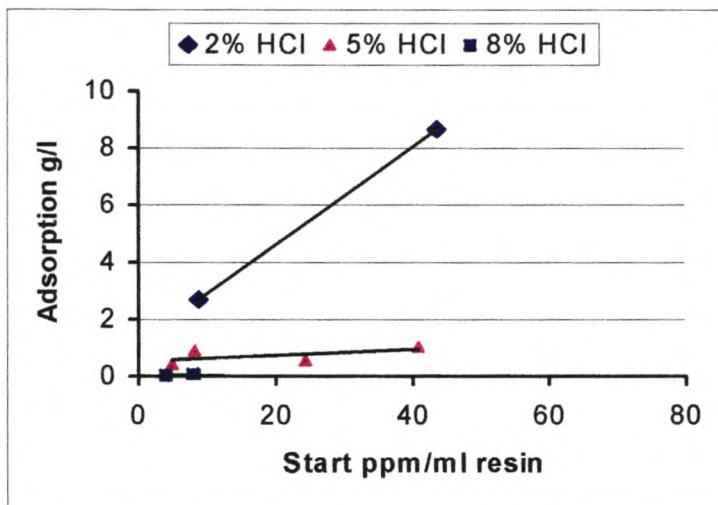


Figure 4.4.3.7: Base Metals adsorption on IR200 with acidity

The adsorption results from the mixed solutions in Table 4.4.3.8 can be seen in Figures 4.4.3.8 and 4.4.3.9, respectively.

Table 4.4.3.8: Ir + Pt + Rh + Ru solutions

Test No:	Pot. (mV)	% HCl	Ir	Pt	Rh	Ru
1	795	2	30	60	55	50
2	805	2	160	100	90	85
3	815	8	60	45	40	40
4	815	8	60	100	90	85

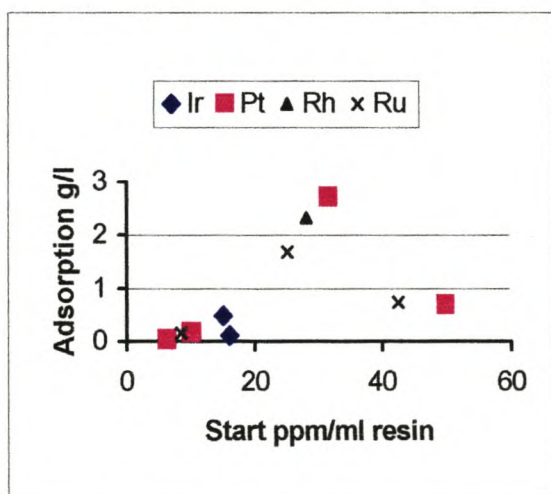


Figure 4.4.3.8: Ir + Pt + Rh + Ru on IR200 at 2% HCl

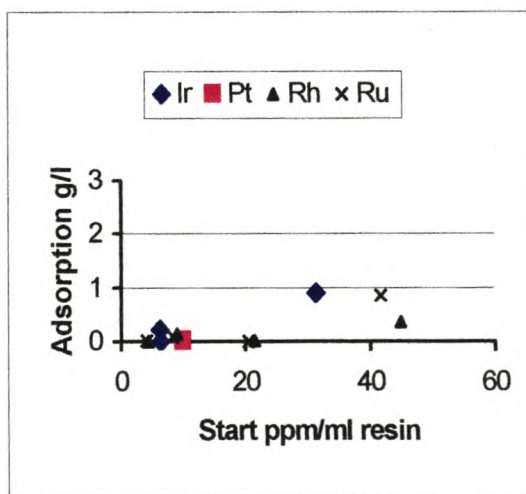


Figure 4.4.3.9: Ir + Pt + Rh + Ru on IR200 at 8% HCl

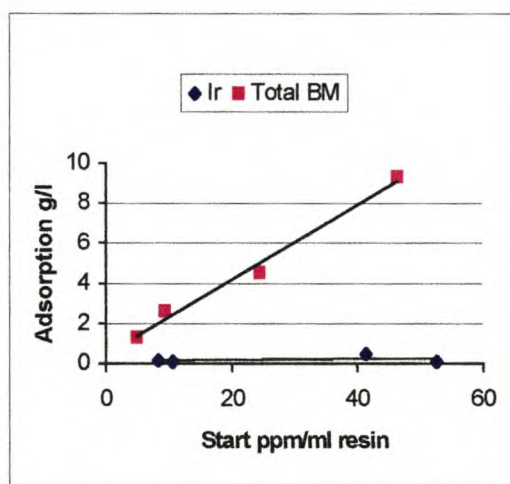


It is evident from the figures that the PGM's are not adsorbed by the resin and that a higher proton concentration reduces the uptake of ions by the resin.

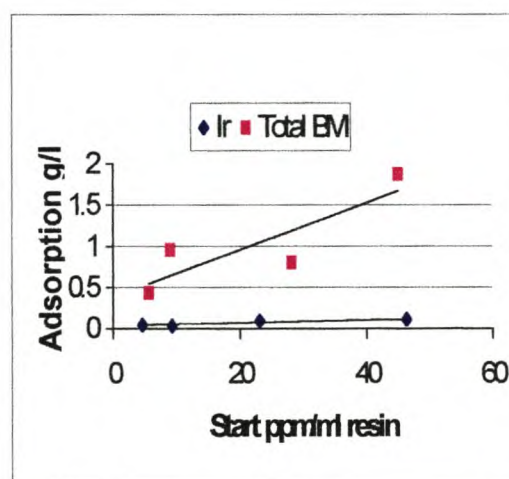
The adsorption from the iridium and base metals solutions can be seen in Figures 4.4.3.10 and 4.4.3.11. The adsorption is shown for 2% and 5% HCl solutions, respectively. The adsorption test was also done from 8% HCl solutions but no adsorption of either base metals or iridium was found. The test solution concentrations are listed in Table 4.4.3.9.

**Table 4.4.3.9: Ir + BM solutions**

Test No:	Pot. (mV)	% HCl	Ir	BM
1	355	2	80	50
2	375	2	105	90
3	385	5	45	55
4	365	5	90	90



**Figure 4.4.3.10: Ir + BM on IR200 at 2% HCl**



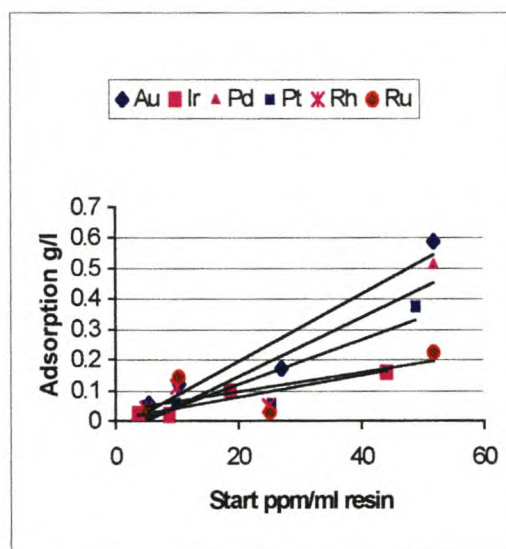
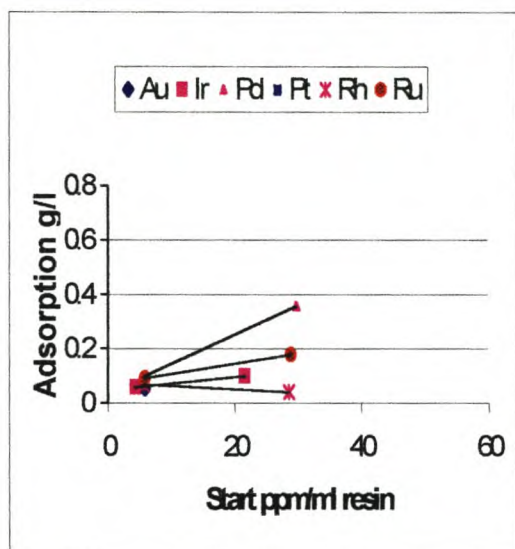
**Figure 4.4.3.11: Ir + BM on IR200 at 5% HCl**

The preference of the resin for the base metals is evident from the figures. The adsorption is decreased at higher chloride concentrations.

The change in adsorption from a mixed solution with all the PGM's was also determined for three acid concentrations. Figures 4.4.3.12 and 4.4.3.13 show the results of the uptake from the 2% and 5% HCl solutions. For the 8% HCl solutions small negligible loadings were measured due to negligible uptake of PGM's by the resin. The test solution concentrations are shown in Table 4.4.3.10.

**Table 4.4.3.10: Au + Ir + Pd + Pt + Rh + Ru solutions**

Test No:	Pot. (mV)	% HCl	Au	Ir	Pd	Pt	Rh	Ru
1	355	2	60	45	60	55	55	60
2	375	5	55	40	50	50	50	50
3	375	5	105	90	105	100	100	105



PGM's not shown in the above figures are due to negligible adsorption. Higher uptake values were obtained from the 5% solution as a more concentrated PGM solution was used. It is evident from the graphs that none of the PGM's are adsorbed by the resin.

#### 4.4.4 Effect of HCl concentration on adsorption by A22 resin

The effect of HCl concentration on adsorption by A22 was determined for 7.1, 10.4, and 13.7% free HCl in the solution (2, 3, and 4 M).

**Figure 4.4.3.12: Au + Ir + Pd + Pt + Rh + Ru on IR200 at 2% HCl**

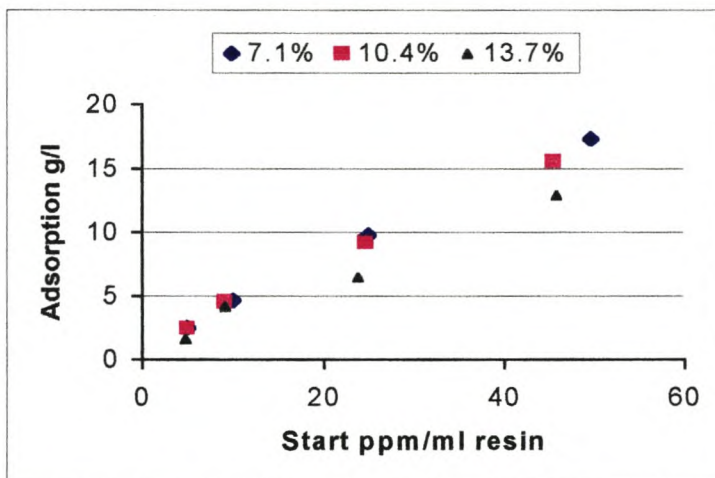
**Figure 4.4.3.13: Au + Ir + Pd + Pt + Rh + Ru on IR200 at 5% HCl**

The adsorption characteristic for gold with acidity can be seen in Figure 4.4.4.1. The test solutions used for the adsorption experiments are shown in Table 4.4.4.1.



**Table 4.4.4.1: Gold test solutions**

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
7.1	50	725	100	700
10.4	50	705	90	695
13.7	45	685	90	680



**Figure 4.4.4.1: Gold adsorption on A22 with acidity**

Gold is adsorbed by the resin at all the chloride concentrations tested, irrespective of the chloride concentration.

It can be seen from Figure 4.4.4.2 that iridium is not adsorbed by the resin at the acid concentrations tested. The test solution concentrations are listed in Table 4.4.4.2.

**Table 4.4.4.2: Iridium test solutions**

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
7.1	40	695	105	695
10.4	60	695	75	675
13.7	40	675	80	810

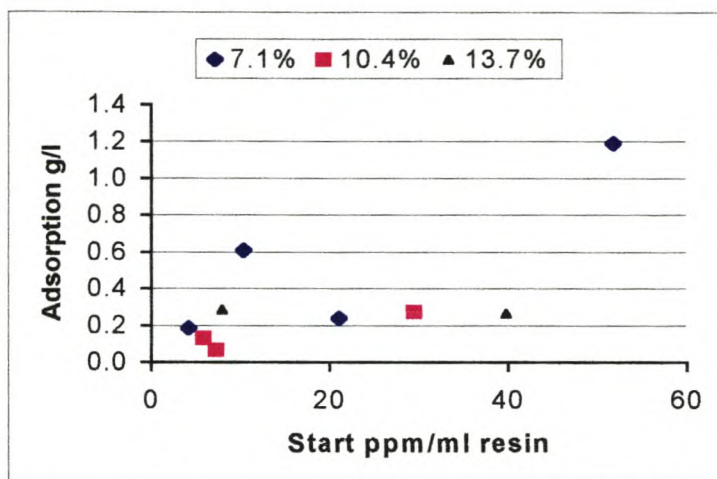


Figure 4.4.4.2: Iridium adsorption on A22 with acidity

The effect of acidity on the adsorption of palladium by A22 resin can be seen in Figure 4.4.4.3. The test solution concentrations are shown in Table 4.4.4.3.

Table 4.4.4.3: Palladium test solutions

Acidity	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
7.1	50	645	95	690
10.4	40	690	85	690
13.7	40	625	85	670

It is evident from the figure that the adsorption is not effected by the acid concentrations tested. The resin maintains its adsorptive capacity for palladium.

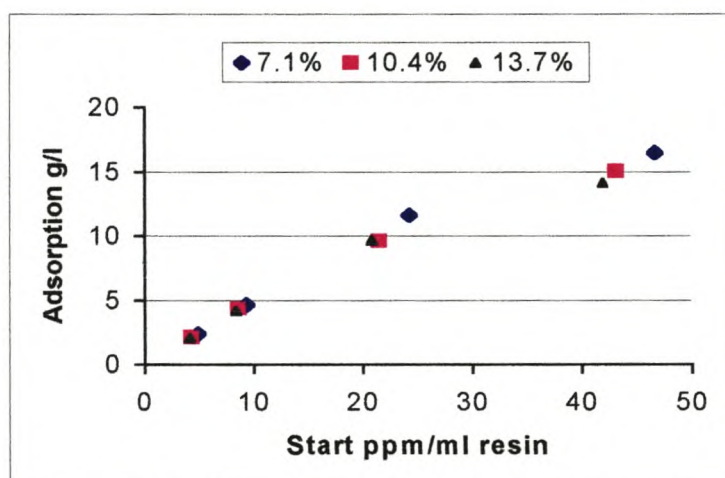


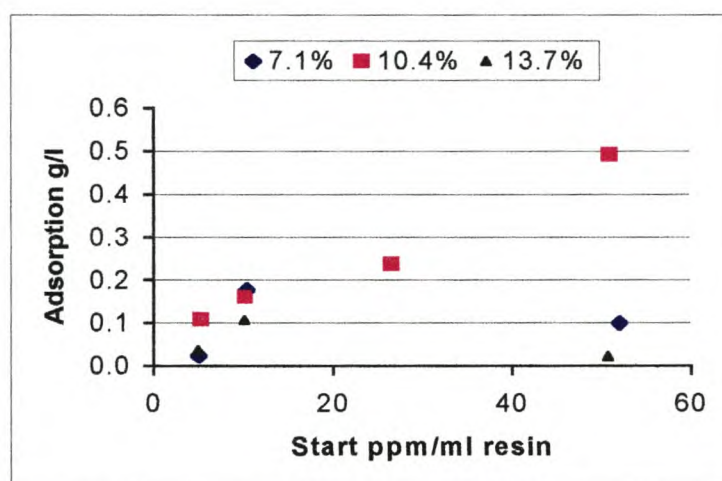
Figure 4.4.4.3: Palladium adsorption on A22 with acidity



The adsorption of platinum was determined from the solutions in Table 4.4.4.4. As can be seen in Figure 4.4.4.4, there is no adsorption of platinum from the solution at the acidities tested. The results tend to indicate an increase in uptake by the resin at 10.4% HCl, but the uptake is small and negligible.

**Table 4.4.4.4: Platinum test solutions**

Acidity % HCl	Test 1		Test 2	
	ppm	Pot. (mV)	ppm	Pot. (mV)
7.1	50	600	105	520
10.4	50	575	100	520
13.7	50	540	100	505



**Figure 4.4.4.4: Platinum adsorption on A22 with acidity**

The rhodium test solutions used can be seen in Table 4.4.4.5. Although there is no adsorption of rhodium (Figure 4.4.4.5), the rhodium uptake measured is higher than that obtained for the previous test at 10.4% HCl (see Figure 4.1.5.4). More resin was used to determine the two data points on the curve in Figure 4.1.5.4, resulting in a much lower start concentration per ml of resin for rhodium.

**Table 4.4.4.5: Rhodium test solutions**

Acidity % HCl	Test 1		Test 2	
	Ppm	Pot. (mV)	ppm	Pot. (mV)
7.1	45	445	100	470
10.4	45	560	90	420
13.7	45	465	90	415

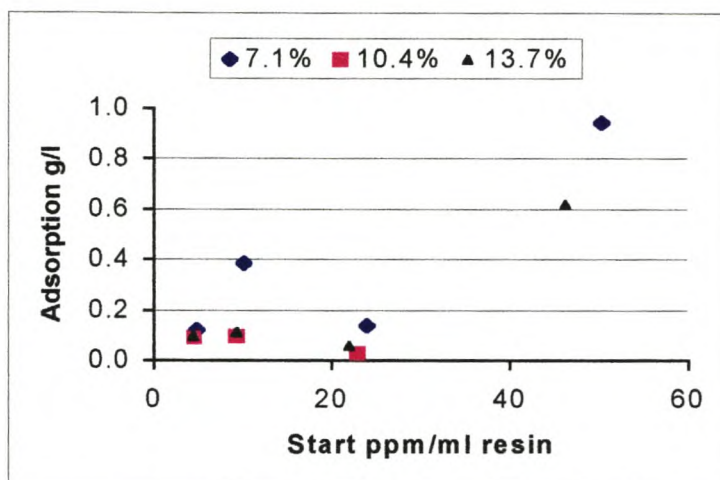


Figure 4.4.4.5: Rhodium adsorption on A22 with acidity

Values obtained from the scattered data and small ruthenium uptake (Figure 4.4.4.6), show that ruthenium is not adsorbed by the resin. At 13.7% HCl, there was no uptake of ruthenium due to the high chloride concentration in the solution. The test solution parameters are displayed in Table 4.4.4.6.

Table 4.4.4.6: Ruthenium test solutions

Acidity	Test 1		Test 2	
	% HCl	Ppm	ppm	Pot. (mV)
7.1	60	680	120	660
10.4	55	700	105	695
13.7	50	685	85	650

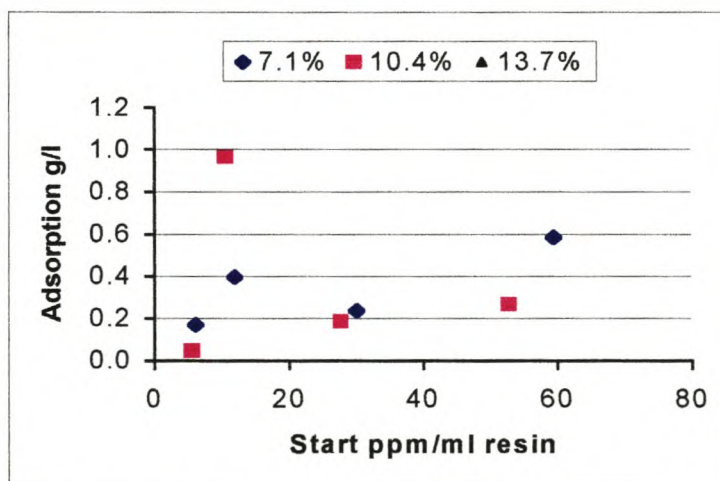


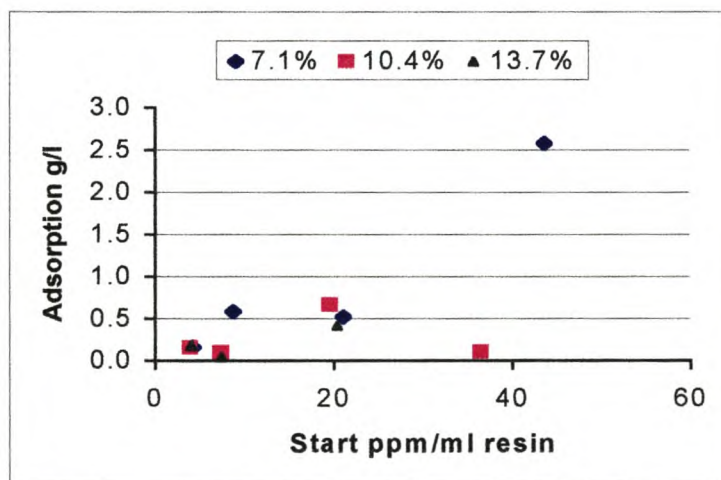
Figure 4.4.4.6: Ruthenium adsorption on A22 with acidity



The adsorption test results of the base metals, with different acidities, are shown in Figure 4.4.4.7. The test concentrations of the solutions are listed in Table 4.4.4.7. The results indicate that at lower acidities some uptake of base metals may occur. At 10.4% HCl concentration very little uptake of base metals are expected. As the base metals is not adsorbed by the resin they will be displaced from an adsorption column by a displacement wash, which follows the adsorption cycle in a semi-continuous process.

**Table 4.4.4.7: Base Metals test solutions**

Acidity % HCl	Test 1		Test 2	
	Ppm	Pot. (mV)	ppm	Pot. (mV)
7.1	40	600	85	685
10.4	40	650	70	650
13.7	40	645	75	650

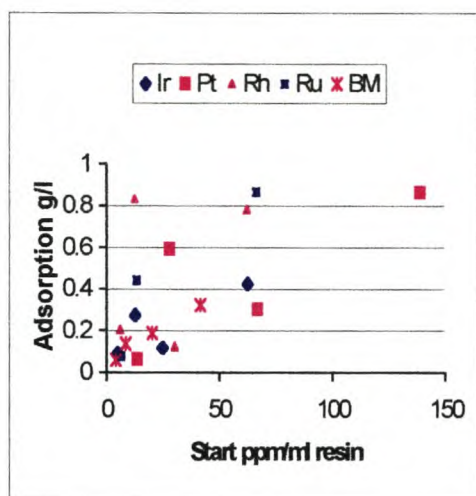


**Figure 4.4.4.7: Base Metals adsorption on A22 with acidity**

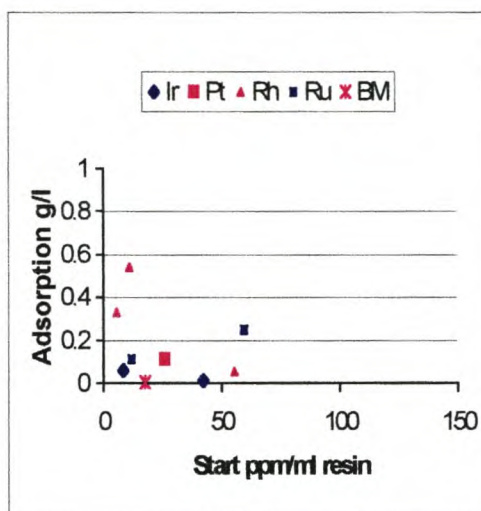
The adsorption from the mixed solution which excludes the addition of palladium, can be seen in Figure 4.4.4.8 at 7.1% HCl, and Figure 4.4.4.9 at 13.7% HCl. The test solutions used for adsorption can be seen in Table 4.4.4.8.

**Table 4.4.4.8: Ir + Pt + Rh + Ru + BM solutions**

Test No:	Pot. (mV)	% HCl	Ir	Pt	Rh	Ru	BM
1	680	7.1	50	135	60	65	40
2	625	7.1	125	280	125	130	80
3	620	13.7	85	120	55	55	35
4	640	13.7	135	260	110	120	75



**Figure 4.4.4.8: Ir + Pt + Rh + Ru + BM on A22 at 7.1% HCl**



**Figure 4.4.4.9: Ir + Pt + Rh + Ru + BM on A22 at 13.7% HCl**

It is evident from the figures above that there is no adsorption of any of the solution components at the acidities tested. An increase in chloride concentration prevents the uptake of ions by the resin due to the increased chloride concentration in the solution.

The effect of the acidity on the adsorption from a base metals and palladium mixed solution can be seen in Figures 4.4.4.10 and 4.4.4.11. It can be concluded from the figures that the resin maintained its selectivity for palladium over the base metals at the acid concentrations tested. The composition of the test solutions used for the adsorption test are shown in Table 4.4.4.9.

**Table 4.4.4.9: Pd + BM solutions**

Test No:	Pot. (mV)	% HCl	Pd	BM
1	690	7.1	95	45
2	685	13.7	90	40
3	630	13.7	180	75



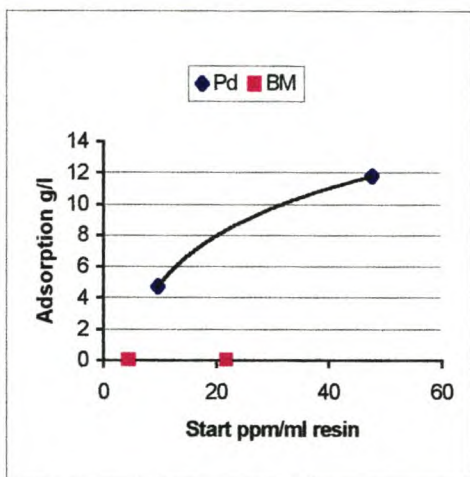


Figure 4.4.4.10: Pd + BM on A22 at 7.1% HCl

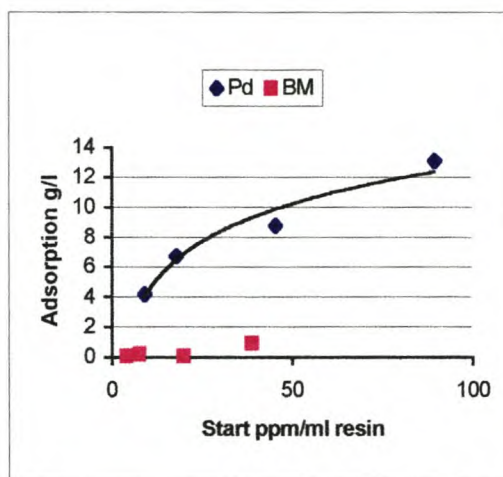


Figure 4.4.4.11: Pd + BM on A22 at 13.7% HCl

The variance of the adsorption with acidity from a mixed solution containing all the PGM's, excluding palladium, can be seen in Figures 4.4.4.12 and 4.4.4.13. The individual PGM's were added to the solution in addition to those already contained in the base metal solution. The solution compositions are listed in Table 4.4.4.10.

Table 4.4.4.10: Au + Ir + Pt + Rh + Ru + BM solutions

Test No:	Pot. (mV)	% HCl	Au	Ir	Pt	Rh	Ru	BM
1	700	7.1	60	60	135	60	65	40
2	395	7.1	115	95	270	120	130	80
3	640	13.7	55	50	130	55	60	40
4	425	13.7	110	160	275	115	120	80

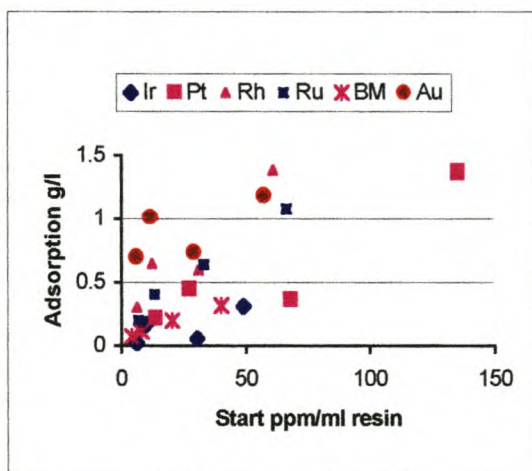


Figure 4.4.4.12: Au + Ir + Pt + Rh + Ru + BM on A22 at 7.1% HCl

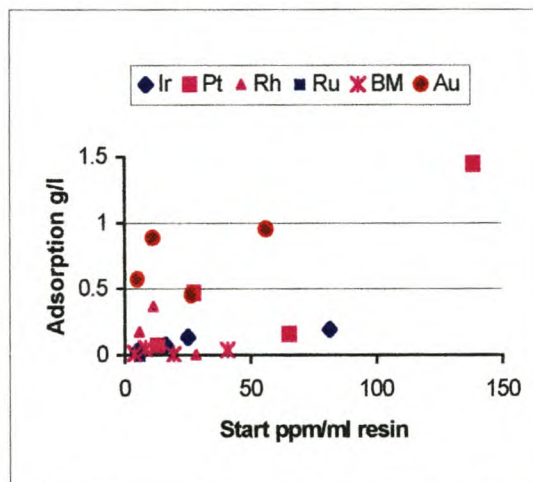


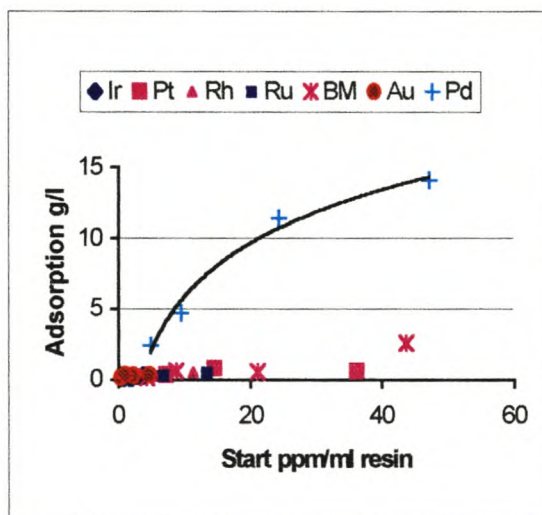
Figure 4.4.4.13: Au + Ir + Pt + Rh + Ru + BM on A22 at 13.7% HCl

It is evident from the above figures that the uptake by the resin is reduced at higher acid concentrations. None of the other PGM's are adsorbed by the resin. The uptake of gold is the highest.

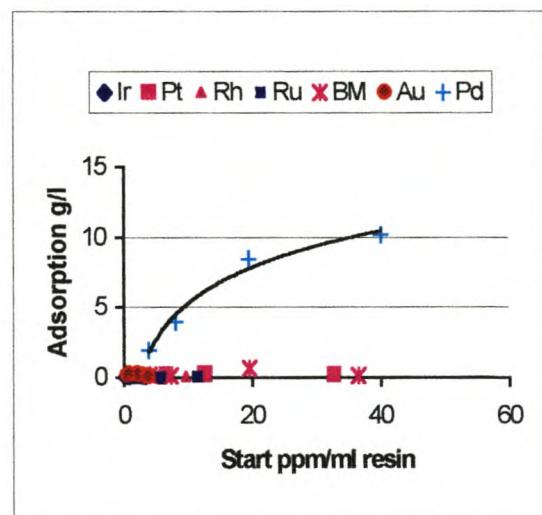
The adsorption of all PGM's and base metals were determined from a base metals solution at three acid concentrations (see Figures 4.4.4.14 to 4.4.4.16). The base metal solutions used for the tests are shown in Table 4.4.4.11.

**Table 4.4.4.11: BM solutions**

Test No:	Pot. (mV)	% HCl	BM
1	600	7.1	40
2	685	7.1	85
3	650	10.4	40
4	650	10.4	75
5	645	13.7	40
6	650	13.7	75



**Figure 4.4.4.14: BM solution on A22 at 7.1% HCl**



**Figure 4.4.4.15: BM solution on A22 at 10.4% HCl**



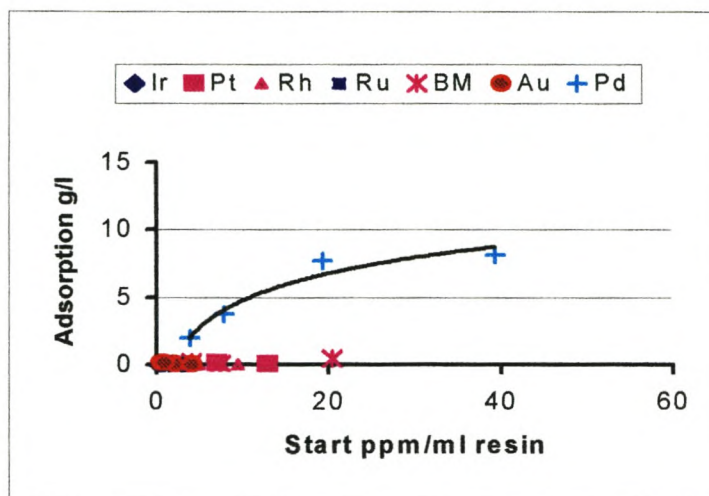


Figure 4.4.4.16: BM solution on A22 at 13.7% HCl

It is evident from the above figures that the adsorption of palladium is reduced with increasing chloride concentrations. The uptake of other ions are also reduced due to the higher chloride ion concentrations.

#### 4.4.5 Summary of the effect of HCl concentration on adsorption characteristics

The effect on the adsorption characteristics of a higher and lower free HCl concentration in the ranges tested can be summarised as in Table 4.4.5.1.

**Table 4.4.5.1: Effect of HCl concentration on equilibrium adsorption**

Resin	PGM's	Effect of HCl concentration on uptake
IRA900	Au	None
IRA900	Ir	None
IRA900	Pd	Decrease at higher [HCl]
IRA900	Pt	None
IRA900	Rh	Decrease at higher [HCl]
IRA900	Ru	Decrease at higher [HCl]
IRA900	BM	Small uptake, no trend observed
IRA900	Rh, Ir	Both decrease at higher [HCl]
IRA900	Pt, Rh, Ru	None
IRA900	Pt, Rh, Ru, Pd, Au, BM	None, only Pd decrease at higher [HCl]
XAD7	Au	None
XAD7	Ir	Small uptake, no trend observed
XAD7	Pd	Small uptake, no trend observed
XAD7	Pt	Small uptake, no trend observed
XAD7	Rh	Small uptake, no trend observed
XAD7	Ru	Small uptake, no trend observed
XAD7	BM	Small uptake, no trend observed
XAD7	Ir, Pd, Pt, Rh, Ru, BM	Small uptake reduced at higher [HCl]
XAD7	Au, Ru	None
IR200	Au	Small uptake, no trend observed
IR200	Ir	Decrease at higher [HCl]
IR200	Pd	Decrease at higher [HCl]
IR200	Pt	Decrease at higher [HCl]
IR200	Rh	Decrease at higher [HCl]
IR200	Ru	Decrease at higher [HCl]
IR200	BM	Decrease at higher [HCl]
IR200	Ir, Pt, Rh, Ru	Decrease at higher [HCl]
IR200	Ir, BM	Decrease at higher [HCl]
IR200	Au, Ir, Pd, Pt, Rh, Ru	Decrease at higher [HCl]
A22	Au	None
A22	Ir	Small uptake, no trend observed
A22	Pd	None
A22	Pt	Small uptake, no trend observed
A22	Rh	Small uptake, no trend observed
A22	Ru	Small uptake, no trend observed
A22	BM	Small uptake, no trend observed
A22	Ir, Pt, Rh, Ru, BM	Small uptake reduced at higher [HCl]
A22	Pd, BM	None
A22	Ir, Pt, Rh, Ru, BM, Au	Small uptake reduced at higher [HCl]
A22	BM	Pd decrease at higher [HCl]



## **CHAPTER 5**

### **STATISTICAL MODEL OF EXPERIMENTAL DATA**

The aims of modelling the ion-exchange process are to assess the effects of the different variables on the adsorption quantity and to furthermore predict the adsorption of a specific ion from solution by a resin. The solutions studied can vary in composition, concentration and free HCl concentrations. Most of the published models developed (see paragraph 2.3) try to generalise the adsorption characteristics to be expected from a wide range of solutions by use of a number of parameters which can be obtained from a limited number of actual adsorption tests. The models for multi-component ion-exchange, referred to in Chapter 2, are mathematically complex. The models developed are usually linked to actual adsorption by a few constants which must be determined experimentally. This is the only way to be able to predict adsorption from different solutions when limited experimental data are available. The assumptions used in the models will not always hold true, especially as the solution chemistry for the PGM's is very unpredictable. A statistical model derived from a large sample of experimental data should therefore be more dependable.

The large experimental data base developed during this investigation can be used for statistical modelling techniques as for each of the four resins tested. Typically about 250 adsorption tests were conducted at various solution compositions, concentrations, and free acid concentrations (see Chapter 3). A linear regression model was developed for each of the PGM's used, which is specific for each of the four resins used. In all the cases, the model is of the general form:

$$Y = B_0 + B_1X_1 + B_2X_2 + \dots + B_mX_m \dots\dots\dots (5.1)$$

Where:

Y is the adsorption expressed as gram of the specific PGM per litre of wet packed resin. The constant ( $B_0$ ) is a fitting constant. The parameters  $B_1, B_2, \dots$  etc., are the fitting parameters provided by the statistical package used (SPSS). The input variables  $X_1, X_2, \dots$  etc., are the initial concentrations of a specific PGM in the



solution divided by the volume of resin used in the test (ppm/ml resin). The free HCl concentration (in % HCl) used for the test is also an input parameter.

For a specific regression model, all of the PGM's present in the solution (as ppm/ml resin) are specified as input variables to explain the adsorption of the dependent variable, e.g. Au adsorption (g/l). All the experimental data for the specific resin is used to find the significant input parameters. The SPSS package provides a significance rating for each of the input parameters specified, see Table 5.1.1. If the resultant significance rating of a parameter is more than 0.05, the input parameter is insignificant in predicting the adsorption of the dependable variable and can be deleted from the model input.

The various species in solution can interact with each other to reduce or to promote the adsorption of a specific complex ion. This interaction can be determined by the model by taking the product of the input variables with one another and to specify this product as an input variable. The model determines if this product is significant in explaining the adsorption of the specific ion. Care must be taken, however, to avoid collinearity as some of the input variables are correlated. The SPSS package gives a condition index which is a measure of collinearity (see Table 5.1.1). The value of this index should be below 40 to avoid collinearity.

All the input variables, which consisted of the free HCl concentration, the start ppm/resin ml for each of the six PGM's and base metal solution, as well as the products of all of the mentioned inputs with each other were screened individually (to avoid collinearity) for significance. Collinearity can be introduced as the base metal solution also contained the precious metals. An increase in base metal solution concentration will also increase the palladium concentration in the solution, this may induce collinearity into the model with palladium concentration as a variable. There are 36 input variables altogether which have been screened to determine the significant input variables, while taking care to prevent collinearity. The regression model tables presented contain only the significant variables identified. The R square value provided by the model indicates the fraction of variance of the dependent variable (which is the equilibrium adsorption quantity) that is explained by the input variables. The model provides the necessary coefficients B for equation 5.1, above,



to calculate the predicted adsorption of the specific component by the resin. It can be seen in Table 5.1.1 that a 95% confidence interval for B is also given. The width of the interval indicates the certainty of the B value. The Beta value is a standardised coefficient which can be used to indicate the extent of the contribution of a specific input variable to the adsorption quantity. The larger the absolute value of Beta, the more important the explanatory input variable. The sign of Beta indicates whether the input enhances or decreases the adsorption of the specific component.

The model for the equilibrium adsorption of each of the six PGM's and the base metals, by each of the four resins, is developed. Where a specific PGM is not adsorbed by the resin, no graphical goodness of fit will be given. The predicted adsorption characteristics are compared to the actual measured values for the solutions used in Chapter 4. Models have been developed for the uptake of Au, Ir, Pd, Pt, Rh, Ru, and base metals, respectively, on each of the four resins, IRA900, XAD7, IR200 and A22. The model predicted uptake of the PGM from single PGM solutions, from mixed solutions, as well as from solutions with different HCl concentrations has been compared.

Variables used for the SPSS package are as follows;

AU - gold initial solution concentration / ml of resin

IR - iridium initial solution concentration / ml of resin

PD - palladium initial solution concentration / ml of resin

PT - platinum initial solution concentration / ml of resin

RH - rhodium initial solution concentration / ml of resin

RU - ruthenium initial solution concentration / ml of resin

BM – base metal initial solution concentration / ml of resin

AC – % free HCl concentration

AUIR, AUPD, ..... - gold initial solution concentration / ml of resin multiplied by  
the iridium initial solution concentration / ml of resin

## 5.1 ADSORPTION BY IRA900 RESIN

### 5.1.1 Gold

Gold is adsorbed well by the resin.

**Table 5.1.1: Regression model for adsorption of gold on IRA900 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.915							
Model							
(Constant)	.785		.023	.109	1.461	1	1.000
AU	.421	1.021	.000	.403	.439	2	1.334
AUBM	-6.700E-04	-.152	.000	-.001	.000	3	1.853

Is clear from Table 5.1.1 that the initial gold solution concentration (AU) is a significant input variable. It should be remembered that the base metal solution also contains the PGM's. It is worth noting that the base metal solution concentration is not a significant variable, as such, in predicting the adsorption of gold by the resin. The gold concentration times the base metal concentration is significant, although to a lesser extent than the gold concentration. The interaction of the gold and base metal ions reduce the adsorption of gold, as indicated by the Beta values of the model. The presence of the base metal ion complexes gives rise to interference with the gold complex ions in such a way as to reduce the adsorption of gold. The input parameters predict 91.5% of the variance of gold adsorption.

The predicted adsorption by the model from the single metal gold solution can be seen in Figure 5.1.1.1. The adsorption of gold was also determined from a mixed solution containing Au, Pd, Pt, Rh, Ru, and BM (see earlier Figure 4.3.1.3). The prediction of gold adsorption by the model from this solution is graphically depicted in Figure 5.1.1.2.



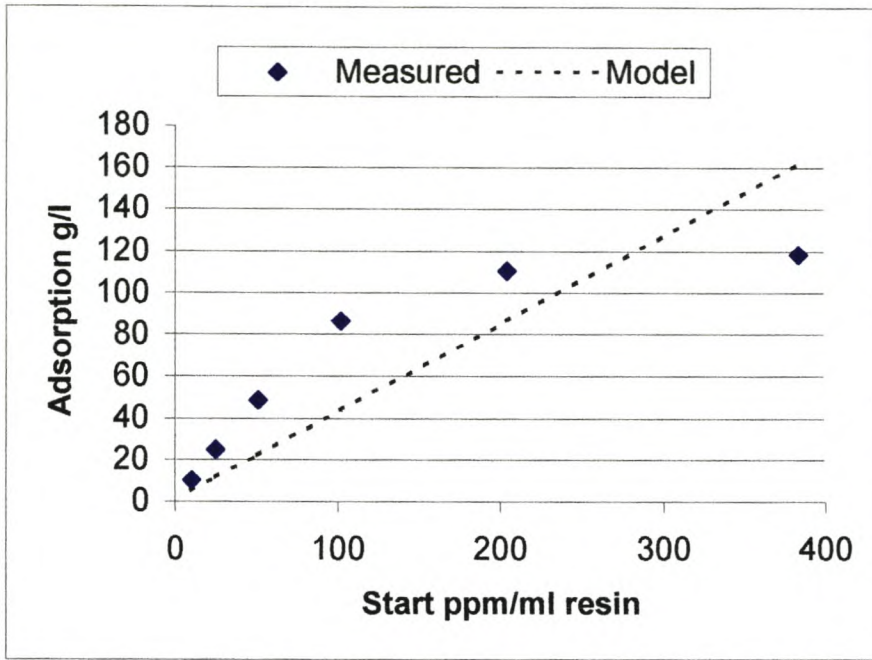


Figure 5.1.1.1: Au Adsorption predicted on IRA900

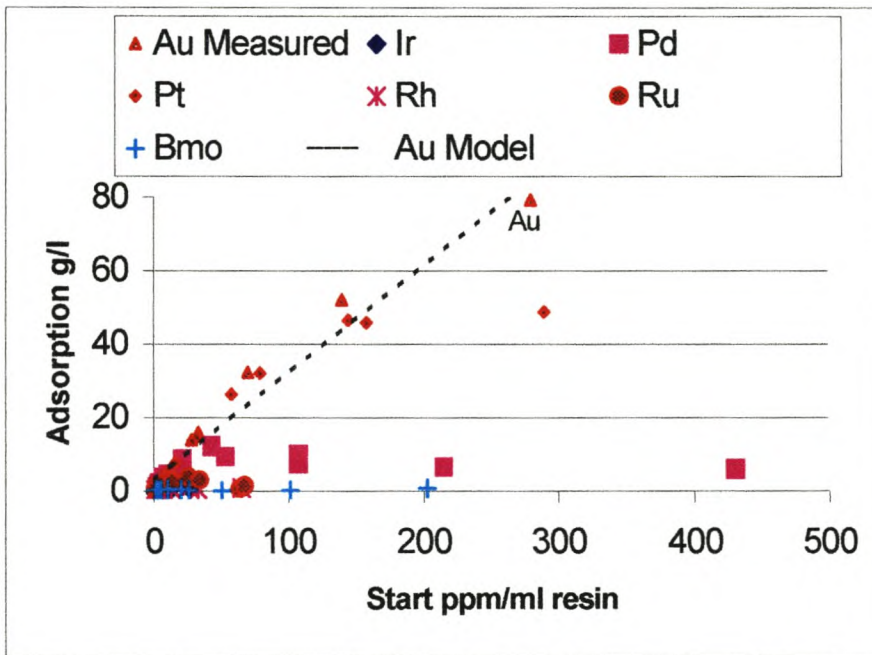


Figure 5.1.1.2: Au Adsorption predicted from mixed solution on IRA900

The free acid HCl concentration has no effect on the quantity of gold adsorbed in the tested range of 6 – 10% (see Figure 4.4.1.1). The acid concentration is also not a significant factor and is not included in the model for gold adsorption (see Table

5.1.1). The prediction of the adsorption of gold from the mixed solution at acidities of 6% and 10% is depicted in Figures 5.1.1.3 and Figure 5.1.1.4.

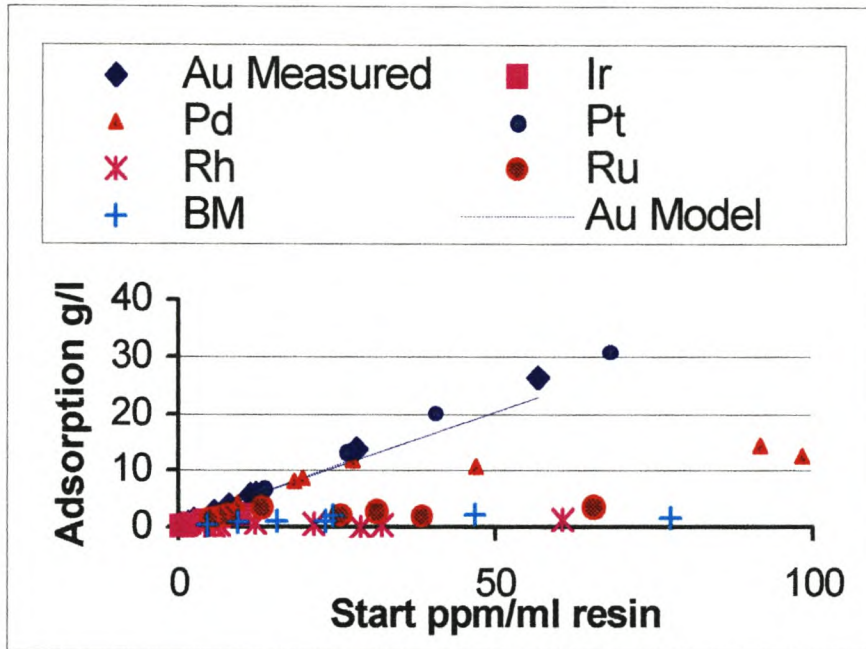


Figure 5.1.1.3: Au Adsorption predicted from mixed solution at 6% HCl on IRA900

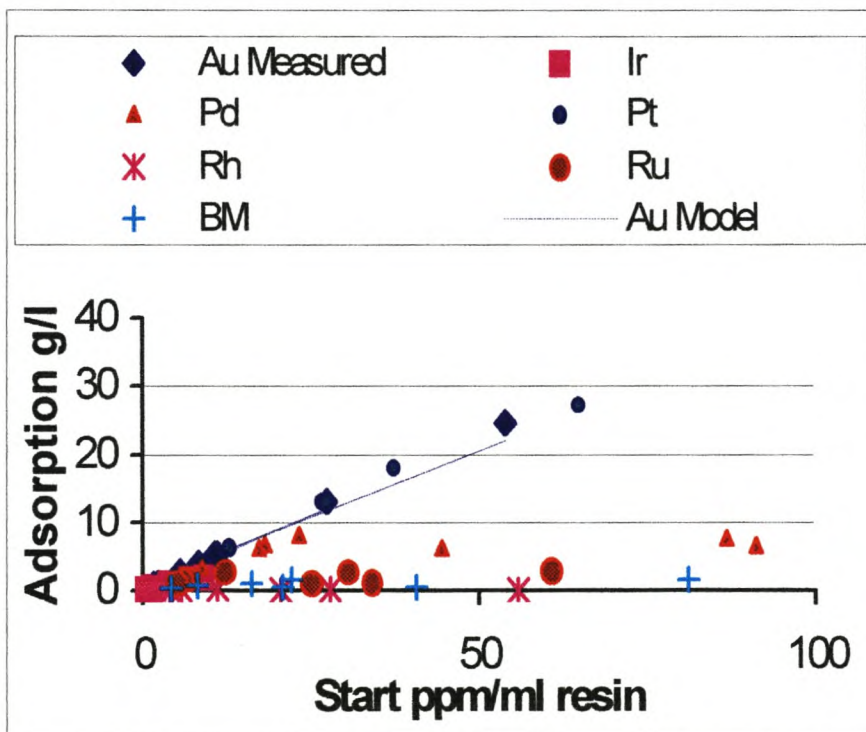


Figure 5.1.1.4: Au Adsorption predicted from mixed solution at 10% HCl on IRA900



The adsorption of gold from the mixed solution is not affected by the acid concentration and is accurately predicted by the model.

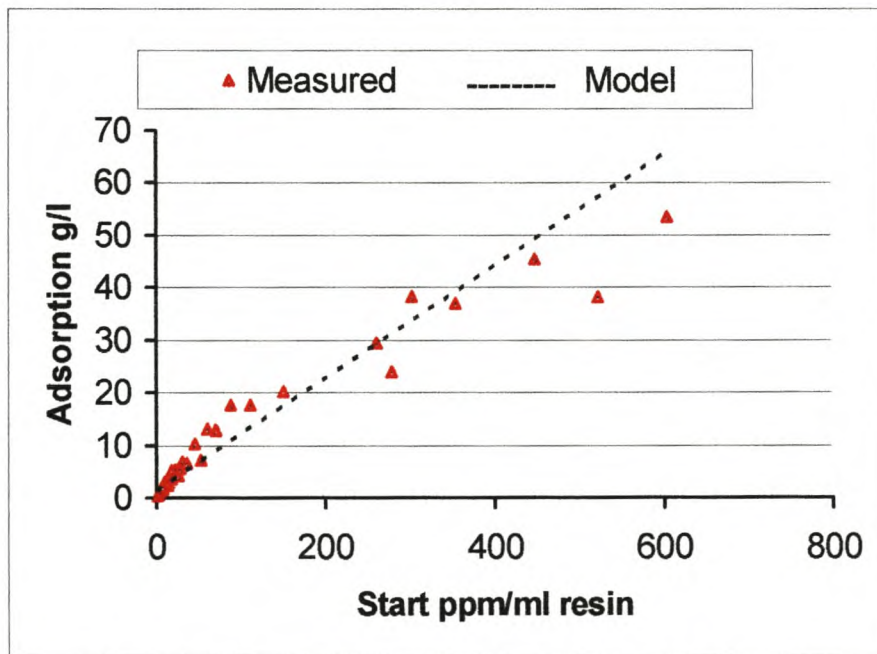
### 5.1.2 Iridium

The model for the adsorption of iridium by IRA900 can be seen in Table 5.1.2.

**Table 5.1.2: Regression model for adsorption of iridium on IRA900 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.848							
Model							
(Constant)	1.027		.000	.477	1.576	1	1.000
IR	.116	1.006	.000	.108	.124	2	1.427
IRRH	-4.082E-05	-.130	.000	.000	.000	3	2.562

It is evident from the table that there is not much interference in the adsorption by other ions in the solution. The amount of the rhodium complex in the solution gives rise to a small reduction in adsorption capacity.



**Figure 5.1.2.1: Ir Adsorption predicted on IRA900**

The model prediction of pure iridium adsorption can be seen in Figure 5.1.2.1. The model closely matches the measured adsorption.

The prediction of adsorption of iridium from a mixed rhodium and iridium solution can be seen in Figure 5.1.2.2. It is evident that the model predicts the adsorption very well.

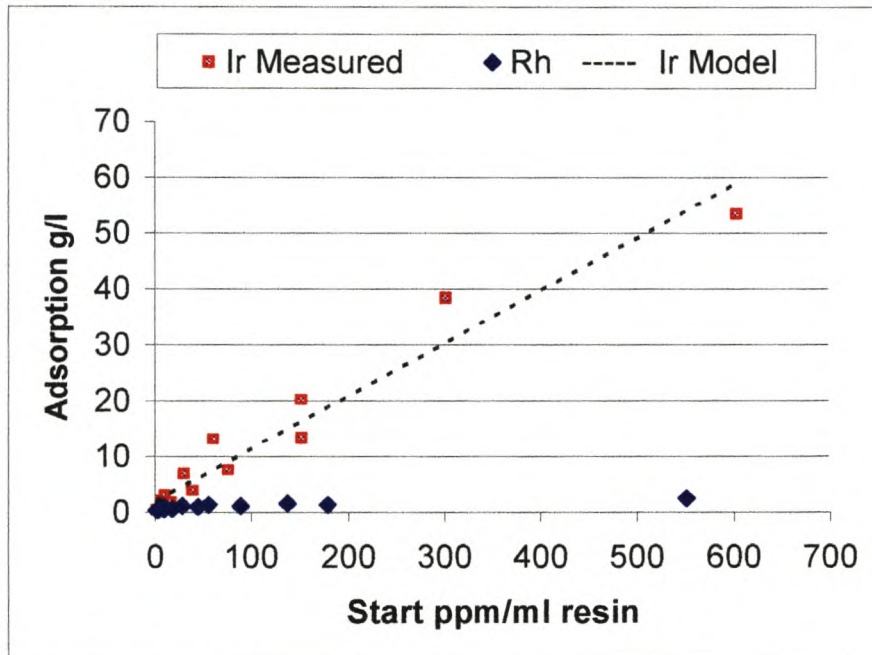


Figure 5.1.2.2: Ir Adsorption predicted from mixed solution on IRA900

It can be seen from the model (Table 5.1.2) that the adsorption of iridium is not affected by the HCl concentration in the range 6-10%. The graph depicting the effect of HCl concentration (Figure 4.4.1.2) also shows no trend with regards to the effect of free acid concentration.

The predicted adsorption of iridium from the rhodium and iridium mixed solution at an acidity of 10% HCl can be seen in Figure 5.1.2.3.



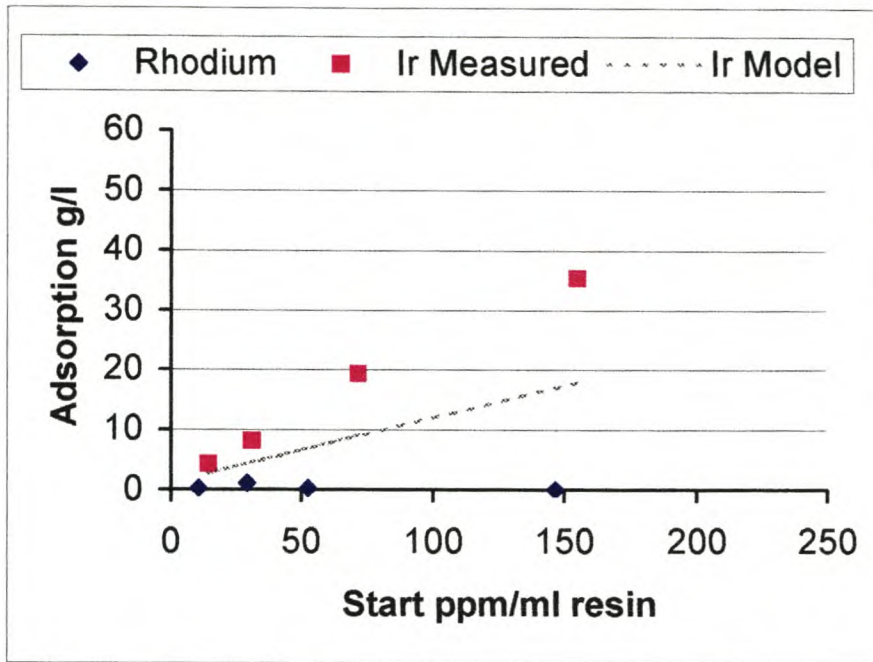


Figure 5.1.2.3: Ir Adsorption predicted from mixed solution at 10% HCl on IRA900

It is clear from the figure that the model underestimates the adsorption of iridium from the mixed solution. The experimental curve for the acidity test was drawn, however, between only a few data points. Higher acidity does not affect the adsorption, and hence more accurate adsorption quantities at a specific start concentration / ml resin, can be seen in Figure 5.1.2.2. The predicted adsorption quantities follow the measured adsorption loading obtained from this figure more closely.

### 5.1.3 Palladium

Palladium is readily adsorbed by the resin.

Table 5.1.3: Regression model for adsorption of palladium on IRA900 resin

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.820							
Model							
(Constant)	.644		.000	.315	.973	1	1.000
PD	.340	2.659	.000	.286	.394	2	1.732
ACPD	-2.121E-02	-1.346	.000	-.028	-.015	3	3.031
PDRU	-6.520E-04	-.895	.000	-.001	-.001	4	18.707

From Table 5.1.3 it is evident that the presence of chloride and ruthenium ions together with the palladium ions in solution reduces the uptake of palladium by IRA900. This may be due to the formation of secondary complex species of palladium or alteration of the electrical charge distribution in the palladium complexed species. The prediction of palladium adsorption from a single PGM solution can be seen in Figure 5.1.3.1. The under predicted adsorption from a single metal solution may be due to the distortion of the model as the data base included many data points relating to adsorption characteristics obtained from analysis of multi-component mixtures.

The predicted adsorption of palladium from a mixed solution can be seen in Figure 5.1.3.2. The predicted adsorption closely matches the measured adsorption. It is evident that the uptake of palladium from multi-component solution is reduced to below 10 g/l, in comparison to adsorption from a single metal solution, Figure 5.1.3.1. The model Beta coefficients also indicates the negative impact of ruthenium in the uptake of palladium.

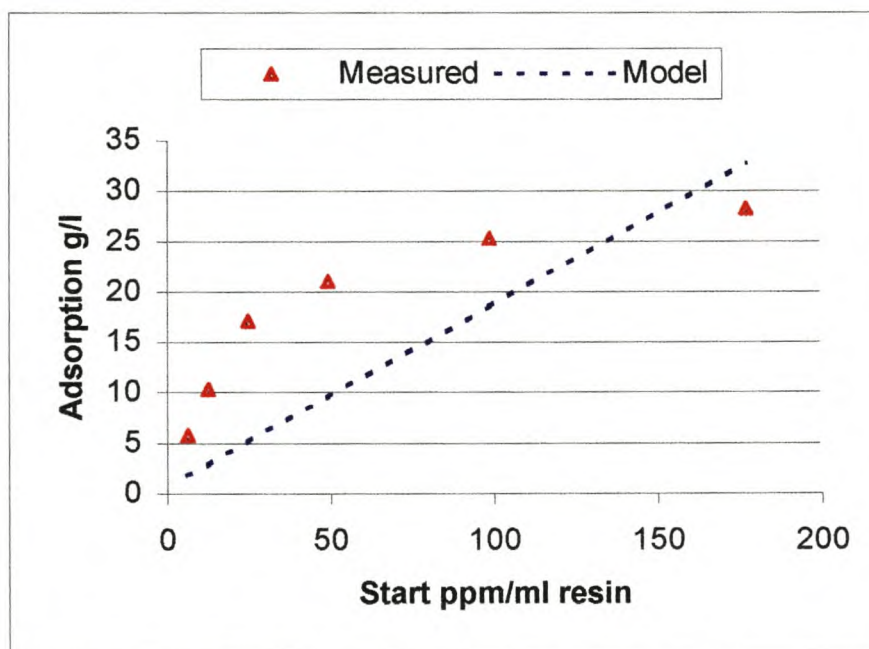


Figure 5.1.3.1: Pd Adsorption predicted on IRA900



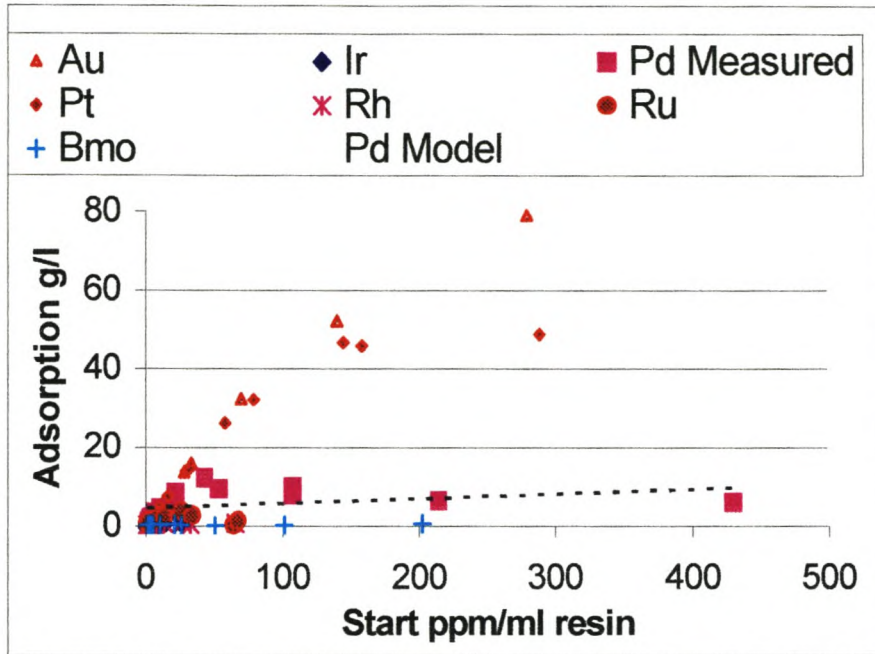


Figure 5.1.3.2: Pd Adsorption predicted from mixed solution on IRA900

It is evident from the model Beta values that the interaction of chloride and palladium ions have a negative effect on the adsorption of palladium. The predicted adsorption of palladium from a single PGM solution at different acidities can be seen in Figure 5.1.3.3. The effect of the free HCl concentration is predicted well by the model.

The adsorption from the mixed solution at 6% and 10% HCl can be seen in Figures 5.1.3.4 and 5.1.3.5. The reduction in palladium uptake at higher acidities is evident.

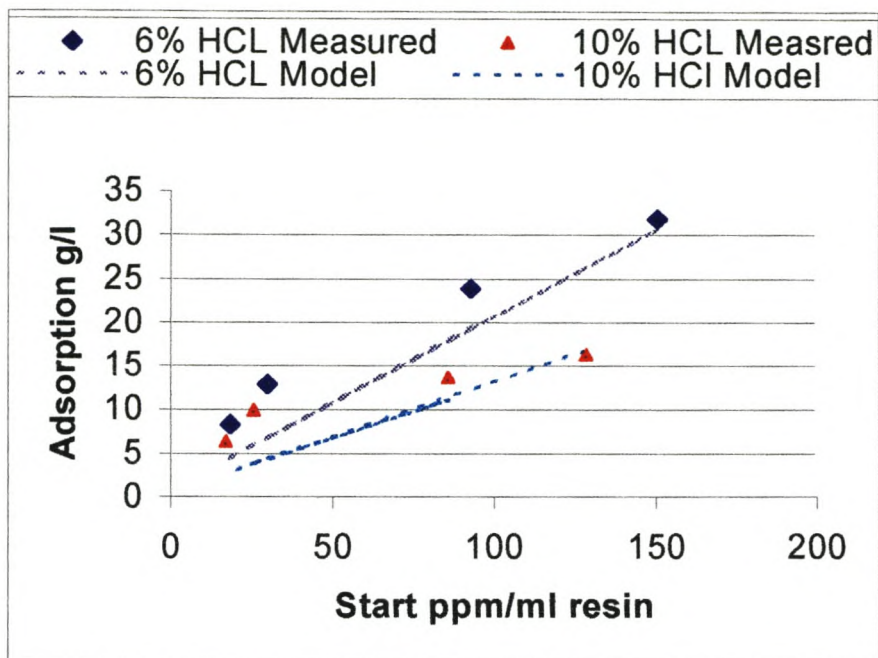


Figure 5.1.3.3: Pd Adsorption predicted with acidity on IRA900

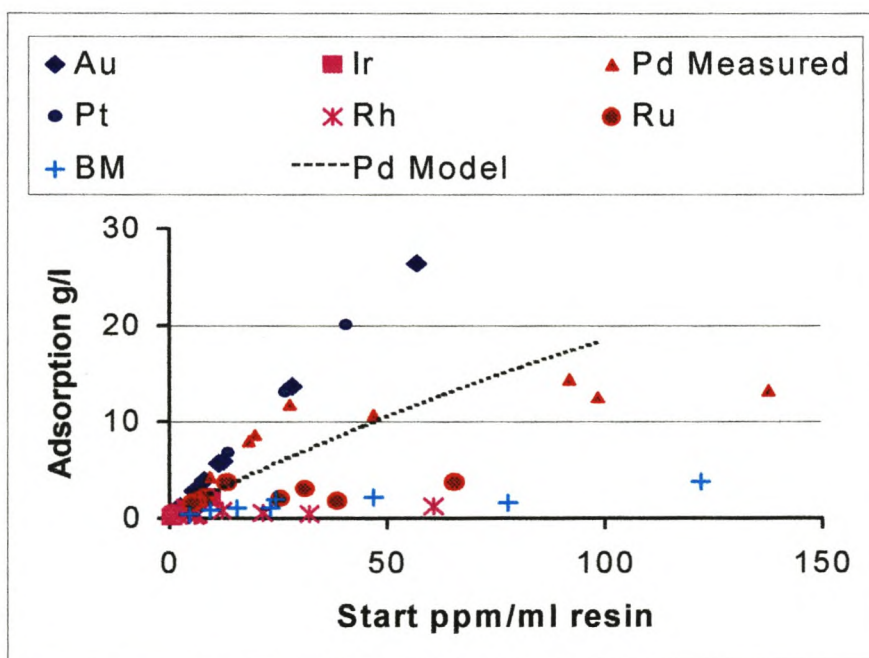


Figure 5.1.3.4: Pd Adsorption predicted from multi-component solution at 6% HCl on IRA900



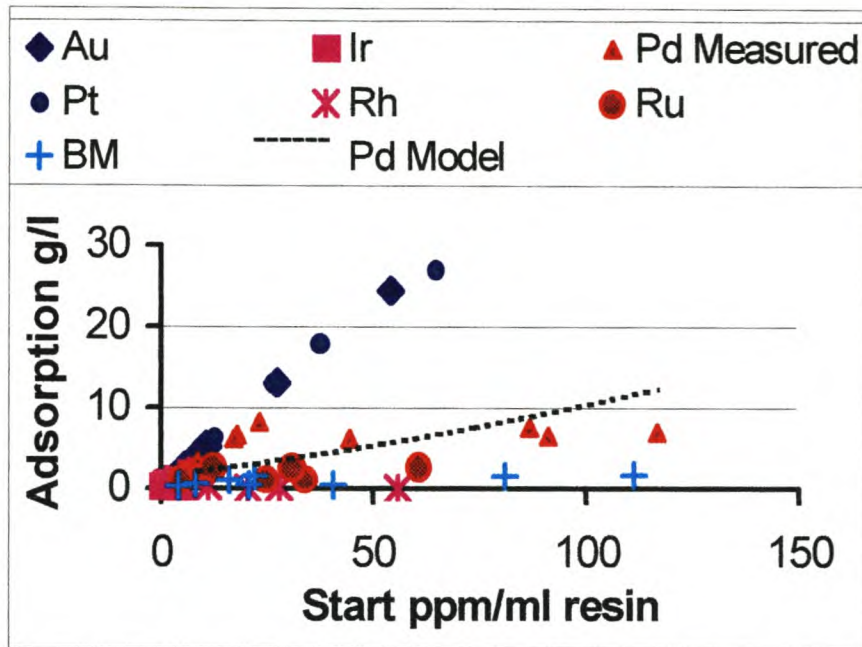


Figure 5.1.3.5: Pd Adsorption predicted from multi-component solution at 10% HCl on IRA900

#### 5.1.4 Platinum

The platinum complex is adsorbed well by IRA900. The model for platinum adsorption can be seen in Table 5.1.4.

Table 5.1.4: Regression model for adsorption of platinum on IRA900 resin

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.786							
Model							
(Constant)	3.483		.000	2.171	4.794	1	1.000
PT	.226	.914	.000	.207	.245	2	1.754
AUPT	-2.603E-03	-1.424	.000	-.004	-.001	3	2.573
PDPT	1.146E-03	.969	.006	.000	.002	4	4.380
PTRH	4.091E-04	.242	.000	.000	.001	5	29.148

It is evident from the Standardised Beta coefficients in the table that the presence of gold is the most important variable determining the quantity of platinum adsorbed by the resin. The presence of gold in the solution interferes with the uptake of platinum. The interaction of palladium and rhodium are significant in terms of the adsorption of platinum. Whereas the interaction of platinum with gold causes a decrease in adsorption, the interaction with palladium and rhodium increases the adsorption of platinum. There is some collinearity in the model, but not at an unacceptable level.

The acidity of the solution is not significant in terms of platinum adsorption in the range tested. The predicted adsorption of platinum from a single metal solution can be seen in Figure 5.1.4.1.

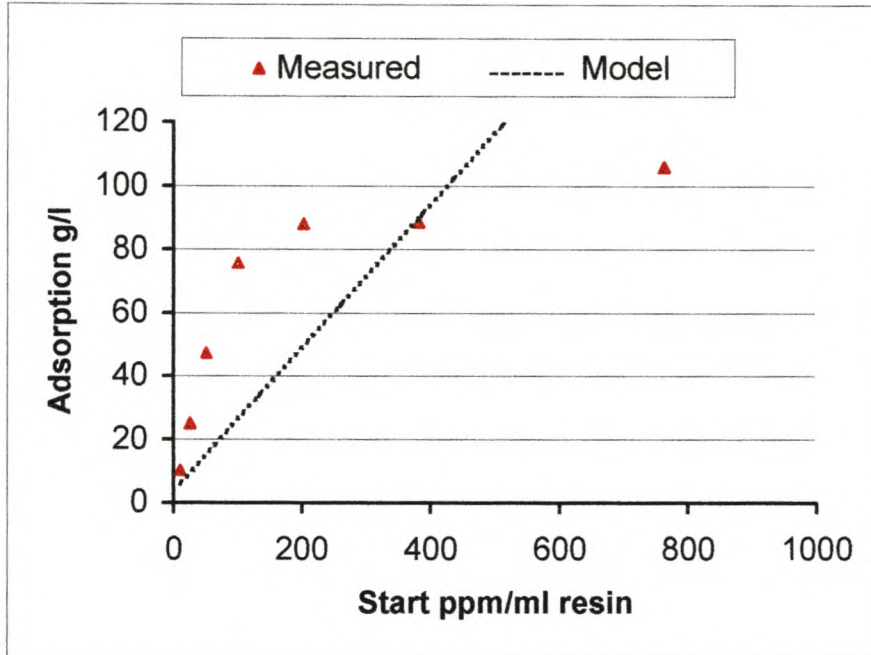


Figure 5.1.4.1: Pt Adsorption predicted on IRA900

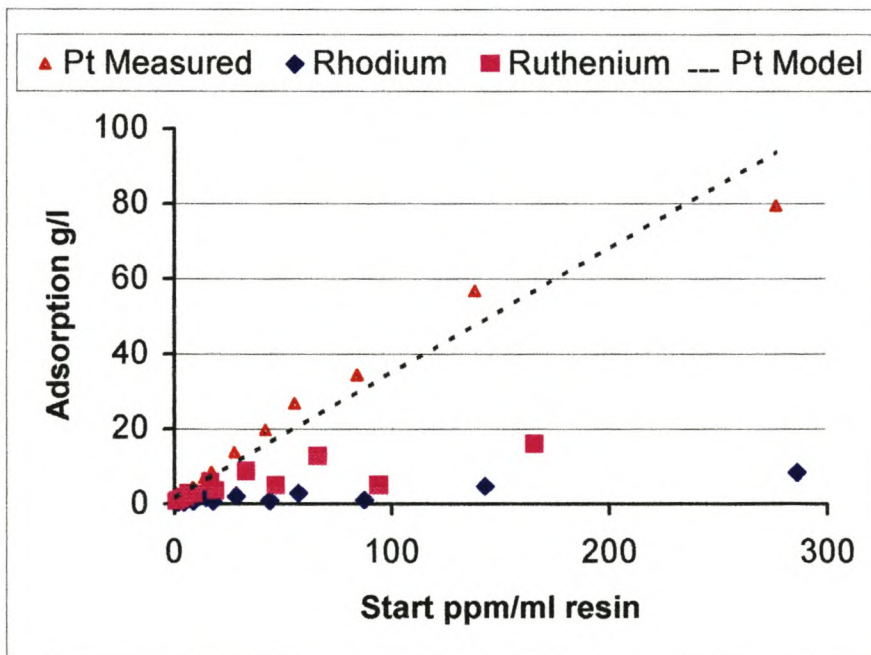


Figure 5.1.4.2: Pd Adsorption predicted from mixed solution on IRA900



The adsorption of platinum from a mixed platinum, rhodium, ruthenium solution can be seen in Figure 5.1.4.2. The predicted adsorption from the mixed solution is better than that for the single metal prediction. The model accommodates all the data provided, and the bulk of the data is for adsorption from more component solutions.

The predicted adsorption of platinum from the mixed solution containing all the PGM's, except iridium, can be seen in Figure 5.1.4.3.

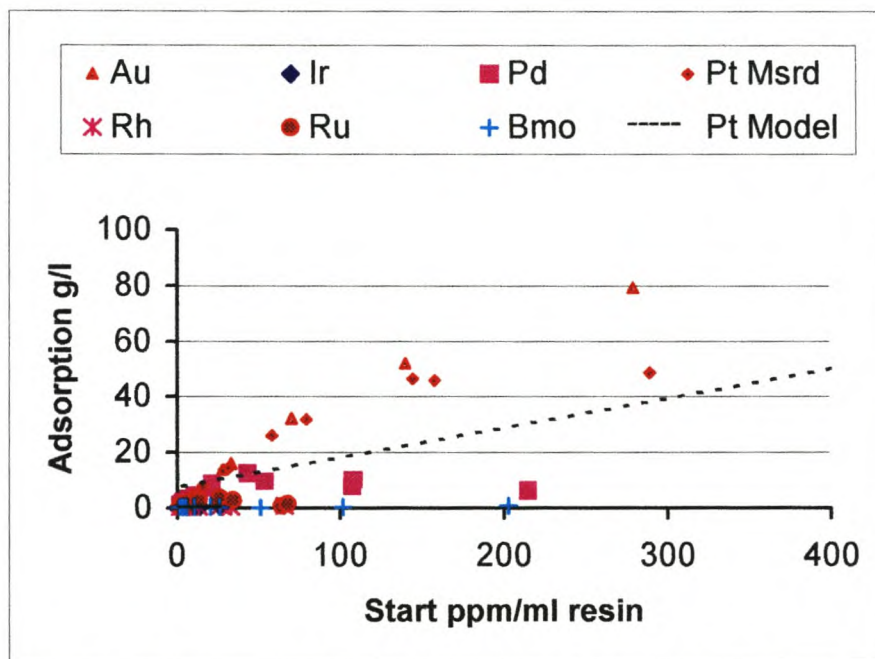


Figure 5.1.4.3: Pt Adsorption predicted from mixed solution on IRA900

The model may at worst underpredict the equilibrium uptake by 10g/l. The acidity of the solution does not effect the uptake of platinum, as can also be seen in Figure 4.4.1.4.

The predicted uptake of platinum from the mixed platinum, rhodium, and ruthenium solution at 6% HCl can be seen in Figure 5.1.4.4.

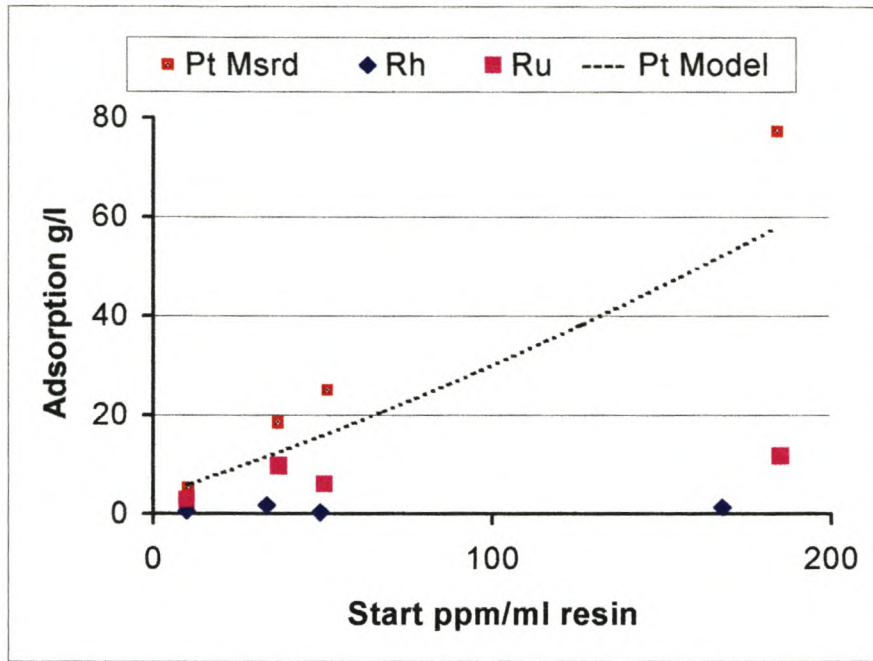


Figure 5.1.4.4: Pt Adsorption predicted from mixed solution at 6% HCl on IRA900

The predicted adsorption from the mixed solution containing all the PGM's and base metals, but excluding iridium at 6% HCl, can be seen in Figure 5.1.4.5.

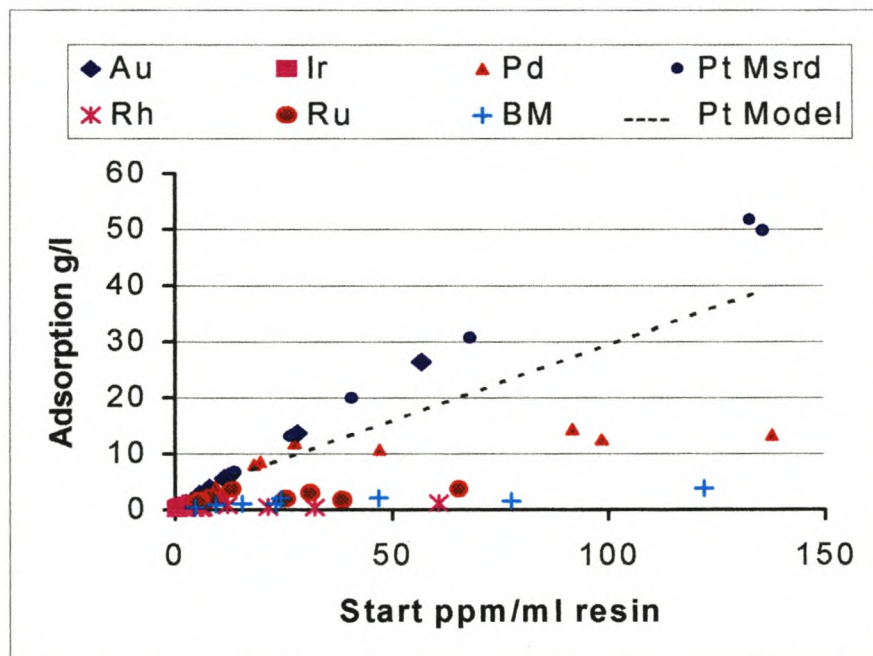


Figure 5.1.4.5: Pt Adsorption predicted from mixed solution at 6% HCl on IRA900



### 5.1.5 Rhodium

The resin has no affinity for rhodium. The model parameters for the predicted uptake of rhodium can be seen in Table 5.1.5.

**Table 5.1.5: Regression model for adsorption of rhodium on IRA900 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.555							
<b>Model</b>	<b>B</b>	<b>Beta</b>		<b>Lower Bound</b>	<b>Upper Bound</b>	<b>Dimension</b>	<b>Index</b>
(Constant)	.262		.000	.172	.351	1	1.000
IR	-2.014E-03	-.189	.001	-.003	-.001	2	1.490
RH	3.021E-02	2.270	.000	.019	.041	3	1.971
ACRH	-3.164E-03	-1.902	.000	-.004	-.002	4	2.413
PDRH	-7.672E-05	-.630	.000	.000	.000	5	3.135
RHRU	6.440E-05	.578	.000	.000	.000	6	24.048

It is evident from the R square value that only 56% of the adsorption of rhodium is explained by the input variables. This is due to the fact that rhodium is not adsorbed by the resin, only equilibrium uptake occurs. The uptake values obtained are very small (see Figure 5.1.5.1). It is interesting from the model that the presence of iridium, which is well adsorbed by the resin, reduces the uptake of rhodium. This can be ascribed to the affinity of the resin for iridium. The predicted uptake of rhodium by the resin from a single metal solution can be seen in Figure 4.1.5.1.

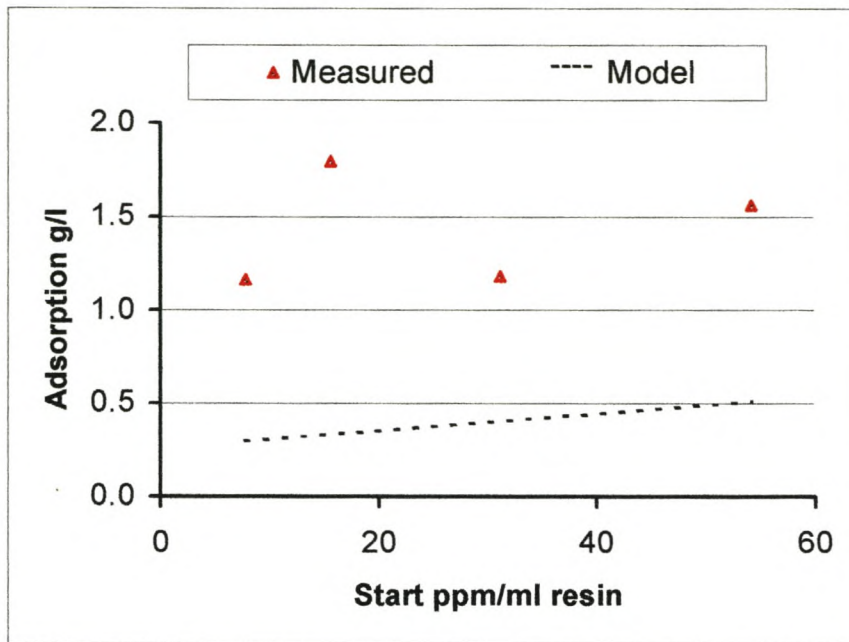


Figure 5.1.5.1: Rh Adsorption predicted on IRA900

The model underpredict the sorption of rhodium from a single metal solution by about 1 g/l.

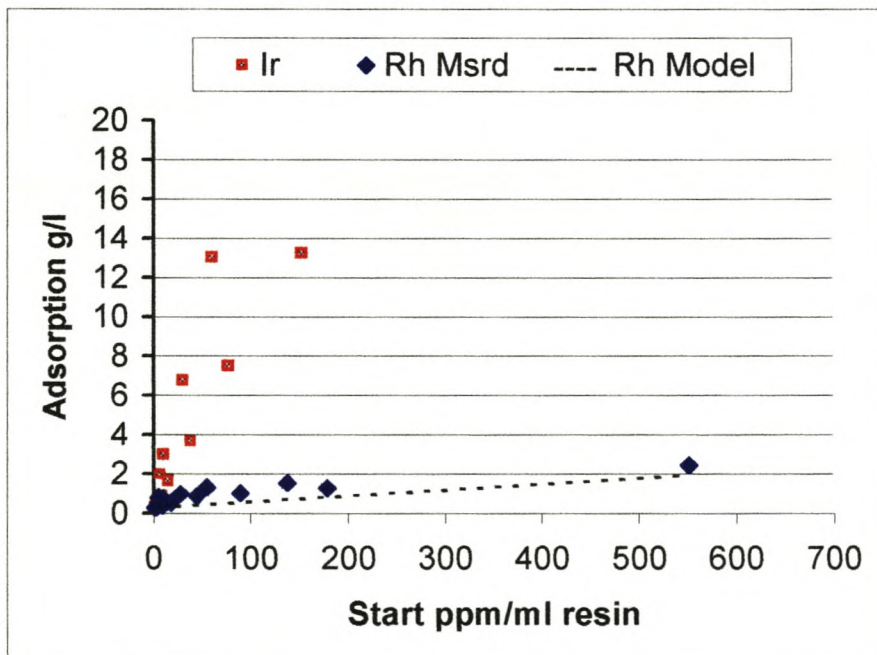


Figure 5.1.5.2: Rh Adsorption predicted from mixed solution on IRA900



The model predicted sorption of rhodium from a rhodium and iridium mixed solution can be seen in Figure 5.1.5.2. Although the predicted uptake differs by about 1 g/l, the uptake is predicted well.

The predicted rhodium uptake from the platinum, rhodium, and ruthenium solution can be seen in Figure 5.1.5.3. The minor uptake of rhodium found is predicted well by the model.

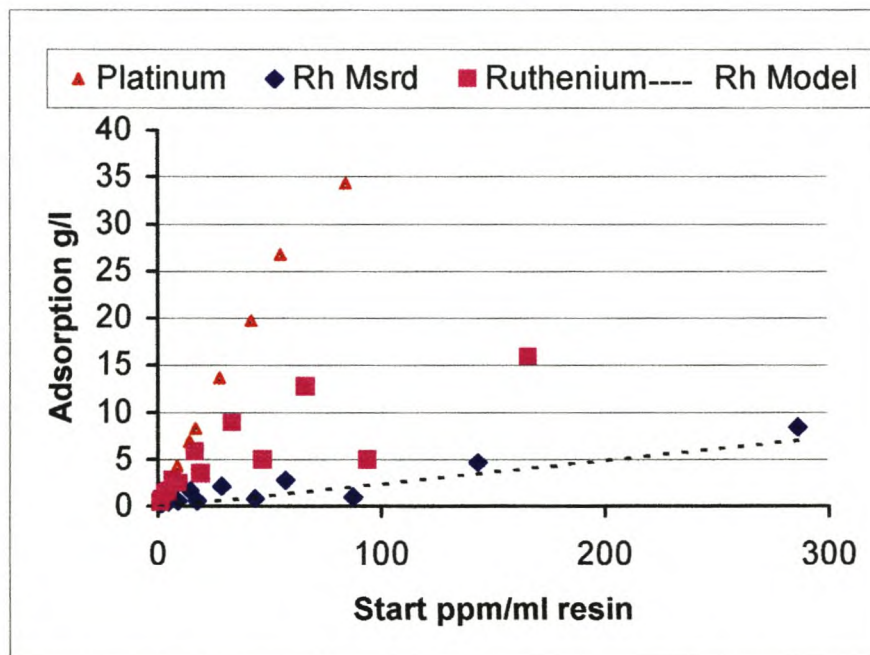


Figure 5.1.5.3: Rh Adsorption predicted from mixed solution on IRA900

The predicted uptake of rhodium from the mixed solution containing all the PGM's, except iridium is not shown graphically as the uptake of rhodium is too low (less than 1 g/l resin).

With the very low uptake of rhodium by the resin, only the graphical fit of the predicted uptake of rhodium with different acidities from the single metal solution is included.

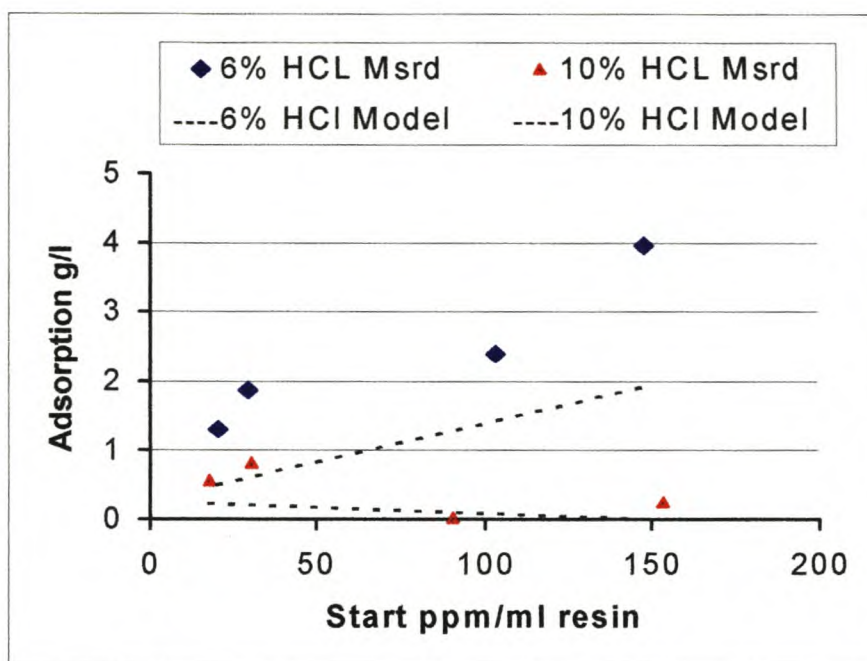


Figure 5.1.5.4: Rh Adsorption predicted with acidity on IRA900

As can be seen from the model and the figure, the higher chloride concentration reduces the equilibrium uptake of rhodium.

### 5.1.6 Ruthenium

The chloride complex ion of ruthenium is adsorbed by IRA900. The high uptake of platinum and gold is not achieved, but the adsorption quantity is similar to that of palladium. The predicted adsorption can be seen in Table 5.1.6.

Table 5.1.6: Regression model for adsorption of ruthenium on IRA900 resin

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.790							
Model							
(Constant)	.865		.000	.584	1.146	1	1.000
AU	-9.564E-03	-.104	.002	-.016	-.003	2	1.801
RHRU	-2.337E-04	-.515	.000	.000	.000	3	1.923
PT	-4.496E-03	-.096	.012	-.008	-.001	4	2.293
RH	-3.887E-03	-.072	.035	-.007	.000	5	2.488
RU	.116	1.295	.000	.107	.125	6	2.766
PD	-2.285E-02	-.258	.000	-.029	-.016	7	4.366

It is evident from the model that gold, platinum, rhodium, and palladium compete with the ruthenium for adsorption sites on the resin, lowering the amount of ruthenium adsorbed. It also points to some interaction of rhodium with the ruthenium



which also reduces the uptake of ruthenium. The most significant parameter is the initial ruthenium concentration.

The predicted ruthenium uptake from a single metal solution is graphically displayed in Figure 5.1.6.1. The model underpredicts the adsorption from a single component solution. The model constant would have been larger to shift the curve upwards but is obtained from all the experimental data, which usually includes more species in the solution.

The adsorption of ruthenium from the platinum, rhodium, and ruthenium mixed solution can be seen in Figure 5.1.6.2. The predicted adsorption closely follows the measured values.

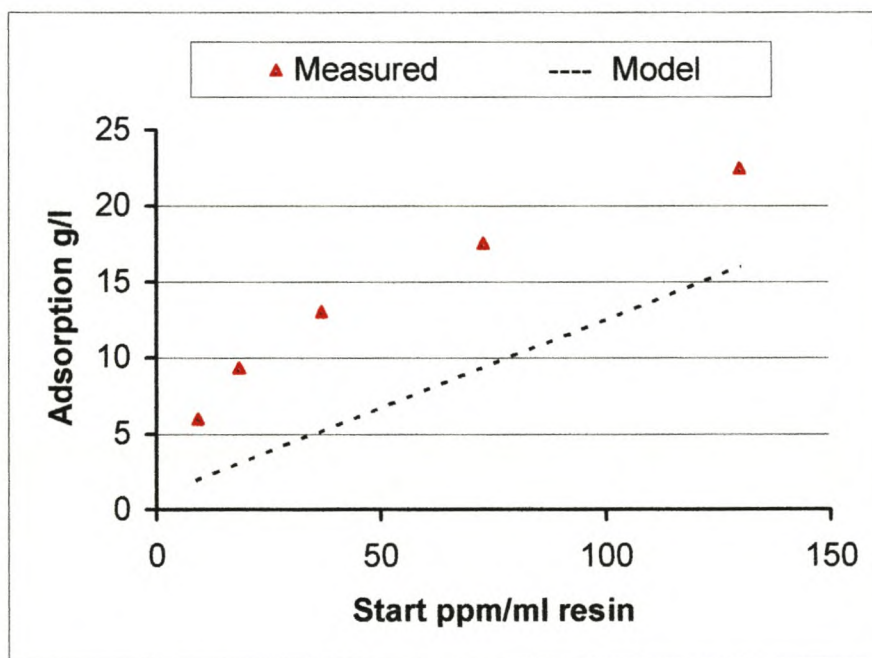


Figure 5.1.6.1: Ru Adsorption predicted on IRA900

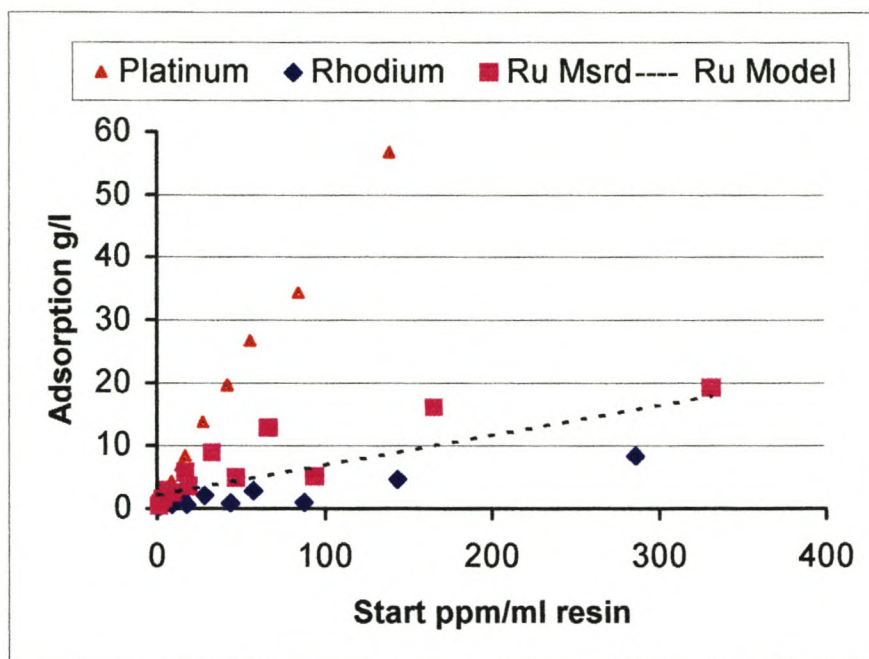


Figure 5.1.6.2: Ru Adsorption predicted from mixed solution on IRA900

It is evident from the model that the acidity of the solutions is not a significant input variable, and the model therefore does not allow for any variation in the uptake of ruthenium at different acidities (see Figure 5.1.6.3). The measured ruthenium adsorption from the single metal solution did show a slight decrease in uptake at higher chloride concentrations.

The predicted adsorption of ruthenium at 6% HCl from the platinum, rhodium, and ruthenium mixed solution is shown in Figure 5.1.6.4.



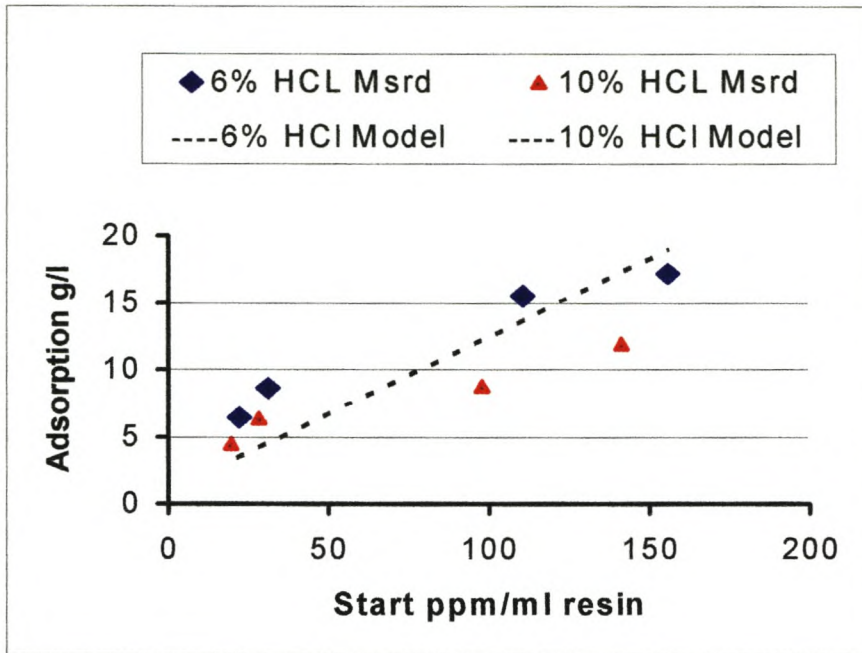


Figure 5.1.6.3: Ru Adsorption predicted with acidity on IRA900

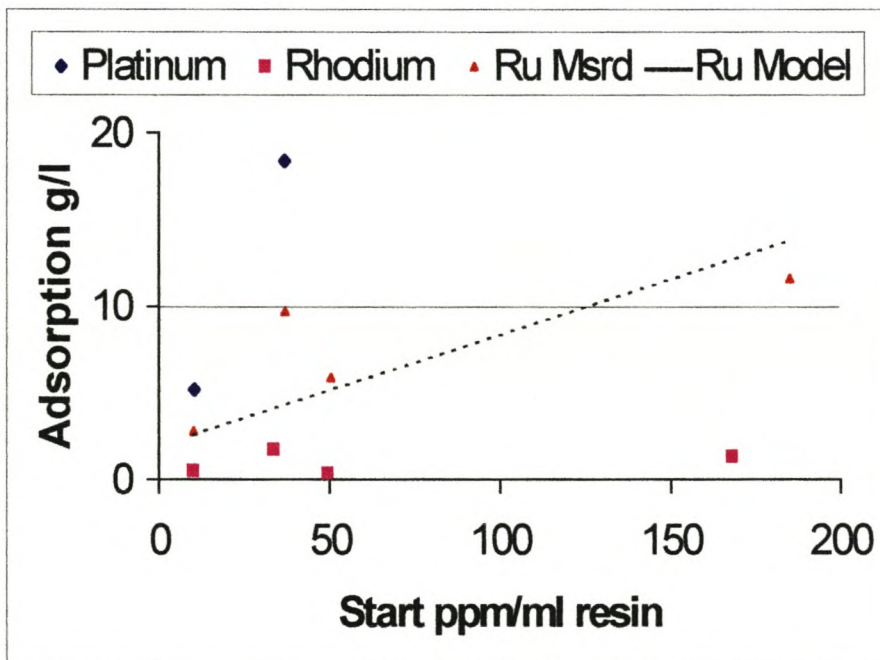


Figure 5.1.6.4: Ru Adsorption predicted from mixed solution at 6% HCl on IRA900

It is evident from the figure that the model predicts the adsorption of ruthenium in different acid concentrations well.

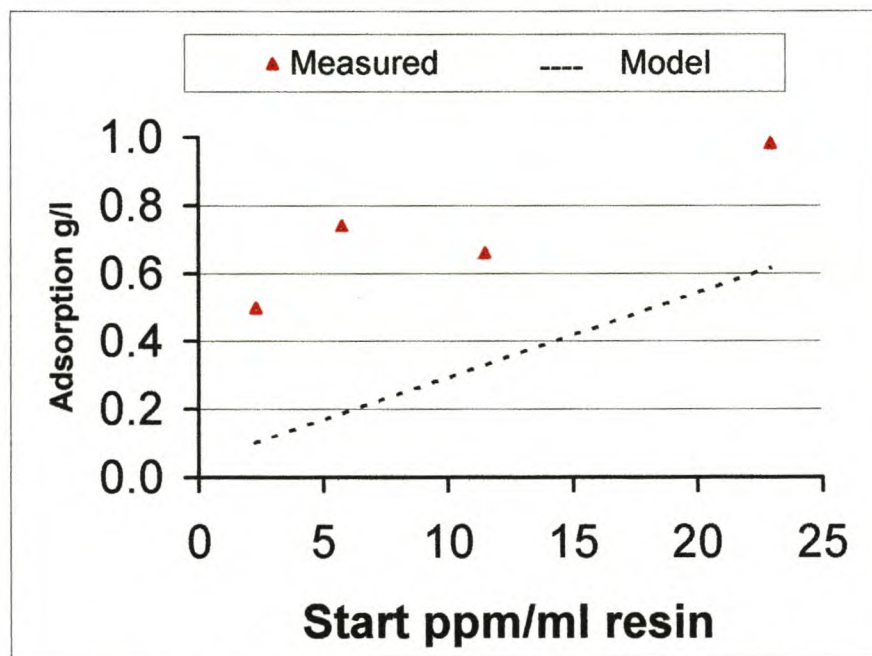
### 5.1.7 Base Metals

The base metals are in solution as cations, and no adsorption of base metals was observed. The sorption that does occur is predicted by the model as detailed in Table 5.1.7.

**Table 5.1.7: Regression model for adsorption of base metals on IRA900 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.618							
<b>Model</b>	<b>B</b>	<b>Beta</b>					
(Constant)	3.432E-02		.024	.005	.064	1	1.000
BMO	2.729E-02	1.548	.000	.023	.031	2	1.686
AUPD	2.991E-05	.712	.050	.000	.000	3	3.434
PDBM	-1.005E-04	-1.759	.000	.000	.000	4	23.088

It is evident from the model that the presence of palladium in the solution reduces the sorption of base metals by the resin. The acidity does not effect the uptake of base metals by IRA900. It is clear from Figure 5.1.7.1 that the base metals are not adsorbed by the resin, the sorption is below 1 g/l resin.



**Figure 5.1.7.1: BM Adsorption predicted on IRA900**

The sorption of base metals from a mixed solution at 6% HCl is shown in Figure 5.1.7.2. Only the lower section of the graph is shown as base metals are not adsorbed by IRA900. The uptake is adequately predicted by the model.



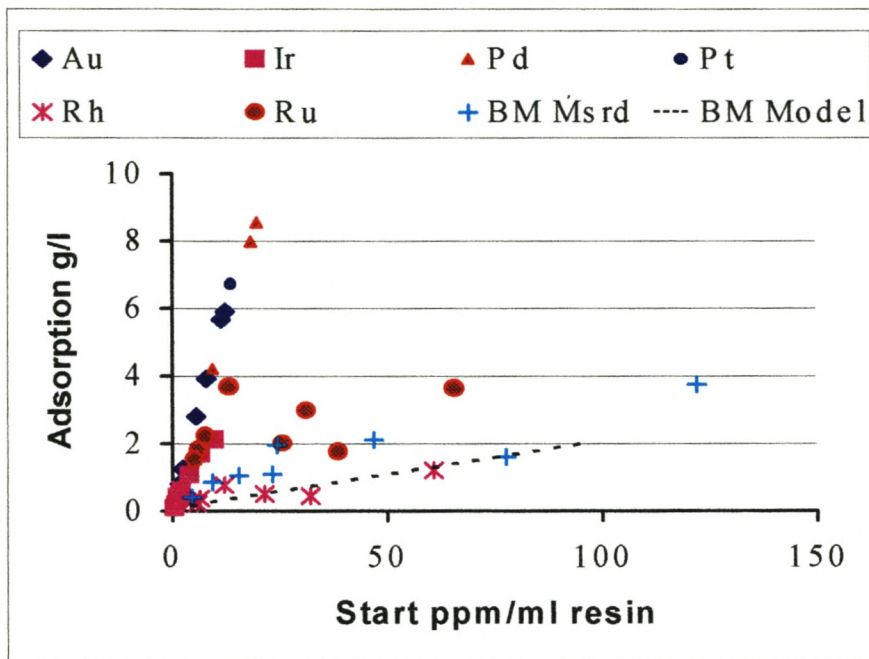


Figure 5.1.7.2: BM Adsorption predicted from mixed solution at 6% HCl on IRA900

## 5.2 ADSORPTION BY XAD7 RESIN

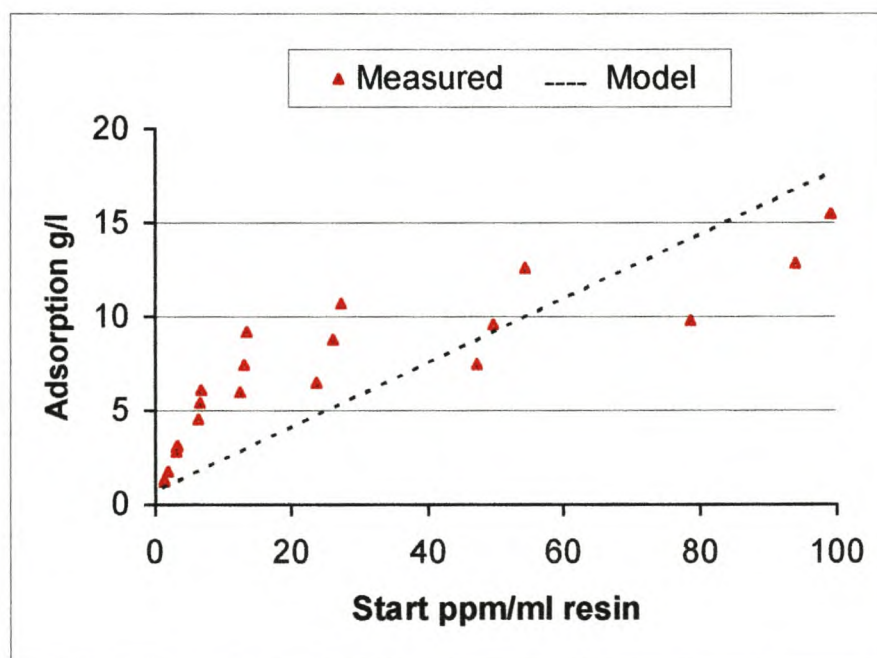
### 5.2.1 Gold

The resin is very selective towards gold.

**Table 5.2.1: Regression model for adsorption of gold on XAD7 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.810							
Model							
(Constant)	.653		.000	.424	.882	1	1.000
AU	.172	1.205	.000	.159	.185	2	1.339
AUPT	3.559E-04	.074	.026	.000	.001	3	1.489
AURU	-5.626E-04	-.610	.000	-.001	.000	4	2.621

It is clear from Table 5.2.1 that the initial gold solution concentration is a significant input variable. There is also some interaction between the gold and ruthenium which tends to decrease the adsorption of gold. With the small Beta value assigned by the model, the significance of the platinum interaction with gold is small. The initial gold and ruthenium concentrations predict 81% of the uptake of gold.



**Figure 5.2.1.1: Au Adsorption predicted on XAD7**



The prediction of gold uptake from a single metal solution can be seen in Figure 5.2.1.1. The prediction of gold from a mixed solution containing ruthenium and gold is graphically depicted in Figure 5.2.1.2.

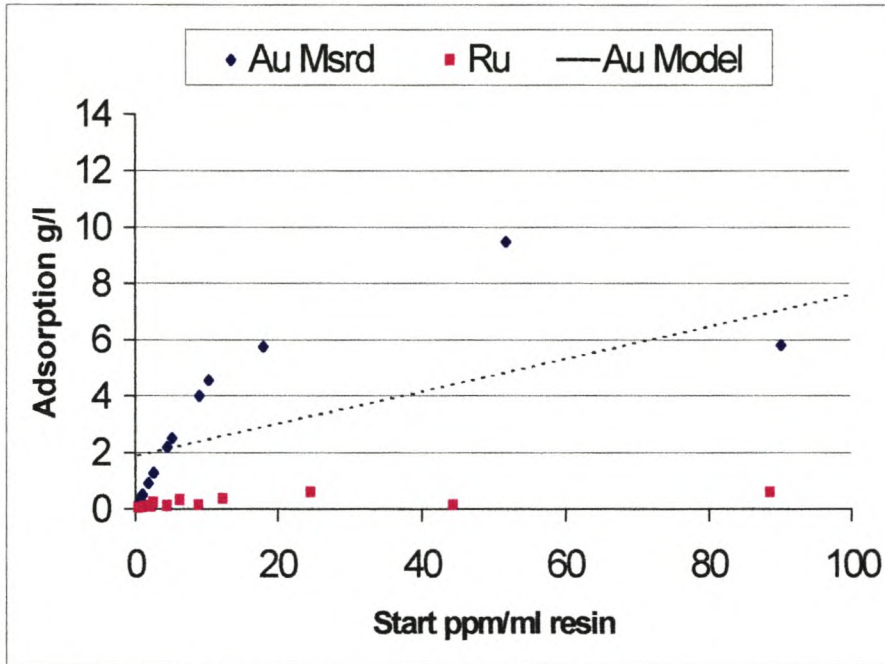


Figure 5.2.1.2: Au Adsorption predicted from mixed solution on XAD7

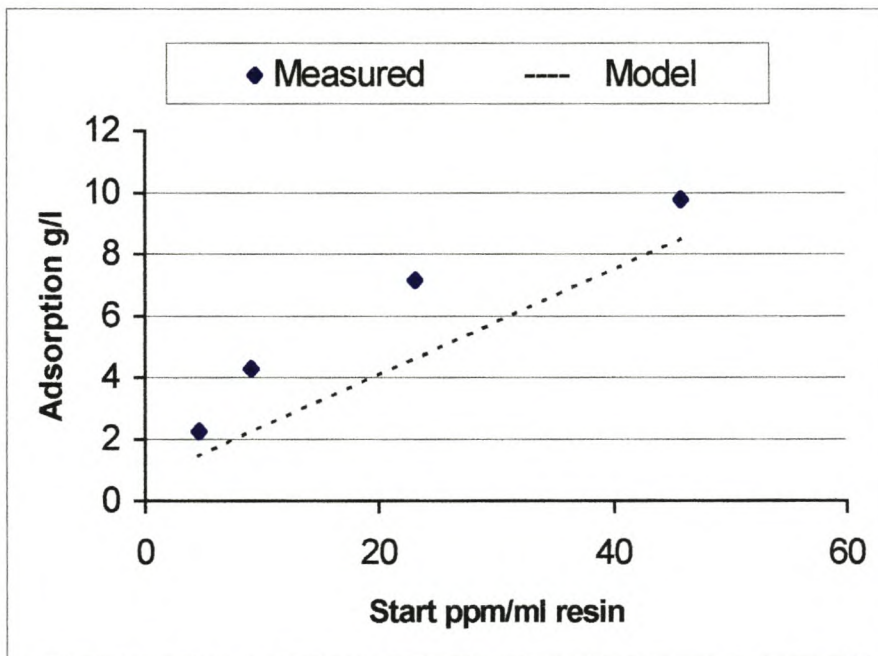
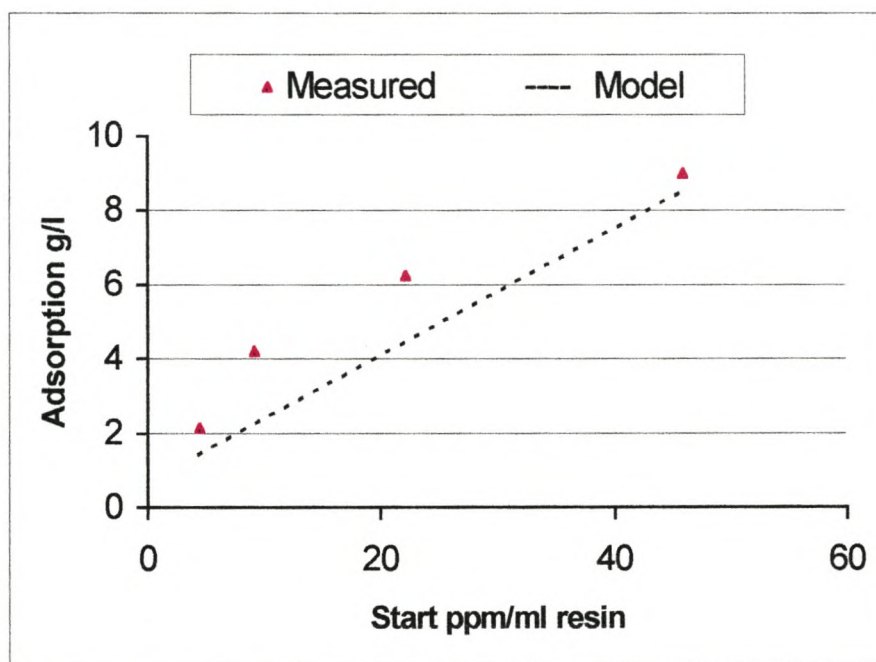


Figure 5.2.1.3: Au Adsorption predicted at 10.8% HCl on XAD7

The free acid HCl concentration has no effect on the quantity of gold adsorbed in the range 10.8 – 17.2% tested (see Figure 4.4.2.1). The acid concentration is also not a significant factor in the model for gold adsorption (Table 5.2.1). The prediction of the adsorption of gold at acidities of 10.8% and 17.2% is depicted in Figures 5.2.1.3 and Figure 5.2.1.4. As the solution acidity is not a variable in the model, the predicted gold uptake at both acidities is the same.



**Figure 5.2.1.4: Au Adsorption predicted from at 17.2% HCl on XAD7**

The predicted adsorption of gold from the mixed gold and ruthenium solution at different acidities can be seen in Figures 5.2.1.5 and 5.2.1.6.



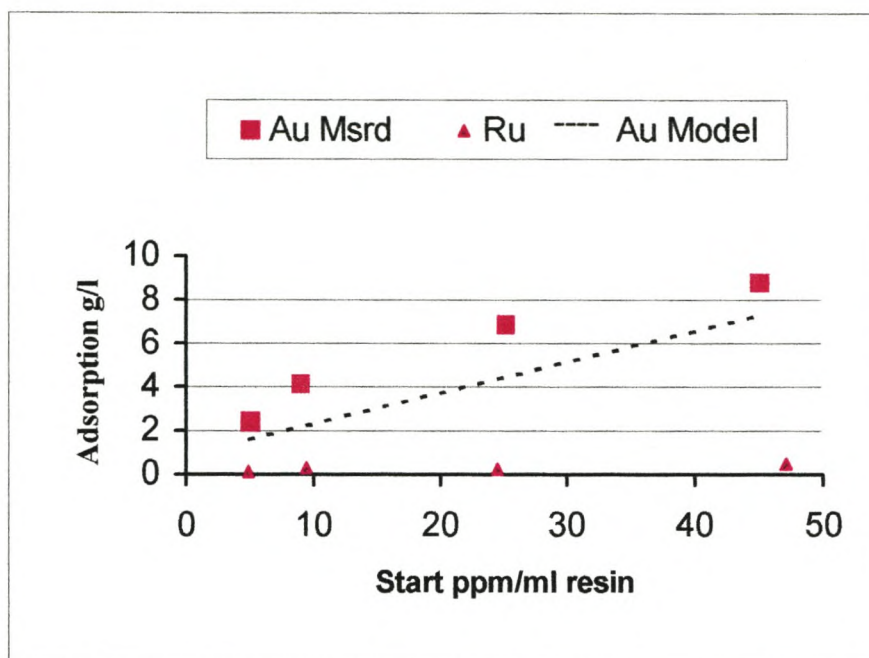


Figure 5.2.1.5: Au Adsorption predicted from mixed solution at 10.8% HCl on XAD7

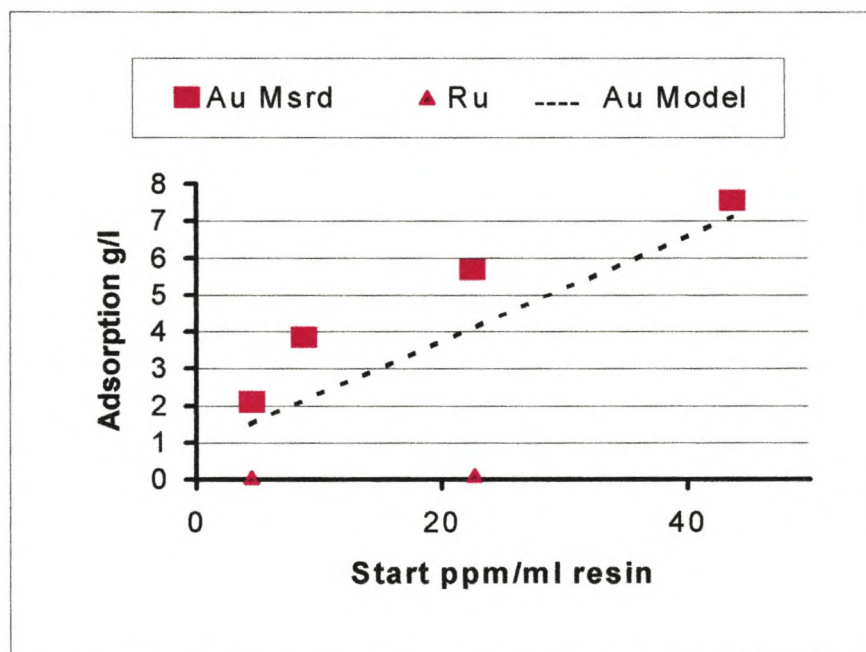


Figure 5.2.1.6: Au Adsorption predicted from mixed solution at 17.2% HCl on XAD7

The adsorption of gold from the mixed solution is not affected by the acid concentration and is adequately predicted by the model.

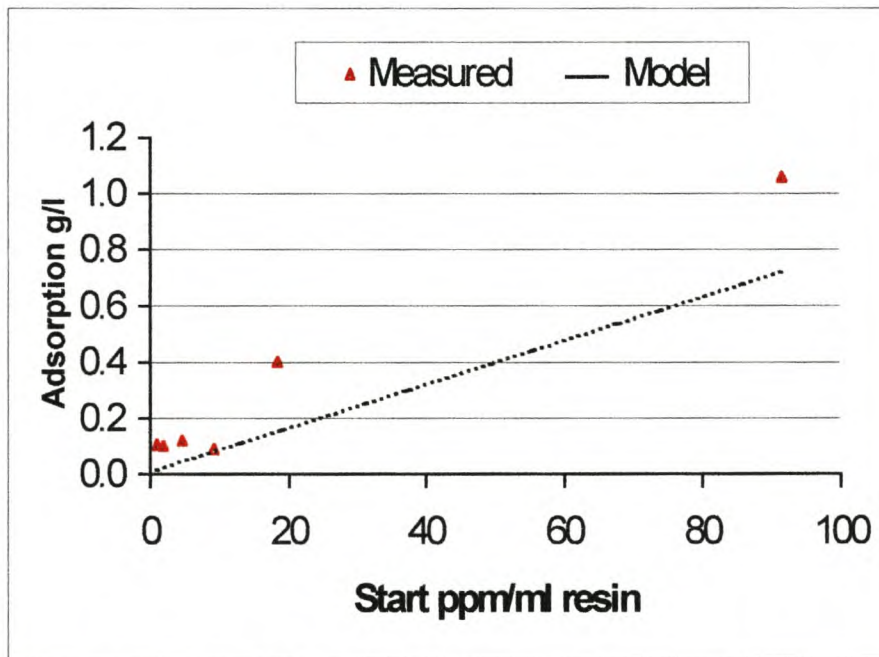
### 5.2.2 Iridium

The model for the adsorption of iridium by XAD7 can be seen in Table 5.2.2.

**Table 5.2.2: Regression model for adsorption of iridium on XAD7 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.883							
Model							
(Constant)	7.806E-03		.491	-.015	.030	1	1.000
IR	3.394E-02	1.770	.000	.025	.043	2	1.745
ACIR	-1.869E-03	-1.351	.000	-.002	-.001	3	3.367
IRBM	-1.599E-04	-1.220	.000	.000	.000	4	21.924

It is evident from the table that the presence of chloride and base metals in the solution with the iridium is significant, reducing the uptake of iridium. The graphical prediction of iridium uptake by the resin can be seen in Figure 5.2.2.1.



**Figure 5.2.2.1: Ir Adsorption predicted on XAD7**

The uptake of iridium is very small as measured and predicted. The acidity of the solution is not a significant input variable to the model, and does not affect the adsorption of iridium. The uptake of iridium from the mixed solutions tested is almost zero, and does not justify graphical display of the predicted uptake values.



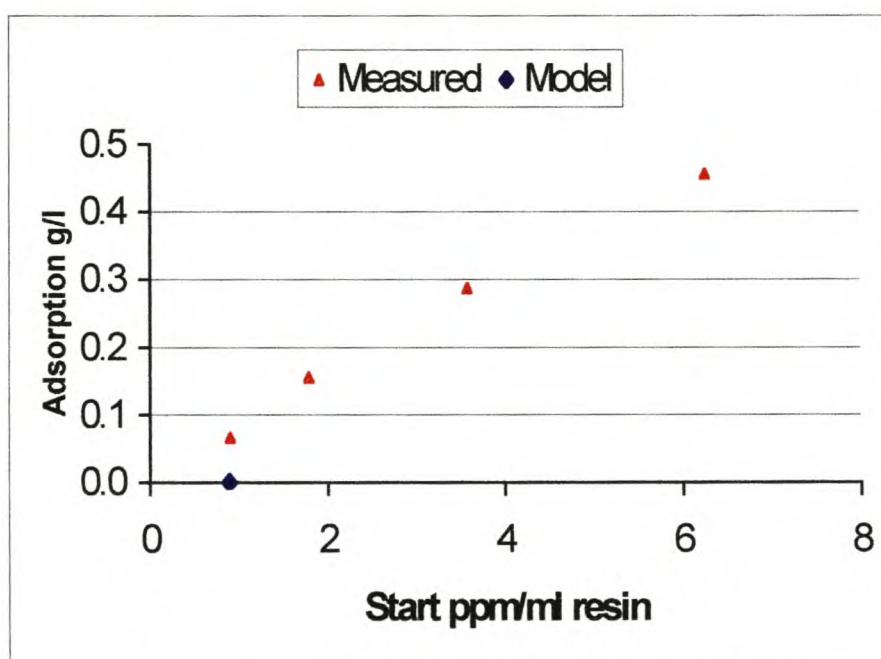
### 5.2.3 Palladium

The uptake of palladium by XAD7 is negligible (see Figure 4.1.3.2). The model parameters for the uptake of palladium by XAD7 is shown in Table 5.2.3. The uptake of palladium is small. The model fit indicates R Square is 0.61, showing that 61% of the uptake of palladium is explained by the input variables of the model.

**Table 5.2.3: Regression model for adsorption of palladium on XAD7 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.608							
Model							
(Constant)	8.8E-03		.668	-.032	.049	1	1.000
BMO	2.572E-02	1.416	.000	.020	.032	2	2.035
PD	6.848E-02	6.458	.000	.056	.081	3	5.435
ACPD	-5.6E-03	-7.318	.000	-.006	-.005	4	8.927
PDBM	-4.750E-05	-.746	.000	.000	.000	5	34.904

The base metal solution also contains palladium, hence the contribution to the increased uptake of palladium. The interaction between the chloride ions and palladium is significant in the reduction of palladium uptake by the resin. The model prediction of palladium adsorption from a single PGM solution can be seen in Figure 5.2.3.1. The measured values are very small (less than 1 g/l) and can be neglected.



**Figure 5.2.3.1: Pd Adsorption predicted on XAD7**

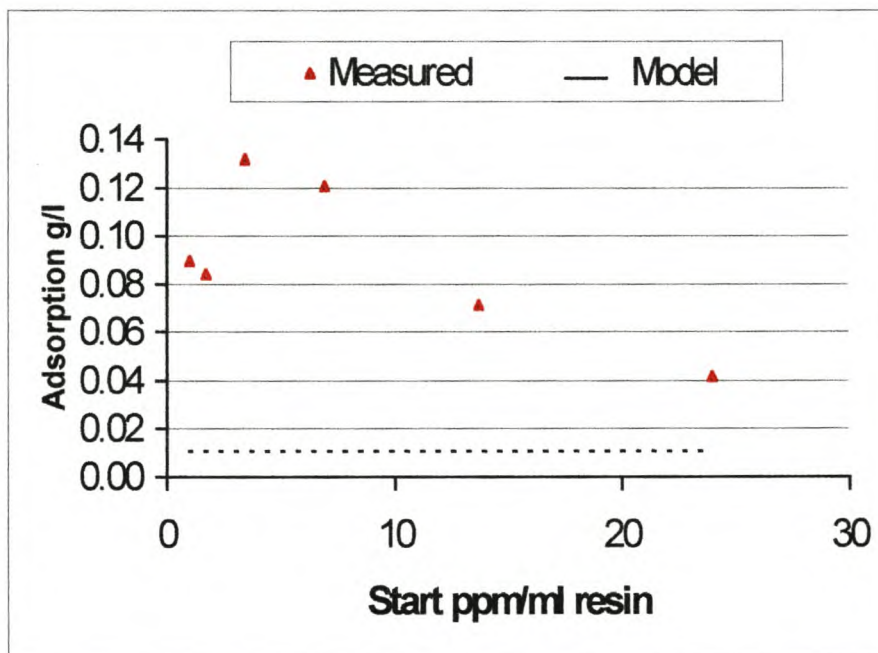
### 5.2.4 Platinum

The platinum complex is not adsorbed by XAD7. The model for platinum uptake can be seen in Table 5.2.4.

**Table 5.2.4: Regression model for adsorption of platinum on XAD7 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.800							
<b>Model</b>							
(Constant)	1.065E-02		.654	-.036	.057	1	1.000
BMO	2.709E-02	.900	.000	.023	.031	2	1.713
PTRH	-2.974E-04	-3.951	.000	.000	.000	3	3.895
IRPT	1.977E-04	2.427	.000	.000	.000	4	32.511

It follows, as is evident in the table, that the presence of base metals in the solution is significant. Although only a very small uptake of platinum was measured, a good fit was achieved, as indicated by a R Square value of 80%. The predicted adsorption of platinum from a single metal solution can be seen in Figure 5.2.4.1.



**Figure 5.2.4.1: Pt Adsorption predicted on XAD7**

The uptake of platinum by XAD7 is insignificant and no further graphical uptake curves will be shown.



### 5.2.5 Rhodium

Rhodium uptake by XAD7 is very small (see Figure 4.1.5.2). The model parameters for the predicted uptake of rhodium by XAD7 can be seen in Table 5.2.5.

**Table 5.2.5: Regression model for adsorption of rhodium on XAD7 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.677							
Model	B	Beta	Sig.	Lower Bound	Upper Bound	Dimension	Index
(Constant)	-2.249E-03		.796	-.019	.015	1	1.000
RH	6.206E-02	6.945	.000	.054	.070	2	1.761
ACRH	-4.176E-03	-6.530	.000	-.005	-.004	3	4.273
PDRH	-2.587E-05	-.861	.000	.000	.000	4	25.862

It is evident from the R square value that only 68% of the adsorption of rhodium is explained by the input variables. The uptake of rhodium is so small that the absolute values of the predicted uptake are meaningless, except for the fact that the uptake is small. The predicted uptake of rhodium by the resin from a single metal solution, as well as mixed solution, is very close to zero.

### 5.2.6 Ruthenium

The predicted adsorption can be seen in Table 5.2.6.

**Table 5.2.6: Regression model for adsorption of ruthenium on XAD7 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.662							
Model	B	Beta	Sig.	Lower Bound	Upper Bound	Dimension	Index
(Constant)	2.309E-02		.376	-.028	.074	1	1.000
RU	5.319E-02	3.108	.000	.038	.069	2	1.809
ACRU	-3.521E-03	-2.796	.000	-.005	-.002	3	1.844
AURU	6.065E-05	.399	.000	.000	.000	4	4.835
RUBM	2.445E-05	.163	.027	.000	.000	5	27.006

It is evident from Figure 5.2.6.1 that ruthenium is not adsorbed by the resin. The predicted ruthenium uptake from a single metal solution is graphically displayed in Figure 5.2.6.1. The model underpredicts the uptake from a single component solution. The uptake of ruthenium is very small and does not justify further graphical visualisation.

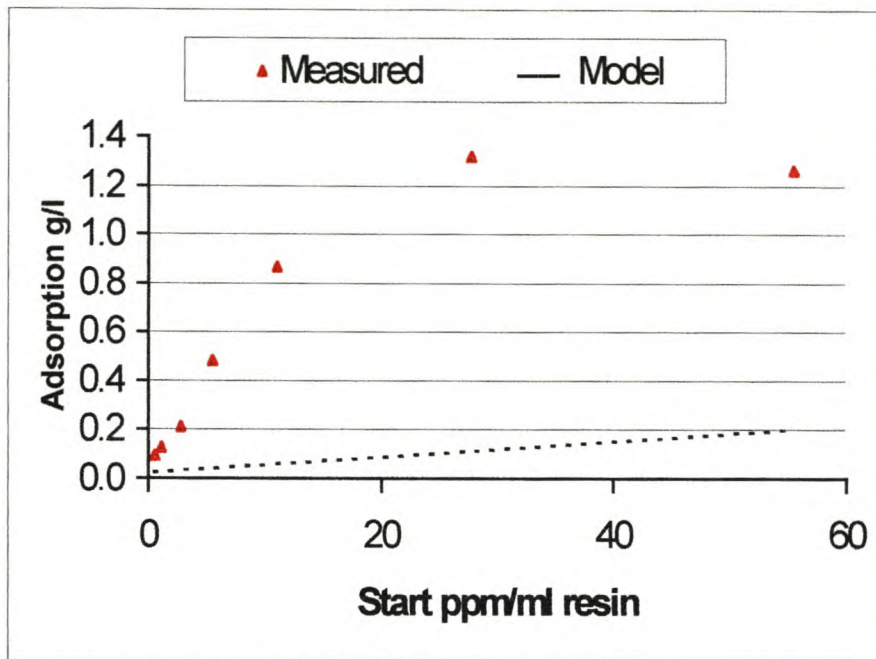


Figure 5.2.6.1: Ru Adsorption predicted on XAD7

### 5.2.7 Base Metals

The base metals are not adsorbed by the resin. The uptake that does occur is predicted by the model as detailed in Table 5.2.7.

Table 5.2.7: Regression model for adsorption of base metals on XAD7 resin

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.824							
Model							
(Constant)	3.330E-02		.026	.004	.062	1	1.000
PDBM	-6.601E-04	-9.059	.000	-.001	-.001	2	1.454
PTBM	4.379E-04	8.523	.000	.000	.000	3	24.438

It is evident from the model that the presence of palladium and platinum in the solution affects the uptake of base metals. Figure 5.2.7.1 shows that the predicted small uptake of base metals fit the measured uptake well. As the base metals are not adsorbed by the resin, no further graphs will be shown to illustrate the fit of the model.



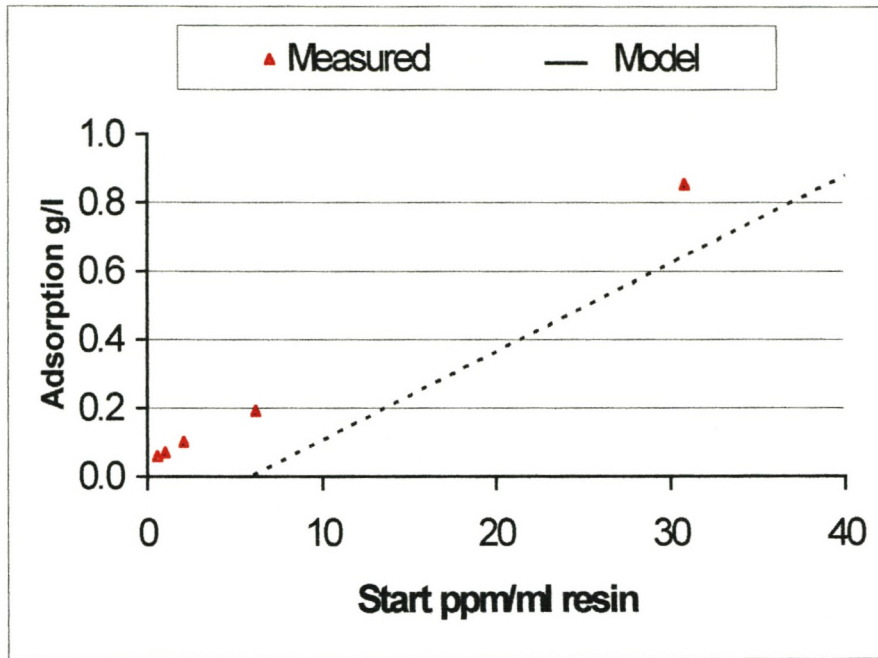


Figure 5.2.7.1: BM Adsorption predicted on XAD7

### 5.3 ADSORPTION BY IR200 RESIN

As there is very little adsorption of PGM by the resin, only limited graphical display of the modelled uptake by the resin is included.

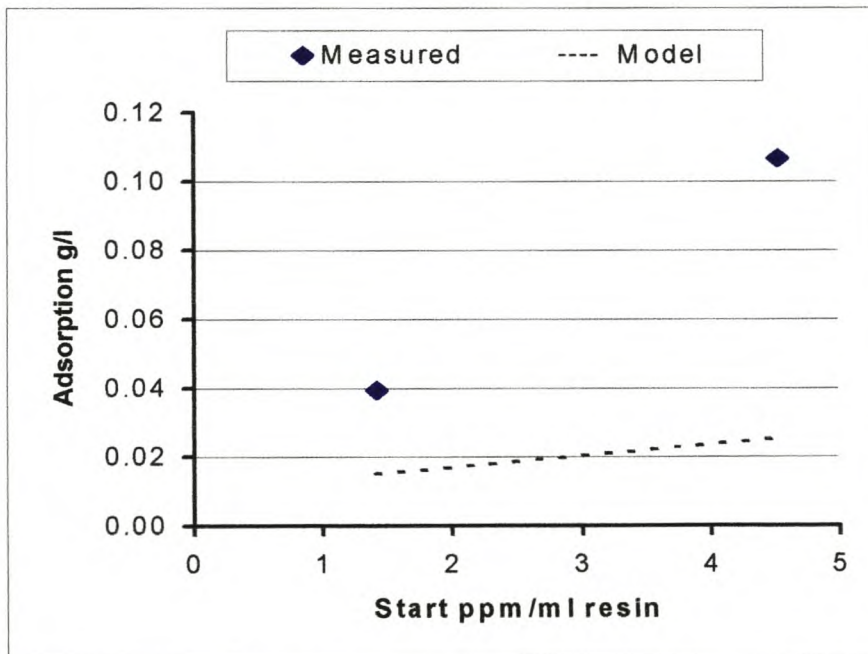
#### 5.3.1 Gold

The uptake of gold is very small (see Figure 5.3.1). The model parameters are given in Table 5.3.1.

**Table 5.3.1: Regression model for adsorption of gold on IR200 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.870							
Model							
(Constant)	1.016E-02		.158	-.004	.024	1	1.000
AU	5.524E-03	.306	.000	.003	.008	2	1.706
ACAU	-1.084E-03	-.252	.000	-.002	-.001	3	2.407
AURH	2.407E-04	.795	.000	.000	.000	4	6.412

It is evident from the table that the co-presence of chloride and rhodium ions in the solution decrease and increase the uptake of gold by the resin, respectively. The uptake is negligible.



**Figure 5.3.1: Au Adsorption predicted on IR200**



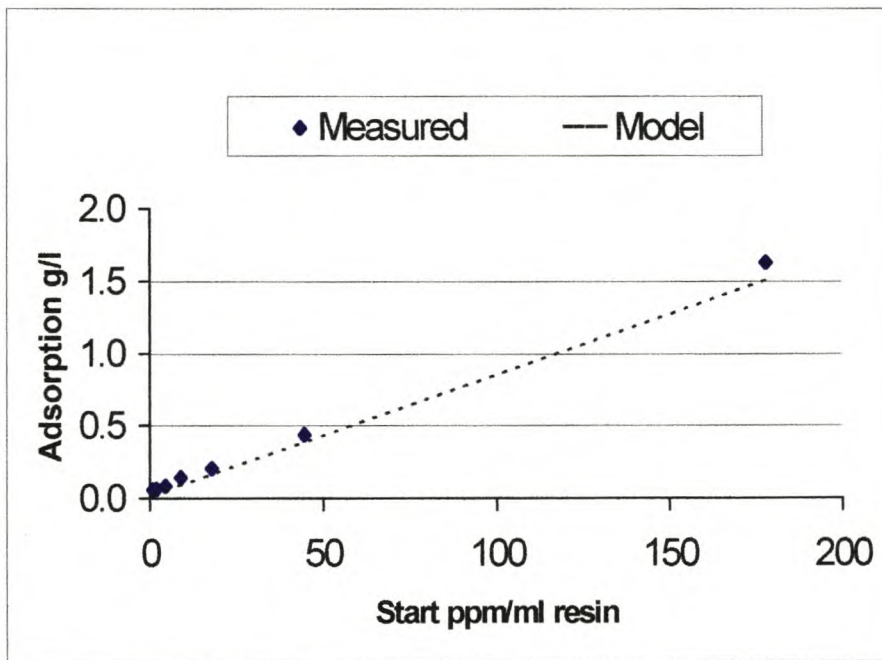
### 5.3.2 Iridium

Iridium is not adsorbed by the resin (see Figure 5.3.2). The modelled uptake parameters are shown in Table 5.3.2.

**Table 5.3.2: Regression model for adsorption of iridium on IR200 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.555							
Model							
(Constant)	1.328E-02		.567	-.032	.059	1	1.000
IR	1.221E-02	.775	.000	.009	.015	2	1.888
ACIR	-2.113E-03	-.443	.000	-.003	-.001	3	2.197
AUIR	1.440E-04	.265	.000	.000	.000	4	2.489
IRPD	-3.759E-05	-.266	.000	.000	.000	5	3.072
IRRU	8.306E-05	.313	.000	.000	.000	6	5.133

It is evident from the table that there is a lot of interaction between the iridium complex ion and the other ions in the solution, which ultimately determine the uptake of iridium by the resin.



**Figure 5.3.2: Ir Adsorption predicted on IR200**

The uptake of iridium is well predicted by the model. The very low uptake of iridium by the resin does not justify further graphical visualisation of predicted uptake.

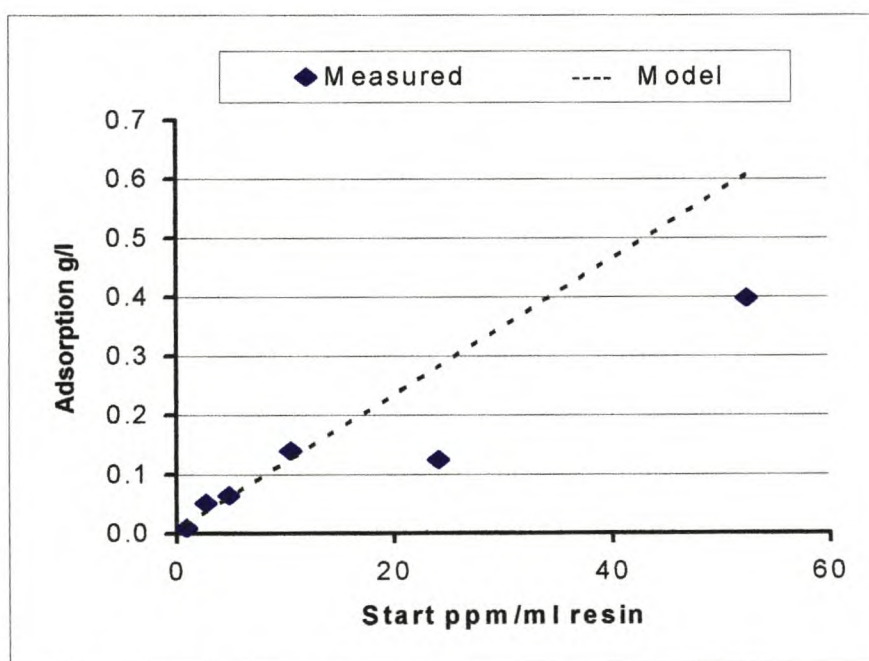
### 5.3.3 Palladium

The uptake of palladium by IR200 is negligible. The model parameters for the uptake of palladium by IR200 are shown in Table 5.3.3.

**Table 5.3.3: Regression model for adsorption of palladium on IR200 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.833							
Model							
(Constant)	9.169E-03		.717	-.041	.059	1	1.000
PD	1.739E-02	.685	.000	.013	.022	2	1.920
ACPD	-3.193E-03	-.384	.000	-.004	-.002	3	2.958
PDRH	-6.275E-04	-1.072	.003	-.001	.000	4	6.345
PDRU	7.443E-04	1.562	.000	.000	.001	5	31.893

It is clear from the model that a lot of interaction between the ions in the solution affects the uptake of palladium. However, as the uptake is very small, there is no adsorption of palladium by IR200. The predicted uptake of palladium from the single metal palladium solution is shown in Figure 5.3.3.



**Figure 5.3.3: Pd Adsorption predicted on IR200**

As the uptake of palladium is negligible from mixed solutions, no further graphical presentation is justified.



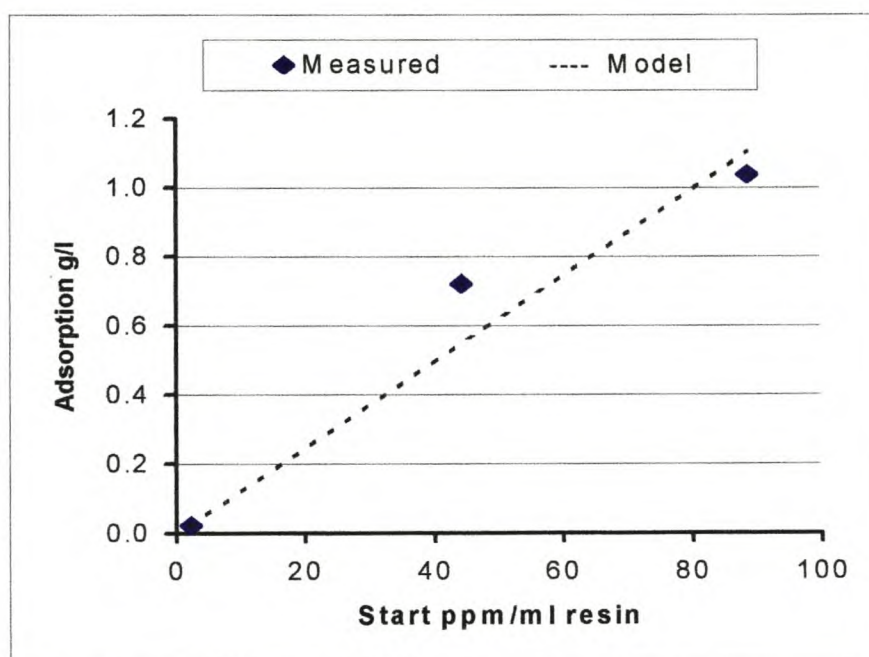
### 5.3.4 Platinum

The platinum complex is not adsorbed by IR200. The model for platinum uptake by the resin can be seen in Table 5.3.4.

**Table 5.3.4: Regression model for adsorption of platinum on IR200 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.813							
<b>Model</b>							
(Constant)	-8.240E-03		.907	-.147	.130	1	1.000
PT	1.261E-02	.315	.000	.007	.019	2	2.148
IRPT	-5.840E-04	-1.477	.000	-.001	.000	3	4.163
PDPT	-3.022E-04	-1.116	.001	.000	.000	4	4.703
PTBM	2.071E-04	.641	.045	.000	.000	5	11.449
PTRU	7.189E-04	.984	.000	.001	.001	6	29.885

It follows, as seen in the table, that the presence of other metal complexes in the solution played a significant part in determining the uptake of platinum. Although only a very small uptake of platinum was measured, a good fit was achieved, as indicated by a R Square value of 81%. The predicted adsorption of platinum from a single metal solution can be seen in Figure 5.3.4.



**Figure 5.3.4: Pt Adsorption predicted on IR200**

The uptake of platinum by IR200 is insignificant and no further graphical uptake curves will be shown.

### 5.3.5 Rhodium

Rhodium uptake by IR200 is very small (see Figure 4.1.5.2). The model parameters for the predicted uptake of rhodium by IR200 can be seen in Table 5.3.5.

**Table 5.3.5: Regression model for adsorption of rhodium on IR200 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.692							
Model							
(Constant)	4.807E-03		.640	-.015	.025	1	1.000
RH	1.459E-02	1.028	.000	.011	.018	2	1.819
ACRH	-3.040E-03	-.777	.000	-.004	-.002	3	2.232
PDRH	1.333E-04	.720	.000	.000	.000	4	3.517
PTRH	-3.917E-05	-.379	.000	.000	.000	5	7.090

It is evident from the R square value that 69% of the adsorption of rhodium is explained by the input parameters. The presence of chloride, palladium and platinum affects the uptake of rhodium. As the uptake is so small, the absolute values of the predicted uptake are meaningless, except the fact that the uptake is small. The predicted uptake of rhodium by the resin from a single metal solution, as well as mixed solution, is very close to zero.

### 5.3.6 Ruthenium

The predicted adsorption can be seen in Table 5.3.6.

**Table 5.3.6: Regression model for adsorption of ruthenium on IR200 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.746							
Model							
(Constant)	7.186E-03		.443	-.011	.026	1	1.000
RH	-4.580E-03	-.355	.000	-.007	-.003	2	1.902
RU	1.337E-02	1.167	.000	.011	.016	3	2.235
ACRU	-1.305E-03	-.421	.000	-.002	-.001	4	2.924
IRRU	-2.199E-04	-1.714	.000	.000	.000	5	5.227
PDRU	3.841E-05	.280	.032	.000	.000	6	7.048
RHRU	2.149E-04	1.260	.000	.000	.000	7	8.119
RUBM	1.076E-04	.601	.001	.000	.000	8	22.903

It is evident from Figure 5.3.6 that ruthenium is not adsorbed by the resin. The uptake found is adversely affected by the co-presence of rhodium. Other PGM's in the solution determine the uptake of ruthenium, especially so for iridium and rhodium.



The predicted ruthenium uptake from a single metal solution is graphically displayed in Figure 5.3.6. The model underpredicts the uptake from a single component solution. The uptake of ruthenium is very small and does not justify further graphical visualisation.

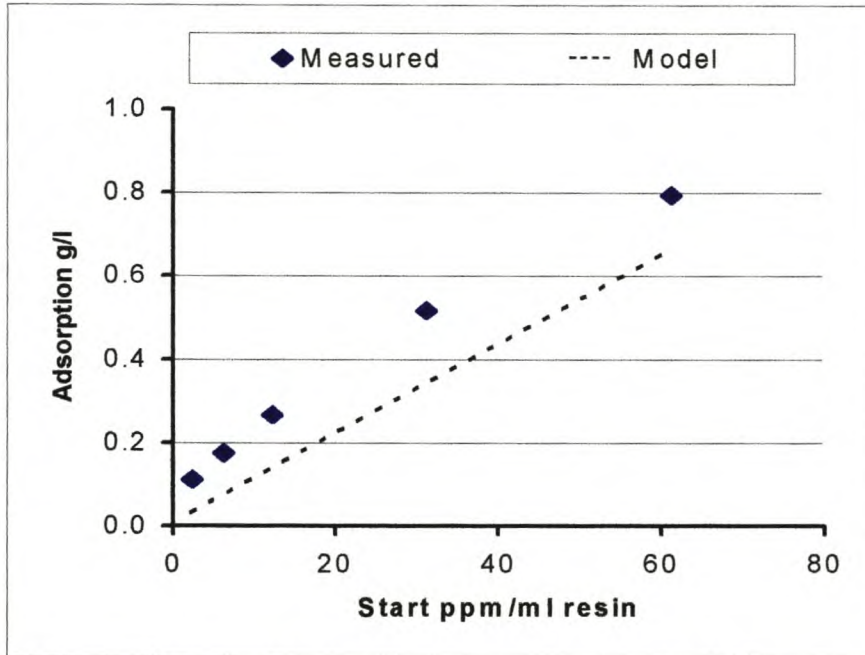


Figure 5.3.6: Ru Adsorption predicted on IR200

### 5.3.7 Base Metals

The base metals are adsorbed from the solution containing PGM's by the resin. The model for the adsorption of base metals are as detailed in Table 5.3.7.

Table 5.3.7: Regression model for adsorption of base metals on IR200 resin

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.965							
Model							
(Constant)	7.705E-02		.069	-.006	.160	1	1.000
BMO	.230	1.869	.000	.216	.243	2	1.792
ACBM	-2.598E-02	-.591	.000	-.028	-.024	3	3.137
AUBM	-7.571E-03	-.482	.000	-.009	-.006	4	8.647

It is evident from the model that the presence of chloride and gold in the solution (apart from the base metals itself) affects the adsorption of base metals. Figure 5.3.7.1 shows that the predicted adsorption of base metals is very close to that measured from a base metals solution.

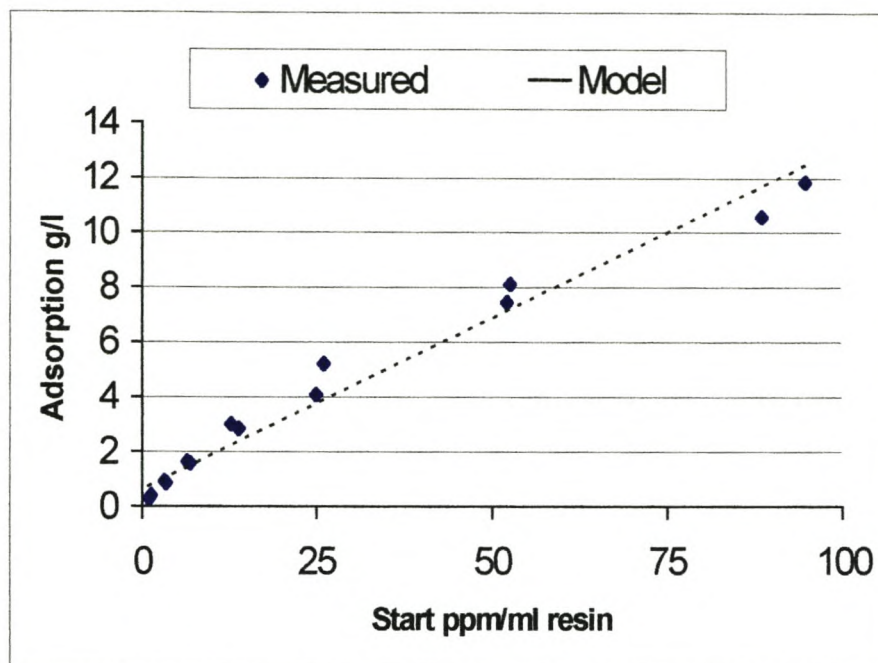


Figure 5.3.7.1: BM Adsorption predicted on IR200

The predicted adsorption from a mixed solution containing additional iridium can be seen in Figure 5.3.7.2.

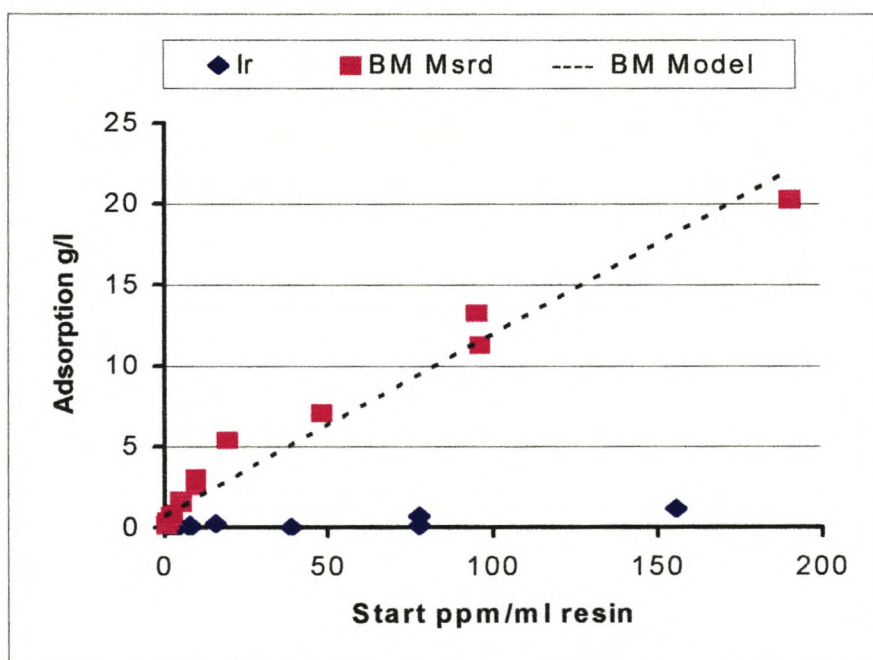


Figure 5.3.7.2: BM Adsorption predicted from mixed solution on IR200



## 5.4 ADSORPTION BY A22 RESIN

### 5.4.1 Gold

Gold is adsorbed well by the resin.

**Table 5.4.1: Regression model for adsorption of gold on A22 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.815							
Model							
(Constant)	.312		.000	.140	.484	1	1.000
AU	.253	1.979	.000	.237	.269	2	1.663
PD	-2.808E-02	-.409	.000	-.033	-.023	3	2.318
AUBM	3.786E-03	4.345	.000	.003	.004	4	4.239
AUIR	-5.381E-03	-5.802	.000	-.006	-.005	5	33.074

Is clear from Table 5.4.1 that the initial gold solution concentration is a significant input variable. The interaction parameter of gold and base metals is the most significant parameter in determining the amount of gold adsorbed. The interaction with the iridium ion reduces the adsorption of gold, possibly by reduction in the accessibility to the resin. Palladium is in competition with the gold for adsorption sites on the resin, and therefore increased concentrations tend to reduce the adsorption of gold.

The predicted adsorption from a single metal gold solution by the model can be seen in Figure 5.4.1.1. The fit obtained for gold adsorption from a single metal solution at a different solution acidity can be seen in Figure 5.4.1.2. The solution acidity is not a significant parameter in the range of acidities tested and the predicted adsorption curves are therefore the same.

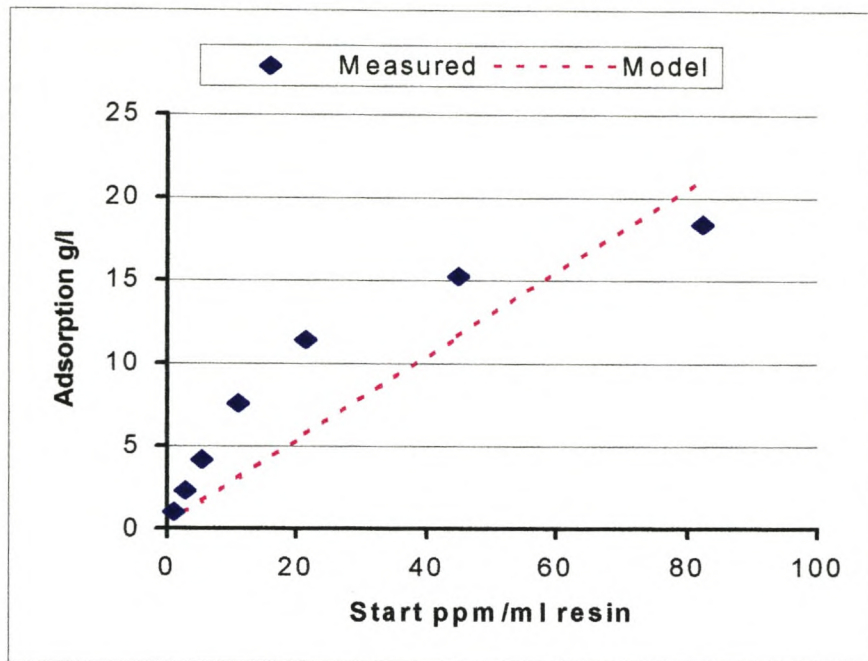


Figure 5.4.1.1: Au Adsorption predicted on A22

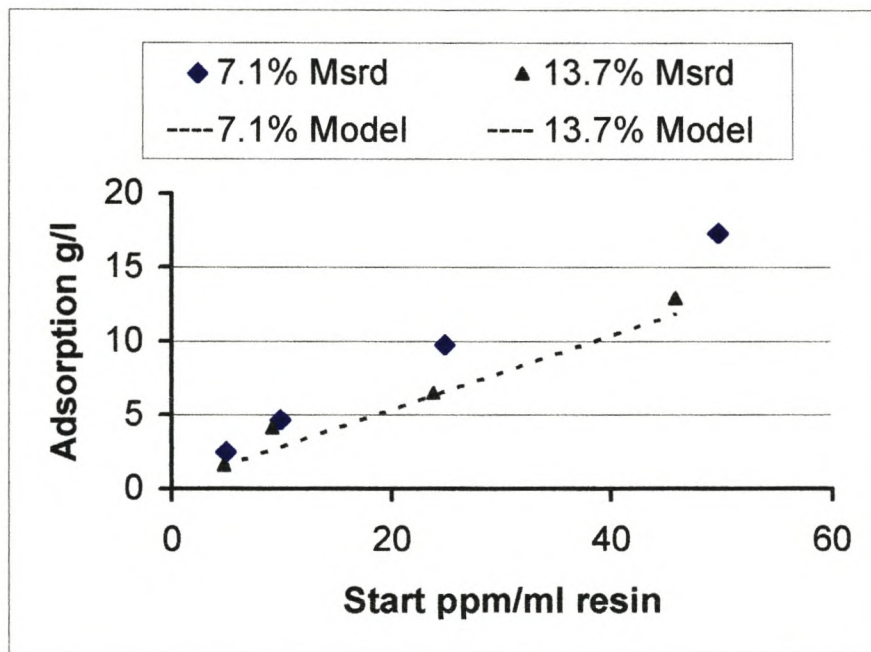


Figure 5.4.1.2: Au Adsorption predicted from gold solution at different acidities on A22



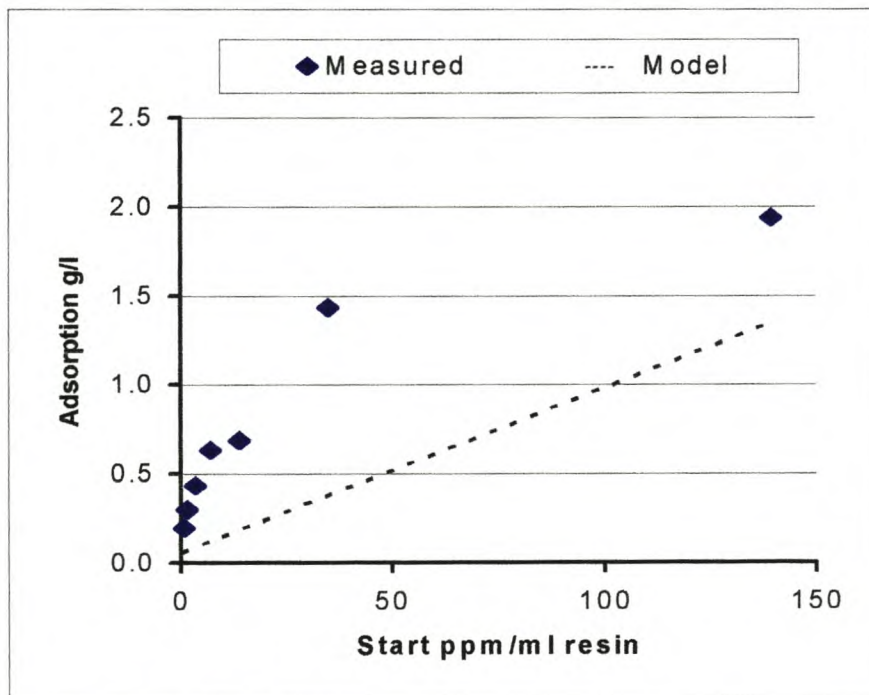
### 5.4.2 Iridium

The resin does not adsorb iridium. The model for the uptake of iridium by A22 can be seen in Table 5.4.2. The given parameters determine 47% of the uptake of iridium by the resin.

**Table 5.4.2: Regression model for adsorption of iridium on A22 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.468							
Model							
(Constant)	5.172E-02		.001	.020	.083	1	1.000
AU	-9.992E-03	-.689	.000	-.012	-.008	2	1.778
IR	2.681E-02	1.994	.000	.018	.036	3	2.203
ACIR	-1.589E-03	-1.288	.000	-.002	-.001	4	16.896

It is evident from the table that the amount of gold and chloride in the solution reduces the uptake of iridium. As gold is adsorbed by the resin, the diffusion of iridium into the resin will be reduced to the extent of gold adsorbed. A large iridium concentration will lead to a high equilibrium concentration of iridium diffused into the resin.



**Figure 5.4.2.1: Ir Adsorption predicted on A22**

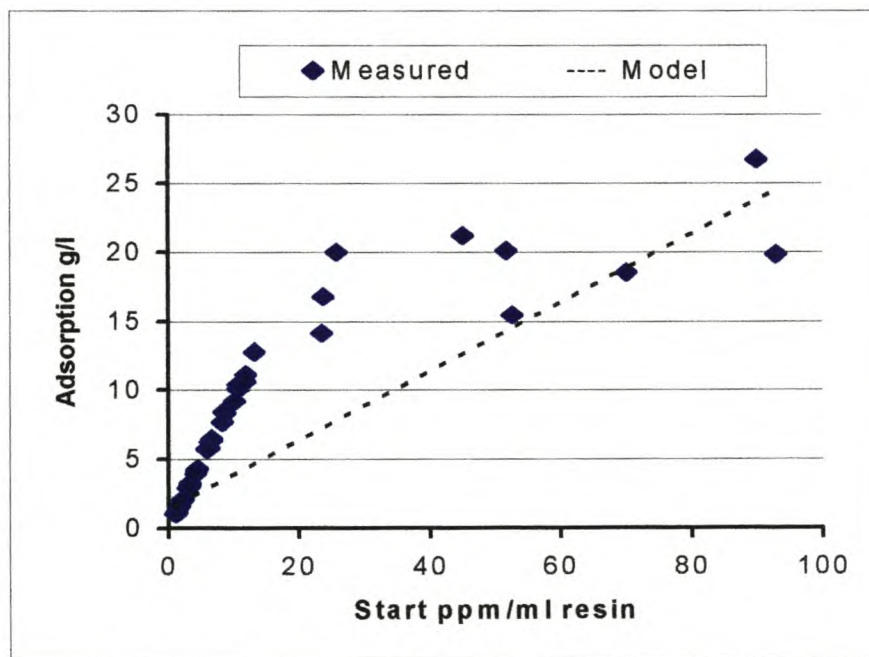
### 5.4.3 Palladium

The resin is used to selectively adsorb palladium. The model results of the adsorption of palladium can be seen in Table 5.4.3.

**Table 5.4.3: Regression model for adsorption of palladium on A22 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.791							
Model							
(Constant)	1.364		.000	.947	1.781	1	1.000
PD	.250	1.651	.000	.230	.270	2	1.829
IRPD	-4.020E-03	-1.776	.000	-.006	-.002	3	2.573
PDPT	-6.975E-04	-1.608	.000	-.001	-.001	4	6.469
PDRH	4.130E-03	2.405	.000	.003	.006	5	38.814

It is evident from Table 5.4.3 that the presence of iridium and platinum complex ions in the solution reduce the adsorption of palladium. The co-presence of rhodium, however, increases the adsorption. The mechanism by which the interaction affects the adsorption will require further study



**Figure 5.4.3.1: Pd Adsorption predicted on A22**

The acidity of the solution does not effect the equilibrium adsorption in the range of acidities tested (see Figure 5.4.3.2). The predicted adsorption of palladium from a mixed solution can be seen in Figure 5.4.3.3.



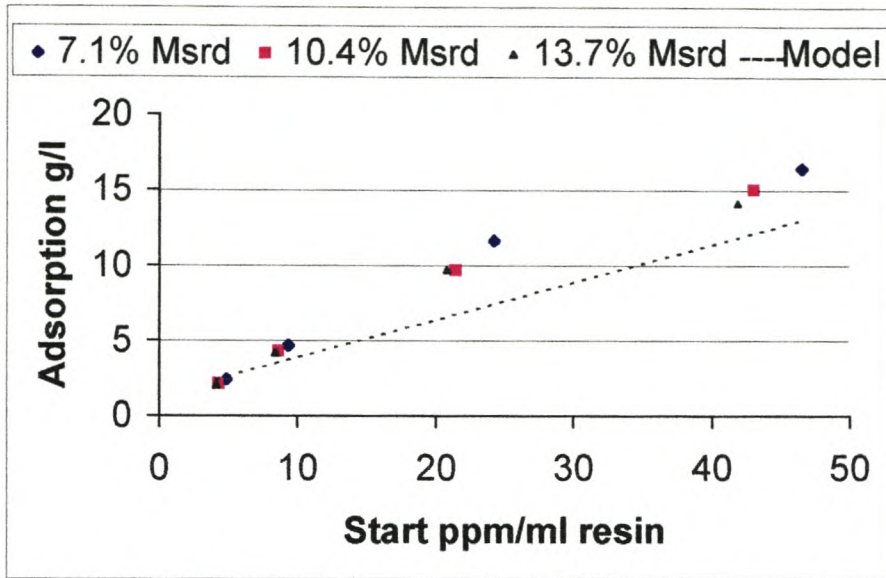


Figure 5.4.3.2: Pd Adsorption predicted with different solution acidity on A22

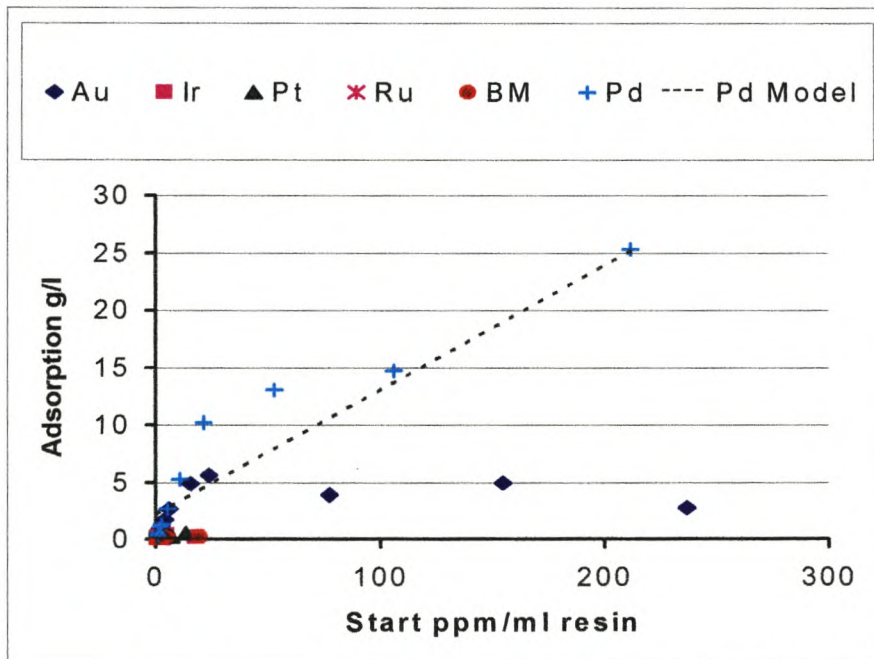


Figure 5.4.3.3: Pd Adsorption predicted from mixed solution on A22

The predicted adsorption of palladium from a base metal solution is also shown (Figure 5.4.3.4). The predicted adsorption from a mixed solution at 7.1% HCl and at 13.7% HCl can be seen in Figures 5.4.3.5 and 5.4.3.6.

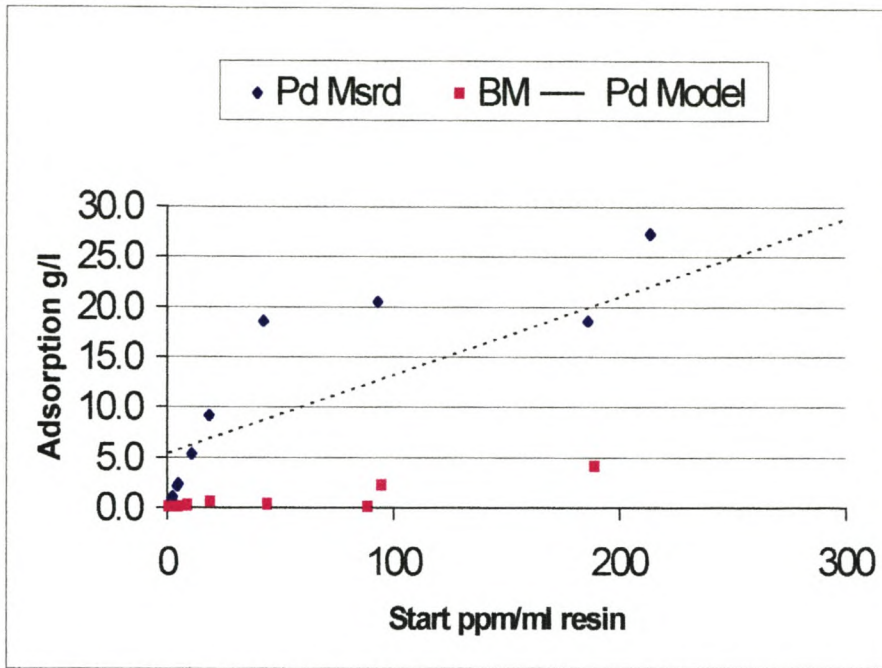


Figure 5.4.3.4: Pd Adsorption predicted from base metal solution on A22

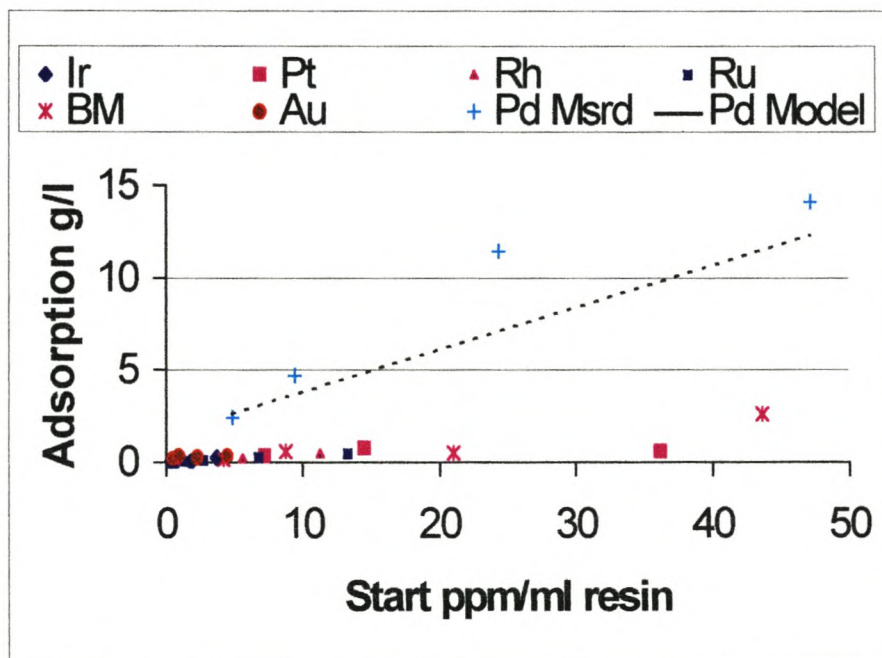


Figure 5.4.3.5: Pd Adsorption predicted from mixed solution at 7.1% HCl on A22



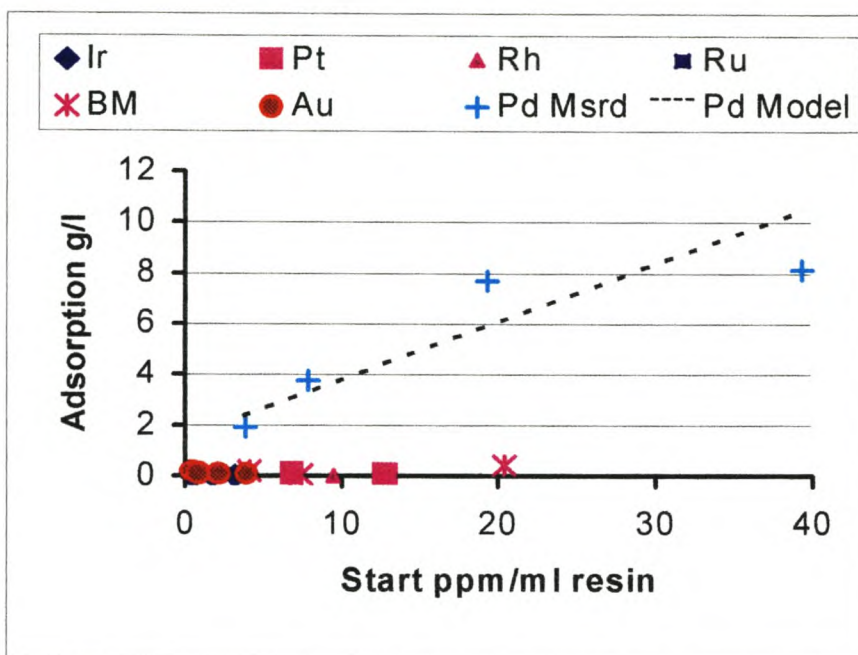


Figure 5.4.3.6: Pd Adsorption predicted from mixed solution at 13.7% HCl on A22

#### 5.4.4 Platinum

The platinum complex is not adsorbed by A22. The model for platinum adsorption can be seen in Table 5.4.4.

Table 5.4.4: Regression model for adsorption of platinum on A22 resin

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.604							
Model							
(Constant)	.313		.000	.174	.452	1	1.000
AU	-6.336E-02	-.825	.000	-.071	-.056	2	1.360
PDPT	8.212E-05	.694	.000	.000	.000	3	1.836

It is evident from the model that the gold complex concentration, which is adsorbed by the resin, reduces the uptake of platinum.

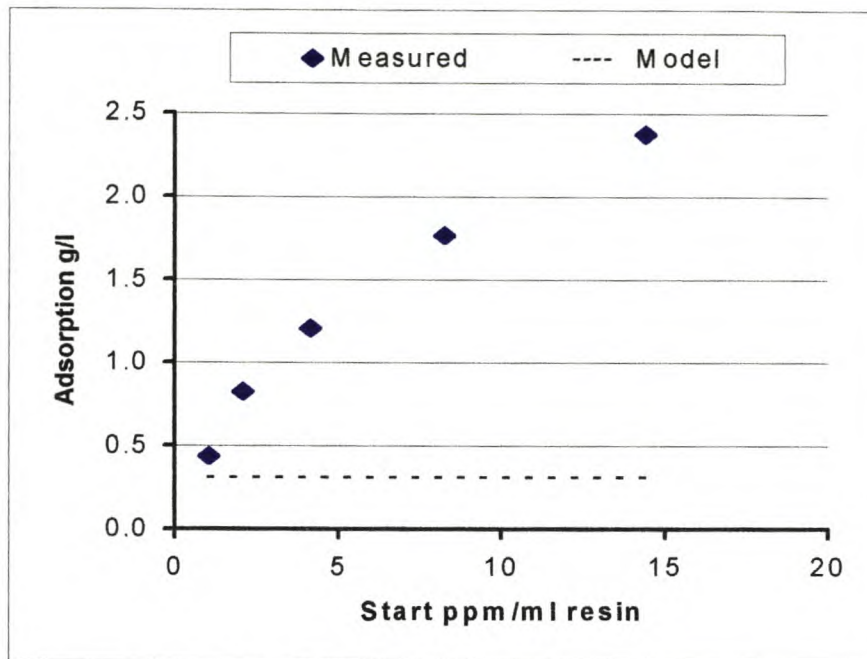


Figure 5.4.4: Pt Adsorption predicted on A22

The uptake of platinum by A22 is insignificant and no further graphical uptake curves will be shown.

#### 5.4.5 Rhodium

Rhodium uptake by A22 is very small (see Figure 4.1.5.4). The model parameters for the predicted uptake of rhodium by A22 can be seen in Table 5.4.5.

Table 5.4.5: Regression model for adsorption of rhodium on A22 resin

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.560							
Model							
(Constant)	9.945E-02		.005	.030	.169	1	1.000
AU	-1.916E-02	-.530	.000	-.025	-.014	2	1.622
IRRH	-8.324E-04	-4.074	.000	-.001	-.001	3	2.248
RHRU	6.635E-04	4.365	.000	.000	.001	4	36.456

It is evident from the R square value that 56% of the uptake of rhodium is explained by the input parameters. The presence of gold, iridium and ruthenium affects the uptake of rhodium. The uptake is so small that the absolute values of the predicted uptake are meaningless, except the fact that the uptake is small. The predicted uptake of rhodium by the resin from a single metal solution, as well as mixed solution, is very close to zero.



### 5.4.6 Ruthenium

The predicted adsorption can be seen in Table 5.4.6.

**Table 5.4.6: Regression model for adsorption of ruthenium on A22 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.494							
<b>Model</b>							
(Constant)	9.250E-02		.016	.018	.167	1	1.000
AU	-2.356E-02	-.648	.000	-.030	-.017	2	1.815
IRRU	-6.576E-04	-3.107	.000	-.001	.000	3	2.259
RHRU	4.699E-04	3.070	.000	.000	.001	4	3.626
PDRU	7.195E-05	.340	.000	.000	.000	5	34.137

Ruthenium is not adsorbed by the resin. The uptake of ruthenium is very small, almost zero, and does not justify graphical visualisation.

### 5.4.7 Base Metals

The model for the adsorption of base metals is as detailed in Table 5.4.7.

**Table 5.4.7: Regression model for adsorption of base metals on A22 resin**

R Square	Unstandardized Coefficients B	Standardized Coefficients Beta	Sig.	95% Confidence interval for B		Collinearity	
				Lower Bound	Upper Bound	Dimension	Index
.590							
<b>Model</b>							
(Constant)	7.587E-02		.029	.008	.144	1	1.000
AU	-2.061E-02	-.604	.000	-.026	-.015	2	1.865
BMO	5.154E-02	1.976	.000	.030	.073	3	2.055
ACBM	-3.274E-03	-1.345	.001	-.005	-.001	4	3.004
AUBM	-5.067E-05	-.218	.011	.000	.000	5	5.123
PDBM	1.776E-05	.150	.012	.000	.000	6	27.439

It is evident from the model that the presence of gold and chloride in the solution reduce the uptake of base metals. Figure 5.4.7.1 shows that the predicted uptake of base metals. The base metals are not adsorbed by the resin.

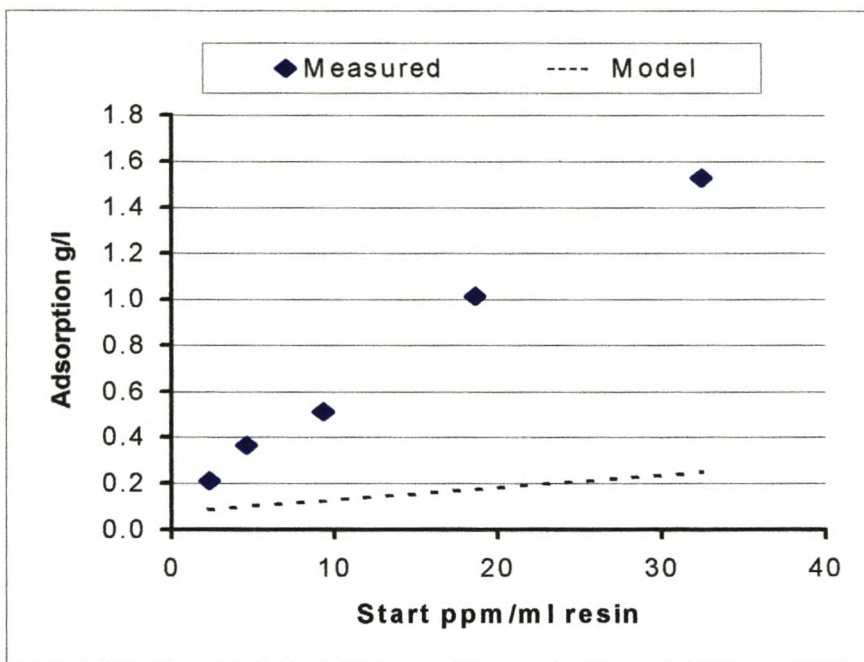


Figure 5.4.7.1: BM Adsorption predicted on A22

The predicted adsorption from a mixed solution can be seen in Figure 5.4.7.2.

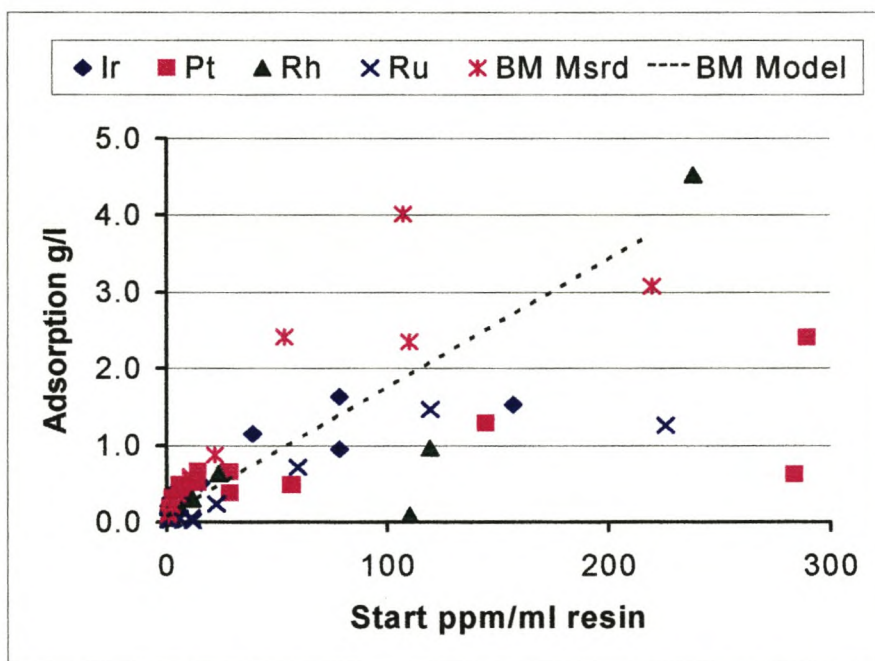


Figure 5.4.7.2: BM Adsorption predicted from mixed solution on A22



## CHAPTER 6

### CONCLUSIONS

Four different ion-exchange resins were initially selected according to their functional groups and the published results on the resins commercially available. They were XAD7, a co-ordinating resin which is reported to be gold specific due to the resin structure. IR200 was used as a cation resin for the adsorption of the base metals. IRA900 was used as a non-selective anion resin for PGM adsorption. A22 is a non-commercial anion resin which is selective for palladium.

The adsorption tests showed that XAD7 resin only adsorbs gold from precious metal and base metals solutions. The selectivity for gold is neither affected by HCl concentration, nor by other component concentrations. A22 resin adsorbs gold and palladium. With gold removed from the solution by XAD7, only palladium is adsorbed by the A22 resin. The adsorptive capacity of the resin is not affected by the HCl concentration. The IR200 resin is selective towards the base metals. The adsorption capacity is reduced at higher chloride concentrations. IRA900 resin adsorbs all of the PGM's, except rhodium. Rhodium is not adsorbed by any of the resins tested. With all PGM's, except rhodium and iridium removed from the solution, iridium can be adsorbed selectively with IRA900 resin. The adsorption of iridium is not affected by changes in the HCl concentrations.

The adsorption characteristics of all the resins tested are similar to those obtained for the single metal solutions. In the case where more than one component is adsorbed by the resin, the adsorption sites are shared. It can be concluded that the additional components in the mixed solutions do not drastically affect the adsorption characteristics. The addition of more metal components to the test solution did affect the adsorption quantities obtained, but not by much.

The statistical models developed from the experimental database for the equilibrium adsorption by each resin predict the uptake well. The solution variables affecting the



uptake by the resin were identified and quantified. The influence of other components in the solution on the equilibrium uptake were determined.

The quantity of metal ion uptake by the resins tested can be divided into one of the following categories:

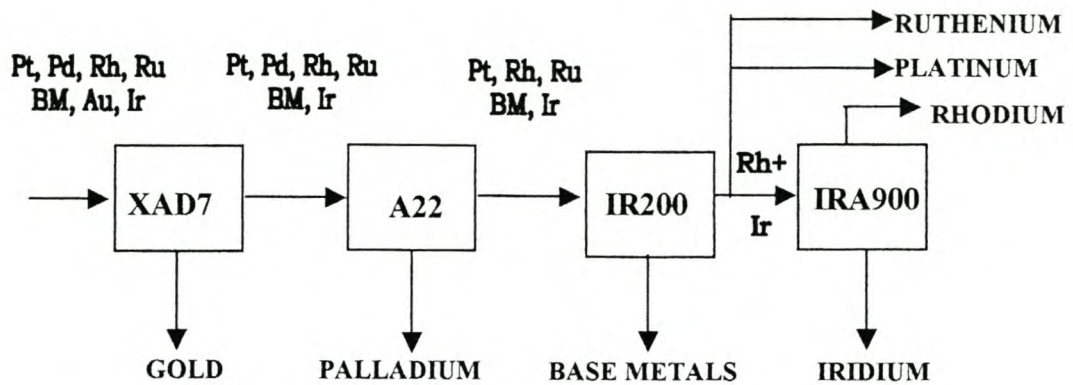
- a) None – The resin does not remove any metal from the solution. The metal ions do not penetrate the resin at all. The ions are excluded due to size restrictions or other electrical charge effects. The uptake determined for this category was less than 1 g/l, and in some cases less than 0.1 g/l.
- b) Small – The uptake of metal for this category was less than 2 g/l. The uptake is not adsorption as such, but can be attributed to equilibrium diffusion from the solution into the resin beads.
- c) Medium – the uptake in this category is adsorption. The adsorption quantity is in the range of 2 to 50 g/l.
- d) Large – The adsorption quantity is more than 50 g/l.

The adsorption test results for the PGM's and base metals on the four resins tested, as well as some of the statistical model results, can be summarised as in Table 6.1. The uptake of metal ions are classified as one of the above categories. The "Influence" column contains the significant solution variables, which determine the quantity of uptake by the resin, as provided by the statistical models. A + sign next to the component indicates that the uptake is increased with an increase of the concentration of the relevant component. The same is true for a negative sign, indicating a decrease of uptake by the resin with an increase in concentration of the specific component. The term AC indicates the acidity of the solution, that is the chloride concentration.

A column based process is semi-continuous with process solution passing through resin columns. After a column is loaded with the target metal, the column is rinsed to remove the remaining process solution from the resin bed. The resin uptake in the "Small" category will be washed from the column during the rinse cycle. Table 6.1 can therefore be modified as in Table 6.2.



A proposed ion-exchange adsorption sequence, based on the adsorption characteristics determined in this dissertation, can be seen in Figure 6.1.



**Figure 6.1: Proposed Ion-exchange Adsorption Sequence**

Only gold is adsorbed by XAD7 resin from a mixed solution. With the gold removed, palladium is the next to be adsorbed by the A22 resin. The IR200 resin will thereafter remove the base metals from the solution. Ruthenium and platinum must be removed by other means. Rhodium is not adsorbed by IRA900 and with all the other components removed, iridium can be extracted with IRA900. Some of the components identified, with an influence on the quantity of adsorption, may already be removed prior to the specific resin column in a sequential adsorption process, but are left in the table for completeness.

It is important to note that this study concerns the equilibrium conditions of resin and solution, and that the effect of kinetics is not addressed. The mobility of an ion can ensure preferential adsorption of the component. Although batch adsorption is not ideal for determination of resin adsorption capacities, a power fit can be used in the statistical modelling to obtain better predicted adsorption values for the higher solution concentrations.

**Table 6.1: Resin uptake quantity summary**

<b>Metal</b>	<b>IRA900</b>		<b>XAD7</b>		<b>IR200</b>		<b>A22</b>	
	<b>Uptake</b>	<b>Influence</b>	<b>Uptake</b>	<b>Influence</b>	<b>Uptake</b>	<b>Influence</b>	<b>Uptake</b>	<b>Influence</b>
<b>Gold</b>	Large	Au+, BM-	Medium	Au+, Pt+, Ru-	None	Au+, Rh+, AC-	Medium	Au+, BM+, Ir-, Pd-
<b>Iridium</b>	Large	Ir+, Rh-	Small	Ir+, AC-, BM-	Small	Ir+, Ru+, Au+, AC-, Pd-	Small	Ir+, AC-, Au-
<b>Palladium</b>	Medium	Pd+, AC-, Ru-	Small	Pd+, BM+, AC-, BM-	Small	Pd+, Ru+, Rh-, AC-	Medium	Pd+, Rh+, Ir-, Pt-
<b>Platinum</b>	Large	Pt+, Pd+, Rh+, Au-	None	BM+, Ir+, Rh-	Small	Pt+, Ru+, BM+, Ir-, Pd-	Small	Pd+, Au-
<b>Rhodium</b>	Small	Rh+, Ru+, Ir-, AC-, Pd-	None	Rh+, AC-, Pd-	None	Rh+, Pd+, AC-, Pt-	None	Ru+, Ir-, Au-
<b>Ruthenium</b>	Medium	Ru+, Au-, Rh-, Pt-, Pd-	Small	Ru+, Au+, BM+, AC-	Small	Ru+, BM+, Rh+, Pd+, Ir-, AC-	None	Rh+, Pd+, Ir-, Au-
<b>Base Metals</b>	Small	BM+, Au&Pd+, Pd-	Small	Pt+, Pd-	Medium	BM+, AC-, Au-	Small	BM+, Pd+, AC-, Au-



**Table 6.2: Resin adsorption quantity summary**

Metal	IRA900		XAD7		IR200		A22	
	Adsorb	Influence	Adsorb	Influence	Adsorb	Influence	Adsorb	Influence
<b>Gold</b>	Large	Au+, BM-	Medium	Au+, Pt+, Ru-	None		Medium	Au+, BM+, Ir-, Pd-
<b>Iridium</b>	Large	Ir+, Rh-	None		None		None	
<b>Palladium</b>	Medium	Pd+, AC-, Ru-	None		None		Medium	Pd+, Rh+, Ir-, Pt-
<b>Platinum</b>	Large	Pt+, Pd+, Rh+, Au-	None		None		None	
<b>Rhodium</b>	None		None		None		None	
<b>Ruthenium</b>	Medium	Ru+, Au-, Rh-, Pt-, Pd-	None		None		None	
<b>Base Metals</b>	None		None		Medium	BM+, AC-, Au-	None	

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## **APPENDIX A**

### **Supplier specification sheet for IRA900 resin**

## ION EXCHANGE RESINS

## PRODUCT DATA SHEET

# AMBERLITE IRA900 Cl

## Industrial Strong Base Anion Exchange Resin

AMBERLITE IRA900 Cl is a macroreticular polystyrene type 1 strong base anion exchange resin containing quaternary ammonium groups. This allows complete removal of all anions, including weakly dissociated ones like silica. The macroreticular structure embodies fixed large pores, presenting a sponge-like matrix. This feature combined with the strong basicity permits the removal of large size soluble organic molecules. In addition the macroreticular structure imparts superior resistance to mechanical and osmotic shock.

**PROPERTIES**

Matrix _____	Styrene divinylbenzene copolymer
Functional groups _____	-N <sup>+</sup> (CH <sub>3</sub> ) <sub>3</sub>
Physical form _____	Ivory beads
Ionic form as shipped _____	Chloride
Total exchange capacity _____	≥ 1.0 eq/L (Cl <sup>-</sup> form)
Moisture holding capacity _____	58 to 64 % (Cl <sup>-</sup> form)
Specific gravity _____	1.050 to 1.080 (Cl <sup>-</sup> form)
Bulk density _____	640 to 710 g/L (Cl <sup>-</sup> form)
Particle size	
Effective size _____	≥ 500 μm
Mean diameter _____	600 - 800 μm
Uniformity coefficient _____	≤ 1.8
Maximum reversible swelling _____	Cl <sup>-</sup> → OH <sup>-</sup> : 25 %
Chemical stability _____	Insoluble in water, dilute solutions of acids or bases and common solvents

**SUGGESTED OPERATING CONDITIONS (for Water Treatment)**

Minimum bed depth _____	700 mm
Service flow rate _____	up to 120 BV*/h
Regenerant	NaOH
Flow rate _____	2 to 8 BV/h
Concentration _____	2 to 4 %
Level _____	50 to 150 g/L
Minimum contact time _____	30 minutes
Slow rinse _____	2 BV at regeneration flow rate
Fast rinse _____	4 to 8 BV at service flow rate

\* 1 BV (Bed Volume) = 1 m<sup>3</sup> solution per m<sup>3</sup> resin



## APPLICATIONS

AMBERLITE IRA900 Cl is the ideal choice in all cases where the highest quality of deionised water is desired. Due to its excellent mechanical strength and good kinetics, it is particularly recommended for applications such as condensate polishing where the resin can be operated at flow rates up to 120 BV/h or 120 m/h. AMBERLITE IRA900 Cl can be used as an organic scavenger placed in front of a deionization system. Working in the chloroform form, it removes the more harmful organic substances from the raw water, protecting subsequent anion exchange resins from possible irreversible organic fouling.

AMBERLITE IRA900 Cl is also suitable for colour removal from sugar syrups.

## PERFORMANCE

The engineering data sheet EDS 0258 A provide information to calculate the operating capacity and silica leakage of AMBERLITE IRA900 Cl used in water treatment.

## LIMITS OF USE

Rohm and Haas manufactures special resins for food processing and potable water applications. As government regulations vary from country to country, it is recommended that potential users seek advice from their Amberlite representative in order to determine the best resin choice and optimum operating conditions.

## HYDRAULIC CHARACTERISTICS (Water Treatment)

Figure 1 shows the bed expansion of AMBERLITE IRA900 Cl, as a function of backwash flow rate and water temperature. Figure 2 shows the pressure drop data for AMBERLITE IRA900 Cl, as a function of service flow rate and water temperature. Pressure drop data are valid at the start of the service run with a clear water and a correctly classified bed.

Figure 1 : BED EXPANSION

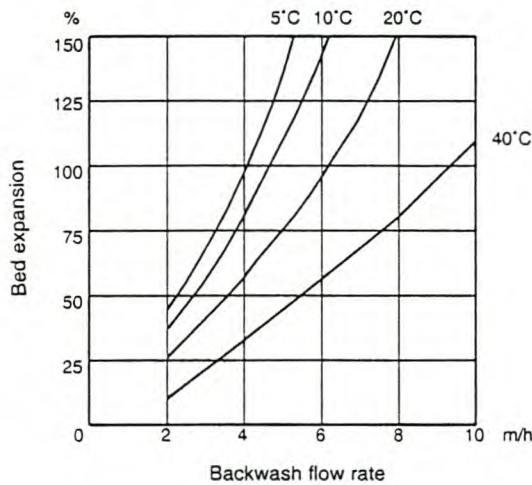
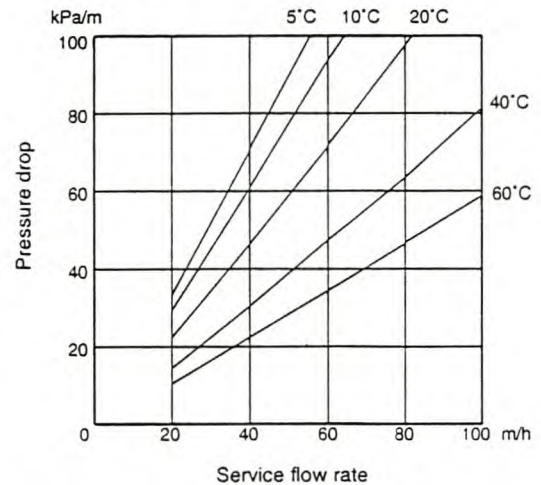


Figure 2 : PRESSURE DROP



### CAUTION

Ion exchange resins and polymeric adsorbents, as produced, contain by-products resulting from the manufacturing process. The user must determine the extent to which organic by-products must be removed for any particular use and establish techniques to assure that the appropriate level of purity is achieved for that use. The user must ensure compliance with all prudent safety standards and regulatory requirements governing the application. Except where specifically otherwise stated, Rohm and Haas Company does not recommend its ion exchange resins or polymeric adsorbents, as supplied, being suitable or appropriately pure for any particular use. Consult your Rohm and Haas technical representative for further information. Acidic and basic regenerant solutions are corrosive and should be handled in a manner that will prevent eye and skin contact. Nitric acid and other strong oxidising agents can cause explosive type reactions when mixed with Ion Exchange resins. Proper design of process equipment to prevent rapid buildup of pressure is necessary if use of an oxidising agent such as nitric acid is contemplated. Before using strong oxidising agents in contact with Ion Exchange Resins, consult sources knowledgeable in the handling of these materials.

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*materials and suggestions for any use prior to their adoption. Suggestions for uses of our products of the inclusion of descriptive material from patents and the citation of specific patents in this publication should not be understood as recommending the use of our products in violation of any patent or as permission or license to use any patents of the Rohm and Haas Company. Material Safety Data Sheets outlining the hazards and handling methods for our products are available on request.*

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## **APPENDIX B**

**Supplier specification sheet for XAD7 resin**



## ION EXCHANGE RESINS

## PRODUCT DATA SHEET

# AMBERLITE XAD7HP

## Industrial Grade Polymeric Adsorbent

AMBERLITE XAD7HP is a polymeric adsorbent, supplied as white insoluble beads. It is a non ionic aliphatic acrylic polymer which derives its adsorptive properties from its patented macroreticular structure (containing both a continuous polymer phase and a continuous pore phase), high surface area and the aliphatic nature of its surface. This macroreticular structure also gives AMBERLITE XAD7HP polymeric adsorbent excellent physical and thermal stability. Due to its aliphatic nature, AMBERLITE XAD7HP polymeric adsorbent can adsorb non polar compounds from aqueous systems, and can also adsorb polar compounds from non-polar solvents.

**PROPERTIES**

Matrix _____	Macroreticular aliphatic crosslinked polymer
Physical form _____	White translucent beads
Moisture holding capacity _____	62 to 68 %
Bulk density _____	620 to 690 g/L
Specific gravity _____	1.06 to 1.08
Particle size _____	0.3 - 1.2 mm (90 % within)
Maximum reversible swelling _____	see Table 1
Surface area _____	≥ 400 m <sup>2</sup> /g
Porosity _____	≥ 0.50 ml/ml

**SUGGESTED OPERATING CONDITIONS**

pH range _____	0 - 14
Maximum temperature limit _____	150°C
Minimum bed depth _____	75 cm
Flow rate	
Loading _____	2 to 16 BV/h
Displacement _____	1 to 4 BV/h
Regeneration _____	1 to 4 BV/h
Rinse _____	1 to 4 BV/h

\* BV (Bed Volume) = 1 m<sup>3</sup> solution per m<sup>3</sup> resin

## **APPENDIX C**

### **Supplier specification sheet for IR200 resin**



## ION EXCHANGE RESINS

## PRODUCT DATA SHEET

# AMBERLITE 200C Na

## Industrial Grade Strong Acid Cation Exchange Resin

AMBERLITE 200C Na is a premium grade strong acid macroreticular cation exchange resin based on sulfonic acid exchange groups on a polystyrenic matrix. Its high degree of crosslinking imparts superior stability to the macroreticular structure of the resin. This gives it far greater resistance to chemical oxidation and higher stability to breakdown from mechanical, thermal or osmotic shocks than any other commercially available cation resins. AMBERLITE 200C Na is recommended for make up demineralisation and mixed bed units, hot process softeners, chemical processing, metal treatment applications and systems involving appreciable oxidative potential or high temperatures.

**PROPERTIES**

Matrix	Styrene divinylbenzene copolymer
Functional groups	SO <sub>3</sub> <sup>-</sup>
Physical form	Beige beads
Ionic form as shipped	Na <sup>+</sup>
Total exchange capacity	≥ 1.75 eq/L (Na <sup>+</sup> form)
Moisture holding capacity	46 - 51 % (Na <sup>+</sup> form)
Specific gravity	1.22 to 1.26 (Na <sup>+</sup> form)
Bulk density	725 to 810 g/L (Na <sup>+</sup> form)
Particle size	
Effective size	≥ 510 µm
Mean diameter	650 - 850 µm
Uniformity coefficient	≤ 1.8
Maximum reversible swelling	Na <sup>+</sup> → H <sup>+</sup> : 6 %

**SUGGESTED OPERATING CONDITIONS**

pH range	0 - 14
Service flow rate	5 to 40 BV*/h
Regenerants	HCl            H <sub>2</sub> SO <sub>4</sub> NaCl
Flow rate (BV/h)	4 to 5            2 to 20            2 to 8
Concentration (%)	5 to 8            0.7 to 6            10
Level (g/L)	40 to 100      40 to 200      80 to 300
Minimum contact time	30 minutes
Slow rinse	2 BV at regeneration flow rate
Fast rinse	4 to 8 BV at service flow rate

\* 1 BV (Bed Volume) = 1 m<sup>3</sup> solution per m<sup>3</sup> resin

## HYDRAULIC CHARACTERISTICS

AMBERLITE 200C Na gives a pressure drop of about 10 kPa/m bed depth per 10 m/h at 15°C.

A backwash flow rate of 18 m/h gives a bed expansion of about 65 % at 15°C.

## LIMITS OF USE

AMBERLITE 200C Na is suitable for industrial uses. For other specific applications such as pharmaceutical, food processing or potable water applications, it is recommended that all potential users seek advice from Rohm and Haas in order to determine the best resin choice and optimum operating conditions.

### CAUTION

Ion exchange resins and polymeric adsorbents, as produced, contain by-products resulting from the manufacturing process. The user must determine the extent to which organic by-products must be removed for any particular use and establish techniques to assure that the appropriate level of purity is achieved for that use. The user must ensure compliance with all prudent safety standards and regulatory requirements governing the application. Except where specifically otherwise stated, Rohm and Haas Company does not recommend its ion exchange resins or polymeric adsorbents, as supplied, as being suitable or appropriately pure for any particular use. Consult your Rohm and Haas technical representative for further information. Acidic and basic regenerant solutions are corrosive and should be handled in a manner that will prevent eye and skin contact. Nitric acid and other strong oxidising agents can cause explosive type reactions when mixed with Ion Exchange resins. Proper design of process equipment to prevent rapid buildup of pressure is necessary if use of an oxidising agent such as nitric acid is contemplated. Before using strong oxidising agents in contact with Ion Exchange Resins, consult sources knowledgeable in the handling of these materials.

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## **APPENDIX D**

### **General guide for selection of ion-exchange resin**

Resin Type	AMBERLITE Designation	Matrix Type	Functional Groups	Standard Ionic Form	True (wet) Density	Shipping Weight (g/litre)	Moisture Content (%)	Operating pH Range	Maximum Operating Temperature (°C)	Total Exchange Capacity eq/l	Total Reversible Swelling %	Remarks	Applications	
GEL TYPE	IRA 416	Styrene-DVB	$\begin{matrix} \text{CH}_2-\text{CH}_2\text{OH} \\   \\ \text{N}^+-(\text{CH}_2)_2 \\   \\ (\text{Type 2}) \end{matrix}$	Cl <sup>-</sup>	1.12	ab 740	45-51	0-14	35 (OH) 75 (Cl)	1.30	Cl <sup>-</sup> -OH <sup>-</sup> 15	Type 2 resin (dimethylethanolamine functionality) of slightly lower basicity than AMBERLITE IRA 420, with higher regeneration efficiency. Due to its slightly lower basicity, it is less effective in the removal of silica from water.	Water conditioning	
	IRA 420	Styrene-DVB	-N <sup>+</sup> -(CH <sub>2</sub> ) <sub>2</sub> (Type 1)	Cl <sup>-</sup>	1.07	ab 730	50-56	0-14	60 (OH) 75 (Cl)	1.30	Cl <sup>-</sup> -OH <sup>-</sup> 20	High capacity, porous resin with excellent exchange kinetics and operating capacity. High resistance to mechanical and osmotic stress.	Water conditioning (deionization including silica removal, deoxygenation, etc.) removal of weakly acidic contaminants from process streams can be used with any existing ion exchange system.	
	IRA 458	Acrylic-DVB	-N <sup>+</sup> -(R) <sub>2</sub>	Cl <sup>-</sup>	1.08	ab 720	57-62	0-14	35 (OH) 75 (Cl)	1.25	Cl <sup>-</sup> -OH <sup>-</sup> 15	Differs from styrene-DVB resins in that it has an acrylic structure which is more hydrophilic and more resistant to organic fouling. It is recommended for treating water with a record of organic fouling problems for conventional, strongly basic anion exchange resins.	Water conditioning (deionization, dealkalization), decolorization of aqueous solutions, removal or recovery of acidic components of various process streams, particularly sugar	
STRONGLY BASIC	IRA 468	Acrylic-DVB	$\begin{matrix} \text{N}^+-(\text{R})_2 \\   \\ \text{N}^+-(\text{R})_2 \end{matrix}$	Cl <sup>-</sup> FB	1.07	ab 710	57-62	0-9	35 (OH)	1.33	OH <sup>-</sup> -Cl <sup>-</sup> 5	Bifunctional anion exchange resin with an exceptionally high operating exchange capacity on waters with a high free mineral acidity content.	Water conditioning when free mineral acidity is 80% or higher and up to 15% silica. Can only be used with upflow regeneration.	
	IRA 478	Acrylic-DVB	$\begin{matrix} \text{N}^+-(\text{R})_2 \\   \\ \text{N}^+-(\text{R})_2 \end{matrix}$	Cl <sup>-</sup> FB	1.06	ab 710	58-63	0-9	35 (OH)	1.25	OH <sup>-</sup> -Cl <sup>-</sup> 6	Bifunctional anion exchange resin with high operating capacity with co or reverse flow regeneration.	Water conditioning, when free mineral acidity is 75% or more and up to 10% silica	
MACRORETICULAR	IRA 900	Styrene-DVB	-N <sup>+</sup> -(CH <sub>2</sub> ) <sub>2</sub> (Type 1)	Cl <sup>-</sup>	1.06	ab 700	58-64	0-14	60 (OH) 75 (Cl)	1.00	Cl <sup>-</sup> -OH <sup>-</sup> 20	Strongly basic anion exchange resin best suited for at high flow rate deionization.	Water conditioning (deionization, silica removal, deoxygenation) recovery of high molecular weight organics from process streams, sugar decolorizing and deashing. High flowrate condensate polishing.	
	IRA 901	Styrene-DVB	-N <sup>+</sup> -(CH <sub>2</sub> ) <sub>2</sub> (Type 1)	Cl <sup>-</sup>	1.06	ab 680	63-68	0-14	60 (OH) 75 (Cl)	0.80	Cl <sup>-</sup> -OH <sup>-</sup> 20	Highly porous macroreticular resin for removal of organic matter and colour bodies from water.	Water conditioning (organic scavenging, removal of high molecular weight organic materials) Colour removal from sugar juices.	
	IRA 904	Styrene-DVB	-N <sup>+</sup> -(CH <sub>2</sub> ) <sub>2</sub> (Type 1)	Cl <sup>-</sup>	1.08	ab 670	56-62	0-14	60 (OH) 75 (Cl)	0.70	Cl <sup>-</sup> -OH <sup>-</sup> 5	Regeneration efficiency is low in the hydroxide cycle but, because of its high pore volume and surface area, widely used in the chloride form for organic scavenging. Resistance to physical attrition is excellent.	Water conditioning (organic scavenging, removal of high molecular weight organic materials)	
	IRA 910	Styrene-DVB	$\begin{matrix} \text{CH}_2-\text{CH}_2\text{OH} \\   \\ \text{N}^+-(\text{CH}_2)_2 \\   \\ (\text{Type 2}) \end{matrix}$	Cl <sup>-</sup>	1.09	ab 700	55-60	0-14	35 (OH) 75 (Cl)	1.05	Cl <sup>-</sup> -OH <sup>-</sup> 20	This type 2 (dimethylethanolamine) resin offers slightly less silica removal capability than AMBERLITE IRA 900, but offers improved regeneration efficiency.	Water conditioning (deionization, dealkalization) and deionization of chemical process streams.	
	IRA 958	Acrylic-DVB	-N <sup>+</sup> -(R) <sub>2</sub>	Cl <sup>-</sup>	1.08	ab 720	66-72	0-14	35 (OH) 80 (Cl)	0.80	Cl <sup>-</sup> -OH <sup>-</sup> 10 to 15	Macroreticular analogue of AMBERLITE IRA 458.	Deionization of process streams, sugar decolorizing and deashing. Organic scavenging.	
WEAKLY BASIC	GEL TYPE	IRA 67	Acrylic-DVB	-N-(R) <sub>2</sub>	Free base	1.06	ab 700	56-62	0-9	35	1.60	FB-Cl <sup>-</sup> 14	The resins have an unusually high capacity for large organic molecules. Also they can be operated in the bicarbonate form to exchange bicarbonate for anions of strong mineral acids.	Deacidification, deionization and desalination of water where the removal of strong mineral acids and adsorption of organics is desired.
		IRA 68	Acrylic-DVB	-N-(R) <sub>2</sub>	Free base	1.06	ab 700	56-62	0-9	60	1.65	FB-Cl <sup>-</sup> 16		Deionization of process streams, isolation of acidic natural products.
	MACRORETICULAR	IRA 35	Acrylic-DVB	-N-(R) <sub>2</sub>	Free base	-	ab 670	65-73	0-9	60	1.00	FB-Cl <sup>-</sup> 15 to 20	Macroreticular analogue of AMBERLITE IRA 68.	Deionization of process streams, removal of high molecular weight acids.
		IRA 93 SP	Styrene-DVB	-N-(R) <sub>2</sub>	Free base	1.04	ab 670	57-61	0-7	100	1.25	FB-Cl <sup>-</sup> 15	High exchange capacity and exceptional resistance to organic fouling. Often used because of the long operating life that can be expected in water treatment. Excellent physical stability and low reversible volume change.	Deacidification, deionization of water (where the removal of strong mineral and organic acids is desired). Performance of this resin is outstanding in the removal of organic materials from surface water supplies.
		IRA 94 S	Styrene-DVB	-N-(R) <sub>2</sub>	Free base	1.04	ab 670	57-61	0-7	100	1.20	FB-Cl <sup>-</sup> 14	Has all the major attributes of AMBERLITE IRA 93 SP including low reversible volume changes. Excellent resistance to oxidation.	Deacidification of process streams.

**Definition of Gel-Type Resins**

The gel type resins of the styrene-DVB type date back to 1947. These materials do not contain any true porosity and therefore must diffuse through the gel structure to the exchange sites. The inter-molecular distances which will limit the size of the ion that can migrate through the gel is often referred to as the apparent porosity. Even in low crosslinked gel-type resins, the apparent porosity is usually no greater than 40 Angstroms. There are hundreds of thousands of installations in operation in the field with these materials.

**Definition of Macroreticular**

The first macroreticular resin (MR) was placed into field service in 1959. These resins can best be described by comparing them with a small ball of tough, rigid sponge having large discrete pores. An average pore diameter of 1300 Angstroms is not unusual. Macroreticular resins offer a number of advantages over the conventional gel-type resins. Firstly, the large discrete pores allow high molecular weight ions to be more completely removed from solution and more completely eluted from the resin on regeneration than would be the case with other materials. Secondly, the open structure of the macroreticular resins permits the use of tough copolymers which would be too dense to effectively act as ion exchange resins if they were used in a strictly gel-type structure. Although the macroreticular resins, on the whole, do have a somewhat lower capacity than the gel-type resins, this is often offset by the longer operating life of the macroreticular resins or the fact they will perform removals not possible by the gel-type resins.



Resin Type	AMBERLITE Designation	Matrix Type	Functional Groups	Standard Ionic Form	True (wet) Density	Shipping Weight (g/litre)	Moisture Content (%)	Operating pH Range	Maximum Operating Temperature (°C)	Total Exchange Capacity eq/l	Total Reversible Swelling %	Remarks	Applications	
STRONGLY ACIDIC	GEL	IR 120	Styrene-DVB	-SO <sub>3</sub> <sup>-</sup>	Na <sup>+</sup>	1.26	ab 850	44-48	0-14	120	2	Na <sup>+</sup> - H <sup>+</sup> 10	Conventional strongly acidic cation exchange resin with 8% DVB by weight. This is the most widely used cation exchange resin in water conditioning.	Water conditioning (water softening, deionization, split-stream dealkalization), separation of rare earths, separation of amino acids, wine stabilisation, etc.
		IR 122	Styrene-DVB	-SO <sub>3</sub> <sup>-</sup>	Na <sup>+</sup>	1.31	ab 880	40-45	0-14	120	2.1	Na <sup>+</sup> - H <sup>+</sup> 6.5	This resin contains 10% DVB by weight, which gives it a greater resistance to oxidation than Amberlite IR 120.	Water conditioning (water softening, deionization, split-stream dealkalization, etc.), Stratabed system.
		IR 132 E	Styrene-DVB	-SO <sub>3</sub> <sup>-</sup>	H <sup>+</sup>	1.22	ab 845	45-50	0-14	120	1.9	Na <sup>+</sup> - H <sup>+</sup> 6.5		Water conditioning, condensate polishing, Ambersep system.
	MIR	200	Styrene-DVB	-SO <sub>3</sub> <sup>-</sup>	Na <sup>+</sup>	1.26	ab 800	46-51	0-14	150	1.75	Na <sup>+</sup> - H <sup>+</sup> 3	Excellent physical stability and resistance to oxidation. Contains over 20% DVB by weight, and can be expected to provide at least three times greater resistance to oxidation than conventional gel-type cation exchange resins.	Water conditioning (water softening, deionization, split-stream dealkalization, etc.), separation of rare earths metals, separation of amino acids, chemical processing etc., where long operating life is desired. Deionization at high flow rate such as condensate polishing.
		252	Styrene-DVB	-SO <sub>3</sub> <sup>-</sup>	Na <sup>+</sup>	1.24	ab 800	50-54	0-14	135	1.80	Na <sup>+</sup> - H <sup>+</sup> 7	Combines a high operating capacity with the exceptional physical stability of the macroreticular resin. Normally used in systems where the aggressiveness does not dictate the use of AMBERLITE 200 but where the use of a gel-type resin would be questionable.	Water conditioning, separation of rare earths metals, separation of amino acids, sugar processing, chemical processing, condensate polishing.
WEAKLY ACIDIC	IRC 50	Methacrylic acid-DVB	-COO <sup>-</sup>	H <sup>+</sup>	1.25	ab 660	42-49	5-14	120	3.5	H <sup>+</sup> - Na <sup>+</sup> 100 H <sup>+</sup> - Ca <sup>2+</sup> 35	This resin has a pK value of 5.3 and it will split the alkaline salts of monovalent cations as well as those of multivalent cations. High physical stability, limited reversible volume change.	Water conditioning (dealkalization, deionization, etc.), special application can be used either in the Na <sup>+</sup> or NH <sub>4</sub> <sup>+</sup> cycle.	
	IRC 76	Macroporous Acrylic acid	-COO <sup>-</sup>	H <sup>+</sup>	1.14	ab 700	54-58	4-14	120	3.9	H <sup>+</sup> - Na <sup>+</sup> 60 H <sup>+</sup> - Ca <sup>2+</sup> 5	Has a pK value of 6.1 and will selectively adsorb organic bases such as antibiotics, alkaloids, peptides, amino acids, and metals present in an alkaline solution.	Antibiotic purification and recovery, copper and nickel recovery.	
	IRC 86	Crosslinked Acrylic acid	-COO <sup>-</sup>	H <sup>+</sup>	1.19	ab 790	48-53	5-10	120	4.2	H <sup>+</sup> - Na <sup>+</sup> 80 H <sup>+</sup> - Ca <sup>2+</sup> 15	High operating exchange capacity, good physical stability.	Water conditioning (dealkalization)	

INERT MATERIALS

Resin Type	AMBERLITE Designation	Matrix Type	True (wet) Density	Shipping Weight (g/litre)	Moisture Content (%)	Operating pH Range	Maximum Operating Temperature (°C)	Total Reversible Swelling %	Remarks	Applications
INERT	IF 12	Polyethylene	0.95	ab 500	-	0-14	80	0	Coarse inert material.	Inert layer for air hold down in upflow regenerated systems.
	RF 14	Polypropylene	0.90	ab 540	-	0-14	90	0	Inert material for counter-flow regeneration and packed bed units.	Inert layer for air hold down in upflow regenerated systems, and reverse flow packed bed systems.
	AMBERSEP 349	Acrylic polymer	1.15	ab 700	10	0-14	70	0	Pale yellow inert material with good wettability.	Inert resin for the macroreticular type Ambersep system.
	AMBERSEP 359	Polymethylmethacrylate	1.17	ab 735	10	0-14	80	0	Polymethylmethacrylate inert material, resistant to hydrolysis, high mechanical stability.	Inert resin for Ambersep (3 layers) mixed bed systems with gel resins.

MIXED BED RESINS

AMBERLITE Designation	Matrix Type	Resin Type	Functional Groups	Ionic form as Supplied	Shipping Weight g/litre	pH Range	Maximum Operating Temperature °C	Total Exchange Capacity eq/l	Applications
MB 8	Styrene-DVB	Strongly acidic Strongly basic	-SO <sub>3</sub> <sup>-</sup> -N <sup>+</sup> -(R) <sub>3</sub>	H <sup>+</sup> /OH <sup>-</sup>	ab 730	0-14	60	0.7 H <sup>+</sup> 0.7 OH <sup>-</sup>	Non regenerable, ready-for-use mixed bed. High quality water deionization (0.5 µS/cm average conductivity).
MB 9	Styrene-DVB	Strongly acidic Strongly basic	-SO <sub>3</sub> <sup>-</sup> -N <sup>+</sup> -(R) <sub>3</sub>	H <sup>+</sup> /OH <sup>-</sup>	ab 745	0-14	60	0.9 H <sup>+</sup> 0.45 OH <sup>-</sup>	Non regenerable ready-for-use mixed bed with an excess of cationic capacity for deionization of high alkalinity water.
MB 20	Styrene-DVB	Strongly acidic Strongly basic	-SO <sub>3</sub> <sup>-</sup> -N <sup>+</sup> -(R) <sub>3</sub>	H <sup>+</sup> /OH <sup>-</sup>	ab 730	0-14	60	0.7 H <sup>+</sup> 0.7 OH <sup>-</sup>	Ready-for-use regenerable mixed bed for water deionization with high silica removal efficiency.
MB 604	Styrene-DVB	Strongly acidic Strongly basic	-SO <sub>3</sub> <sup>-</sup> -N <sup>+</sup> -(R) <sub>3</sub>	H <sup>+</sup> /OH <sup>-</sup>	ab 720	0-14	60	0.8 H <sup>+</sup> 0.8 OH <sup>-</sup>	Ready-for-use non regenerable mixed bed for ultrapure water systems.



AMBERLITE	Standard	L or C	D	Stratabed	RF	AMBERSEP	S	Special Ionic Form OH <sup>-</sup> H <sup>+</sup>	AMBERPACK
IR 120	•	•		•	•	•		•	•
IR 122	•			•					
IR 132 E		•				•		•	
IRC 50	•								
IRC 76	•			•	•				•
IRC 86	•			•	•				
IRA 416	•			•	•			•	•
IRA 420	•	•		•	•	•		•	•
IRA 458	•	•			•		•		•
IRA 468	•								
IRA 478	•	•			•				•
IRA 67	•				•				•
IRA68	•								
200	•	•	•			•		•	•
252	•	•			•	•		•	
IRA 900	•	•	•	•	•	•		•	•
IRA 901	•								
IRA 904	•								
IRA 910	•		•	•	•				•
IRA 958	•				•		•		
IRA 35	•				•		•		
IRA 93 SP	•			•	•				•
IRA 94 S	•								

Standard : 0.3 to 1.2 mm particle size.  
 L or C : Special particle size for high flow rate operation.  
 D : Special particle size for continuous Ion Exchange process.  
 STRATABED : Special particle size for Stratified bed process.  
 RF : Special particle size for Packed bed process.  
 AMBERSEP : Special particle size for Ambersep mixed bed applications.  
 S : Special particle size for mixed beds and sugar decolourisation.  
 H or OH : Resins in the regenerated form.  
 AMBERPACK: Special particle size for AMBERPACK system.



Compared with the conventional mixed beds, the AMBERSEP system provides the following advantages:

- perfect physical and visible separation
- very low ionic leakage
- very short rinse requirements.

	Designation	Type	True Wet Density			Particle size (mm)
			Na <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>	H <sup>+</sup>	
CATION EXCHANGERS	AMBERSEP 120 H	Gel	1.26	1.24	1.22	0.6 - 1.20
	AMBERSEP 132 E-H	Gel	1.31	1.29	1.22	0.6 - 1.20
	AMBERSEP 200 H	Macroreticular	1.26	1.24	1.19	0.7 - 1.20
	AMBERSEP 252 H	Macroreticular	1.24	1.19	1.18	0.7 - 1.20
ANION EXCHANGERS	AMBERSEP 420	Gel		1.07		0.35 - 0.85
	AMBERSEP 900	Macroreticular		1.06		0.35 - 0.85
	AMBERSEP 900 OH	Macroreticular		1.05		0.35 - 0.85
INERT MATERIALS	AMBERSEP 349	Inert copolymer		1.15		0.60 - 0.90
	AMBERSEP 359	Inert copolymer		1.17		0.42 - 0.71

NUCLEAR GRADE AMBERLITE ION EXCHANGE RESINS

	AMBERLITE Type	Ionic Form	Particle Size mm	Total Exchange Capacity eq/l	Remarks
ANION EXCHANGERS	IRN 77	H <sup>+</sup>	0.4 - 1.2	1.9	A strongly acidic cation exchange resin containing a minimum of 99% of its exchange sites in the hydrogen form.
	IRN 218	Li <sup>+</sup>	0.4 - 1.2	1.75 - 1.9	A strongly acidic cation exchange resin containing a minimum of 99% of its exchange sites in the lithium form.
CATION EXCHANGERS	IRN 78 L	OH <sup>-</sup>	0.4 - 1.2	1.0	A strongly basic anion exchange resin with a minimum of 95% of its exchange sites in the OH <sup>-</sup> form, a maximum of 0.2% in the Cl <sup>-</sup> form, 0.2% in the SO <sub>4</sub> <sup>2-</sup> form and 5% in the CO <sub>3</sub> <sup>2-</sup> form.
	IRN 78 L/C-L	OH <sup>-</sup>	0.4 - 1.2	1.1	Similar to IRN 78 L but with a maximum of 0.1% in the Cl <sup>-</sup> form. Recommended for BWR nuclear plants.
MIXED BED RESINS	IRN 150 L	Mixture of IRN 77 IRN 78 L	H <sup>+</sup> OH <sup>-</sup>	0.4 - 1.2	Mixed bed containing 1 eq H <sup>+</sup> for 1 eq OH <sup>-</sup> .
	IRN 150 L/C-L	IRN 77 IRN 78 L C-L	H <sup>+</sup> OH <sup>-</sup>	0.4 - 1.2	Similar to Amberlite IRN 150 L and differing only in chloride content. The anion component is Amberlite IRN 78 L C-L. Exists with 2 eq H <sup>+</sup> for 1 eq OH <sup>-</sup> .
	IRN 217 L	IRN 218 IRN 78 L	Li <sup>+</sup> OH <sup>-</sup>	0.4 - 1.2	A mixture of strongly acidic cation and strongly basic anion exchange resins containing one equivalent of lithium for each equivalent of hydroxide ion.
	IRN 217 L/C-L	IRN 218 IRN 78 L/C-L	Li <sup>+</sup> OH <sup>-</sup>	0.4 - 1.2	Similar to Amberlite IRN 217 L and differing only in chloride content. The anion component is Amberlite IRN 78 L/C-L.

## APPENDIX E

- ◆ **Presentation at Minerals Engineering '99 Conference in Falmouth, Cornwall, UK. September 22 – 24, 1999. “The Adsorption of Precious Metals and Base Metals on a Quaternary Ammonium Group Ion-Exchange Resin.”**
  
- ◆ **Presentation at IEX2000 Conference at the University of Cambridge, UK. July 16 – 21, 2000. “The Adsorption of Base Metals and Precious Metals on IR200 Ion-Exchange Resin.”**
  
- ◆ **Presentation at XXI International Mineral Processing Congress in Rome, Italy. July 23 – 27, 2000. “The Adsorption of Precious and Base Metals on XAD7 ion-Exchange Resin.”**





## THE ADSORPTION OF PRECIOUS METALS AND BASE METALS ON A QUATERNARY AMMONIUM GROUP ION EXCHANGE RESIN\*

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### ABSTRACT

*Adsorption tests were conducted with a quaternary ammonium group ion exchange resin to determine the equilibrium adsorption of precious- and base metals. The resin used is a macroreticular polystyrene type 1 strong base anion exchange resin. The adsorption was determined for synthetic single metal solutions as well as for multi-component solutions. The effect of the  $Cl^-$  concentration on the equilibrium adsorption was determined for three different HCl concentrations, i.e. 6, 8 and 10%. The effect of chloride strength in the solution was also determined for mixed and base metal solutions. Pure metals, i.e. platinum, palladium and gold, were dissolved in aqua-regia and diluted to 2000 ppm (as metal) in 4M HCl. Ruthenium, rhodium and iridium were dissolved from pure salts in HCl. A 2000 ppm base-metal solution was prepared by dissolving all the required components, including precious metals, to match an in-plant industrial base-metals solution composition. For each precious metal the equilibrium adsorption was determined for typically two solution concentrations. Data points were established by varying the amount of resin added to the solution. The equilibrium concentrations were determined by ICP analysis after 24 hours exposure using the bottle-roll technique. © 2000 Published by Elsevier Science Ltd. All rights reserved.*

### Keywords

Ion exchange

### INTRODUCTION

Selective recovery of pure precious group metals (PGM's) from chloride solutions has always been a major challenge to chemists trying to selectively isolate single metal compounds of high purity. Recently the focus has moved towards ion exchange technology and the use of active groups on a resin which can selectively extract specific species from a solution. Due to the tendency of PGM ions to form anionic complexes, the focus for PGM recovery is more towards anion exchange resins. The PGM industry is refining the chloride complexes of the precious metals as this is the solution products after aqua-regia leaching, used to dissolve the metal sulphides. The PGM's dissolve forming complexes with the general formula  $[MCl_x]^{n-}$ . However, the thermodynamics and kinetics of aqueous solution containing PGM's are not always well understood and therefore, remained tenaciously elusive [Dhara and Sudhir, 1993]. To study the adsorption of PGM ions in an industrial solution containing a variety of PGM and base metal ions will therefore be difficult as there are just too many interacting species in the solution.

For this reason single component solutions of the precious metals were prepared by using pure metal, and in some cases pure metal salts. The salts were used in instances where the dissolution of the metals is very

\* Presented at *Minerals Engineering '99*, Falmouth, Cornwall, England, September 1999



difficult. A base metal solution, including the PGM's, was prepared by adding all the individual components to match an industry composition of their base metal solution.

The adsorption characteristics of single metals were determined and thereafter more components were added to the solution to study the effect of other ions competing for the adsorption sites on the resin.

### RESIN USED

The resin matrix is a styrene divinylbenzene copolymer. The active functional group is a quaternary ammonium group  $-N^+(\text{CH}_3)_3$ . The resin is a commercial type 1 strong base anion exchange resin. The resin is usually used for complete removal of all anions, including weakly dissociated ones like silica. The macro-reticular structure embodies fixed large pores, presenting a sponge-like matrix. The large discrete pores mean that high molecular weight ions can be more completely adsorbed from solution and more completely eluted from the resin on regeneration. The structure imparts superior resistance to mechanical and osmotic shock. The resin allows for fast kinetics and are also used for condensate polishing. It is also very effective as an organic scavenger when placed in front of a de-ionisation system. The resin is also suitable for colour removal from sugar syrups. The resin is supplied in the chloride form.

The resin was prepared in glass columns with upward flow of solution. The solution was pumped with a variable speed peristaltic pump. The upward flow of solution has to be very slow to allow displacement of the air from the resin and the connecting tubes as air pockets tend to lift the resin upwards and out of the column. The resin is firstly washed with distilled water to remove all foreign ions from the factory floor. The resin was then washed with caustic solution. The large  $\text{OH}^-$  ions force open all the small pores in the resin to free and displace foreign ions. The resin was then washed again with 2M NaCl to convert the resin back to the  $\text{Cl}^-$  form. The smaller  $\text{Cl}^-$  ions have the ability to displace the  $\text{OH}^-$  ions because of a large charge density. This was followed with a water wash and finally with 8% HCl to prepare the resin for adsorption. The resin was then taken from the column and put in a 5 litre plastic drum from where small amounts were taken for adsorption tests.

### SOLUTION PREPARATION

Platinum, palladium and gold solutions were prepared by dissolution of the pure metals in aqua-regia. The mass required for a 2000 ppm stock solution were weighed off and boiled in aqua-regia until dissolved. More HCl was added, and the solution was boiled further to drive off all the nitric acid as  $\text{NO}_x$  fumes. The resulting free HCl in the solution was determined by titration. The solution was then diluted with the correct amounts of water and acid to achieve the desired final free acid and metal concentration. From this 2000 ppm stock solution further dilution to the actual test concentrations was done. Ruthenium, iridium, and rhodium were dissolved from the pure salts. Ruthenium was dissolved from the  $(\text{NH}_4)_2(\text{RuNOCl}_5)$  salt, iridium from  $(\text{NH}_4)_2(\text{IrCl}_6)$ , and rhodium from the DETA salt  $(\text{DETAH}_3)(\text{RhCl}_6)$ . DETA being the  $\text{C}_4\text{N}_3\text{H}_{10}$  chain.

The composition of an industrial base metal solution was matched by adding all the required components in the correct quantities. Ruthenium, rhodium and iridium were added from the already prepared pure stock solutions. The composition and reagents used for preparation of the base metal solution can be seen in Table 1.

Aqua-regia was added to dissolve all the solid components. All nitric was boiled off from the solution. The solution was then diluted to the required acid and 2000 ppm PGM plus base metal concentration.

### EXPERIMENTAL

To establish equilibrium data points at a specific PGM concentration the adsorption from the solution was determined by varying the amount of resin added to the specific solution concentration. The volume of solution used for each test was either 500 or 1000 ml. Seven different quantities of resin were added to a



specific solution concentration ranging between 0.5 ml to 100 ml. The amount of resin added to the solution was varied to achieve a low as well as a high total loading on the resin. In batch experimentation the final concentration is unknown and it is therefore difficult to predict the eventual equilibrium concentration beforehand. The resin was measured out in a small plastic measuring cylinder and tapped against the bench for settlement of the resin beads. The test solution was diluted from the 2000 ppm stock solution prepared to the required metal concentration and free acid concentration. A sample of the test solution was taken as reference before addition of the resin beads. All analysis were done by inductively coupled plasma (ICP). The reference sample was also titrated to check that the targeted free HCl concentration was correct. The resin was added to the solution and rolled in bottles for 24 hours to ensure equilibrium was attained. The bottles were rolled on a roller bench to facilitate multiple simultaneous tests. After exposure a sample of the solution was taken and analysed by ICP. The adsorption was calculated by difference to the reference sample concentration.

TABLE 1 Preparation and composition of base metal solution

	Stock individual ppm	Stock Individual Gram	Reagent Used	Metal MM	Reagent MM	Gram reagent Required
Pt	845.1	9.1	Pt	195.09	195.09	9.1
Pd	422.5	4.6	Pd	106.4	106.4	4.6
Au	28.2	0.3	Au	196.967	196.967	0.3
Rh	98.6	1.1	2764	Ppm	ml stock req.	385
Ru	126.8	1.4	2619.8	Ppm	ml stock req.	523
Ir	42.3	0.5	7408	Ppm	ml stock req.	62
Ag	70.4	0.8	AgNO <sub>3</sub>	107.87	169.87	1.2
Ni	28.2	0.3	Ni(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	58.71	290.8	1.5
Cu	56.3	0.6	Cu(NO <sub>3</sub> ) <sub>2</sub> ·3H <sub>2</sub> O	63.54	241.6	2.3
Fe	56.3	0.6	Fe(NO <sub>3</sub> ) <sub>3</sub> ·9H <sub>2</sub> O	55.847	404	4.4
Pb	84.5	0.9	Pb(NO <sub>3</sub> ) <sub>2</sub>	207.19	331.2	1.5
As	14.1	0.2	As <sub>2</sub> O <sub>3</sub>	74.922	197.84	0.4
Se	42.3	0.5	Se	78.96	78.96	0.5
Te	84.5	0.9	Te	127.6	127.6	0.9
Total	2000.0	21.6				
Non PGM	436.6	4.7				

The following equilibrium adsorption tests were conducted:

Single component PGM's isotherms,

Base metal solution isotherm,

Effect of additional PGM's in the solution on adsorption,

Effect of different Cl<sup>-</sup> concentration (pH) on adsorption.

IUPAC Recommendations on ion exchange nomenclature define "theoretical specific capacity" as the milliequivalents of ionogenic group per gram of dry ion exchanger [Lehto and Harjula, 1995]. The ionogenic group in this instance is the quaternary ammonium group -N<sup>+</sup>(CH<sub>3</sub>)<sub>3</sub>, it holds the ions capable of exchanging for other ions in the external solution. The actual uptake will not reach the theoretical capacity, for example, if there are exchange sites to which various ions have different accessibility's. Some sites may be entirely inaccessible to larger ions. The IUPAC recommendations also include the "practical specific capacity" of an ion exchanger. This is total amount of ions expressed in milliequivalents taken up per gram of ion exchanger under specific conditions, which should always be given. The usual way to present adsorption isotherms is to plot the amount of say  $x$  adsorbed / capacity of the resin for  $x$  against the concentration of  $x$  in the solution / total concentration of  $x$ , in this case  $x$  will be one of the PGM's or base metals. From the above it is evident that the practical capacity depends on the experimental conditions. All the experimental work were batch experiments. To determine the maximum resin uptake of an specific ion, that is the practical capacity, the counter ion which is displaced from the resin must be continuously



removed, such as in a column. The batch equivalent should be a large number of successive batch equilibration's in series.

## RESULTS

From the experimental data analysis it became evident that effective visualisation of the quantitative adsorption data can be obtained by combining the variable parameters like solution concentration and quantity of resin used into a single ratio and to plot this ratio against the gram adsorbed per litre of resin. It is also evident that for each solution concentration the adsorption, expressed as gram/litre resin, increase as the amount of resin used, decrease. This is due to the ratio of exchangeable ions in solution divided by the number of potential adsorption sites on the resin. Therefore the ratio used for the graphs is the initial concentration of precious metal in solution (which determine the potential quantity of ions to be adsorbed onto the resin) divided by the ml of resin used (which determine the total amount of adsorption sites available for adsorption). The isotherms presented are therefore presented as such. It is evident that where the resin has a high preference for the ion to be exchanged the initial slope of the isotherm, that is for small ppm / ml resin, will be high. This indicates that the resin has a high affinity for the ion to be exchanged and that high loading will be attained in dilute solutions.

### Adsorption isotherms

For the single PGM solutions seven adsorption data points were determined for each test solution concentration to construct the adsorption isotherms. It should be noted that inaccuracies occur at the very small resin volumes, that is where the ratio "Start ppm / ml resin" is large. Solution potentials was measured with a platinum redox electrode with reference to Ag/AgCl. All isotherms were determined at 8% free HCl concentration.

The isotherm for gold, Figure 1, was determined by adsorption from a 300 ppm gold solution. The solution potential was 732 mV. Gold is in solution as the  $\text{AuCl}_4^-$  ion. The isotherm for iridium was determined by adsorption from a couple of solutions, 139, 224, 354, 261 and 391 ppm iridium solutions. It is known that the iridium ion  $\text{IrCl}_6^{3-}$  hydrolyse with time. The duration of the bottle roll equilibration was varied to check for hydrolysis, but no hydrolyses was noticed. The solution potential was ~900 mV. The palladium isotherm was determined by adsorption from a 266 ppm palladium solution at 444 mV. Palladium is in solution as the  $\text{PdCl}_4^{2-}$  ion. Adsorption of platinum was determined from a 305 ppm solution at 418 mV. Platinum is in solution as the  $\text{PtCl}_4^{2-}$  ion. The rhodium isotherm was determined by adsorption from a 293 ppm solution at 531 mV. Rhodium is in solution as one of the following chlorocomplexes [Lehto and Harjula, 1995],  $\text{RhCl}_4(\text{H}_2\text{O})^-$ ,  $\text{RhCl}_5(\text{H}_2\text{O})^{2-}$ , or the  $\text{RhCl}_6^{3-}$  ion, depending on the equilibrium between these species. Ruthenium adsorption was determined by adsorption from a 300 ppm solution at 834 mV. Ruthenium is in solution as one of the following chlorocomplexes [Lehto and Harjula, 1995],  $\text{RuCl}_5(\text{H}_2\text{O})^{2-}$ , or the  $\text{RuCl}_6^{3-}$  ion, depending on the equilibrium between these species.

All of the above single component isotherms are displayed together in Figure 1. This is convenient for comparison to adsorption curves from a base metals solution containing the PGM's as well. From Figure 1 it is evident that the resin has the highest adsorptive capacity for gold. Platinum is also adsorbed well but the maximum resin loading is lower than for gold. Some sorption of palladium, ruthenium and iridium is evident but in much lower quantities. Rhodium and base metals are not adsorbed at all by the resin.

The base metal adsorption isotherm, depicted in Figure 2, was determined at 8% free HCl concentration. Adsorption of total base metals was determined from a 73 ppm total base metals solution. The 73 ppm is only the base metals, excluding the PGM's. The total metal concentration of the solution was 334 ppm at 838 mV. Although the concentrations of all base metals were determined individually by ICP they were added together for simplicity. The base metals form cationic complexes, and should therefore not be adsorbed by the anion resin. Some sorption does occur however and the test was done for completeness.



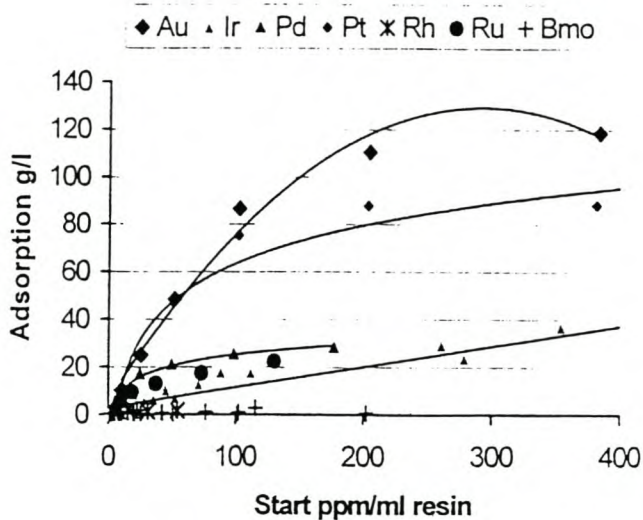


Fig.1 Combined isotherms.

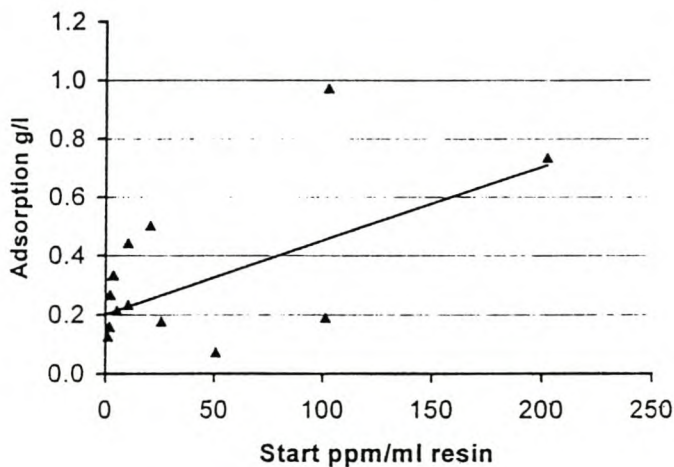


Fig.2 Base metals adsorption isotherm.

**Effect of additional PGM's in the solution**

All adsorption tests were performed with 8% free HCl concentration. The first mixed solution tested for adsorption contains platinum, rhodium and ruthenium. Two solution concentrations were prepared. The first contained 277 ppm platinum, 286 ppm rhodium and 331ppm ruthenium at 816 mV. The second contained 84 ppm platinum, 88 ppm rhodium and 94 ppm ruthenium at 810 mV. The adsorption from both these solutions can be seen in Figure 3. In comparison to the single component adsorption isotherms, Figure 1, it is evident that platinum is still the most preferred, although the quantity adsorbed at a specific initial concentration / ml resin has decreased. There is also a slight decrease in ruthenium adsorption. It is interesting to note that some adsorption of rhodium occur from this solution.

The second mixed solution contains platinum, rhodium, ruthenium, gold, palladium and base metals. Two test solution concentrations were prepared. The first contained 1000 ppm total metals at 810 mV and the second contained 500 ppm total metals at 840 mV. The adsorption from this solution is depicted in Figure 4.

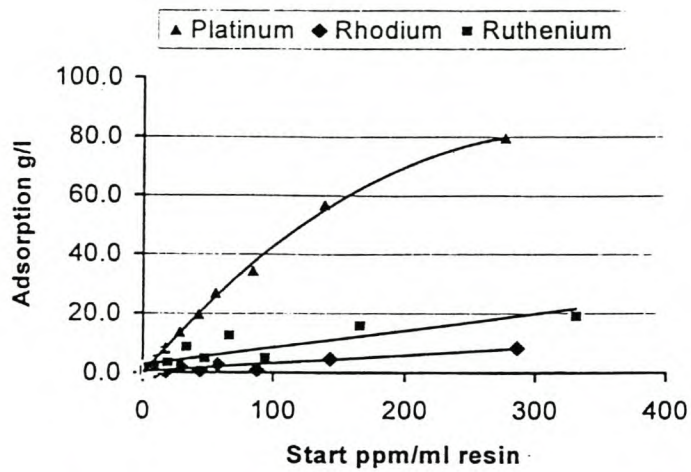


Fig.3 Equilibrium adsorption from platinum, rhodium and ruthenium solution.

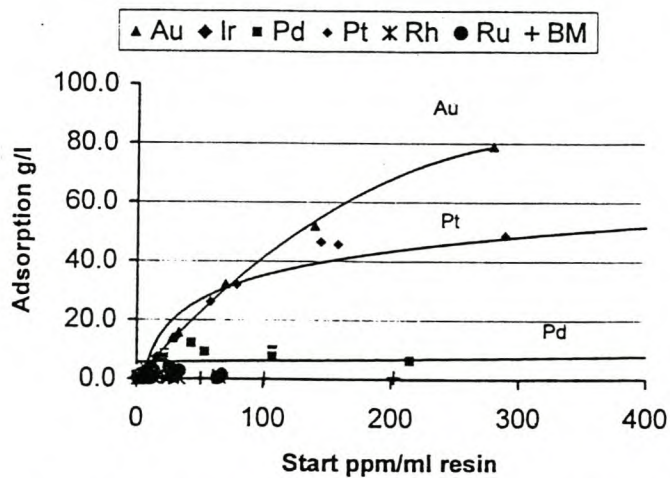


Fig.4 Equilibrium adsorption from Au+Pd+BM+Pt+Rh+Ru solution.

In comparison to the single component isotherms, Figure 1, it is evident that the quantity of adsorption of all components are reduced due to the presence of multiple ions competing for the adsorption sites. It is also evident that apart from gold, platinum and palladium no other ions are adsorbed.

The adsorption from a base metals solution, as in Table 1, was determined. The adsorption, Figure 5, is from the base metals solution without any addition of components.

From Figure 5 it is evident that the adsorption from the base metals solution is almost identical to adsorption of the mixed solution depicted in Figure 4. It can therefore be concluded that increased PGM concentrations does not effect the adsorption from a mixed solution by much.

Iridium is not preferred for adsorption from a mixed solution. An adsorption test was done to investigate the separation of iridium from a base metals solution. Two test solutions were prepared for this test. The first contained 50 ppm, only the base metals content, the solution potential was 840 mV. The second contained 100 ppm base metals. The solution potential was 810 mV. The adsorption characteristic is depicted in Figure 6.



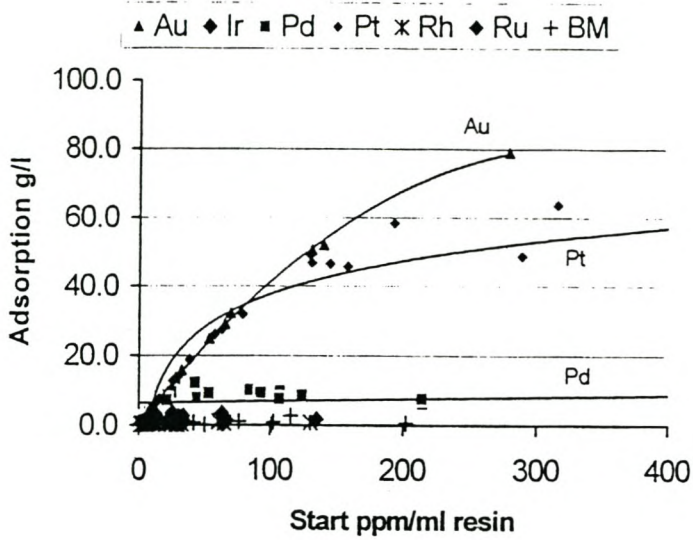


Fig.5 Absorption from a base metals solution.

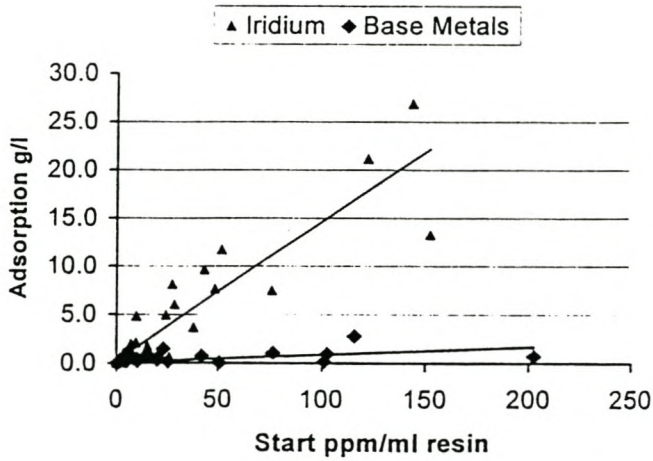


Fig.6 Iridium plus base metals adsorption.

It is evident from Figure 6 that iridium can be effectively separated from a base metal solution by the resin. The separation of rhodium and iridium was also investigated, see Figure 7. Two test solutions were prepared for this test. The first contained 76 ppm iridium and 89 ppm rhodium at 922 mV. The second contained 302 ppm iridium and 275 ppm rhodium at 913 mV.

It is evident from Figure 7 that rhodium and iridium can be effectively separated by the resin.

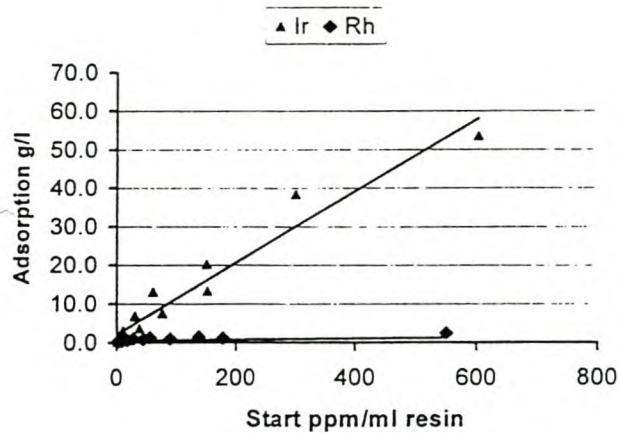


Fig.7 Iridium plus rhodium adsorption.

**Effect of different  $Cl^-$  concentrations (pH) on adsorption**

The effect of HCl concentration on the adsorption was determined for a 6, 8, and 10% free HCl in the solution. For each of the three chloride strengths, two test solution strengths have been tested, and for each solution the equilibrium adsorption was determined on 2ml and on 10 ml resin.

The chloride concentration had no visible effect on the adsorption of gold as can be seen in Figure 8.

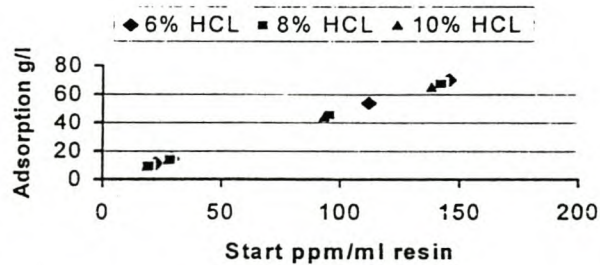


Fig.8 Gold adsorption with acidity.

The chloride concentration has only a small effect on the adsorption of iridium, as can be seen in Figure 9. The adsorption seem to be more at higher and lower than 8% HCl concentrations.

The adsorption of palladium improve at lower chloride concentrations as depicted in Figure 10.

The adsorption of platinum does not change much with acidity, with 8% being the intermediate between 6% and 10% as can be seen in Figure 11.

Although the adsorption of rhodium is negligible there is however a distinct drop in adsorption at higher chloride strength, as can be seen in Figure 12.

From Figure 13 it is evident that the ruthenium adsorption decrease with higher chloride concentrations.



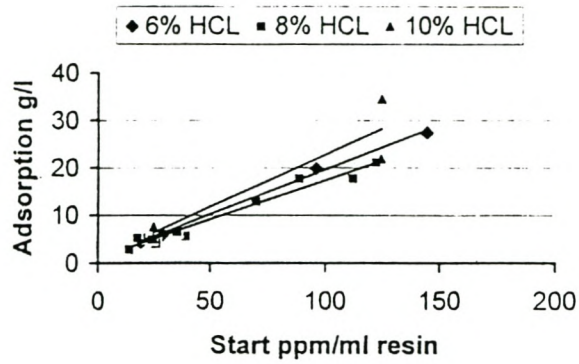


Fig.9 Iridium adsorption with acidity.

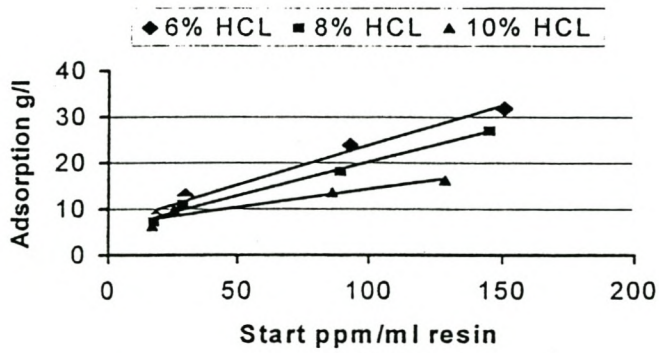


Fig.10 Palladium adsorption with acidity.

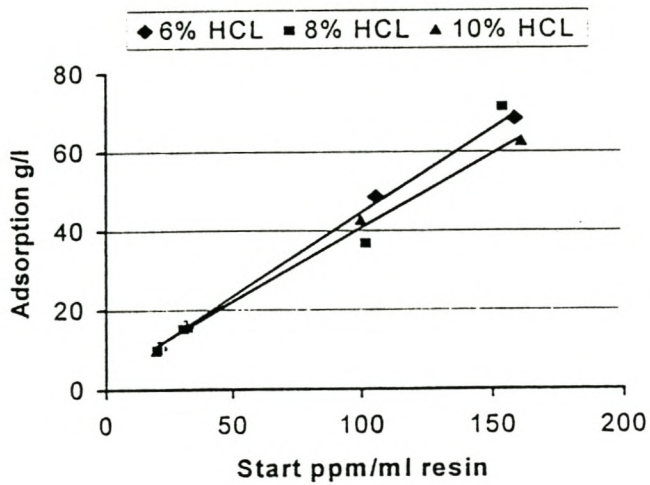


Fig.11 Platinum adsorption with acidity.

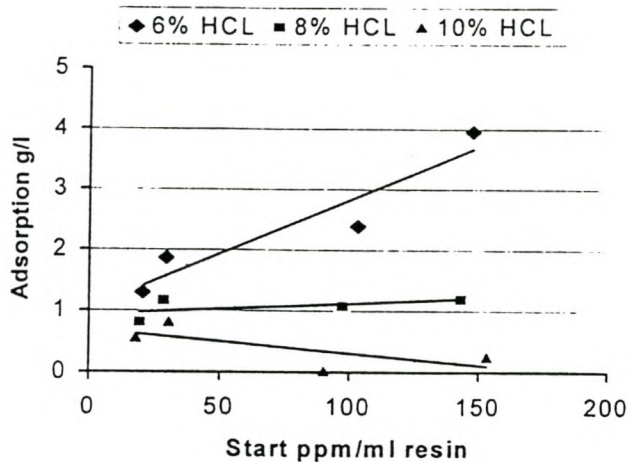


Fig.12 Rhodium adsorption with acidity.

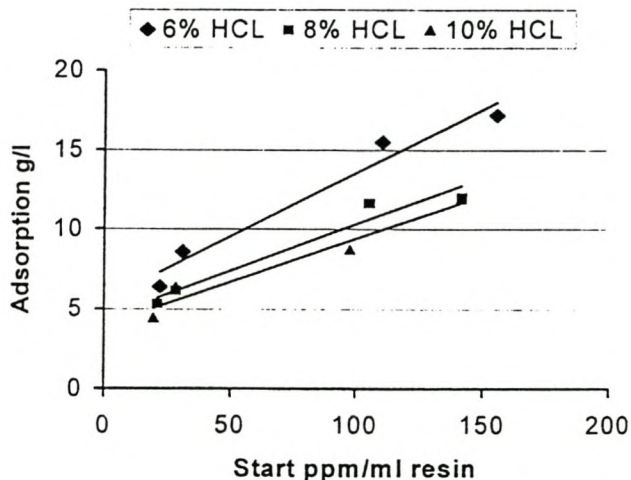


Fig.13 Ruthenium adsorption with acidity.

Although the base metals form mostly cationic complexes in chloride media some sorption does occur. From Figure 14 it is evident that the sorption decrease with higher chloride concentration, as to be expected.

The effect of acid concentration on multiple component solutions as listed in the paragraph “Results” were determined.

Chloride concentration in the range 6 to 10% had no significant change in the adsorption characteristic from the platinum, rhodium and ruthenium mixed solution. In the second multi-component mixed solution, Figure 15 and 16, the effect of chloride concentration is also very small. The palladium adsorption however seems to be adversely effected at the higher chloride concentrations.



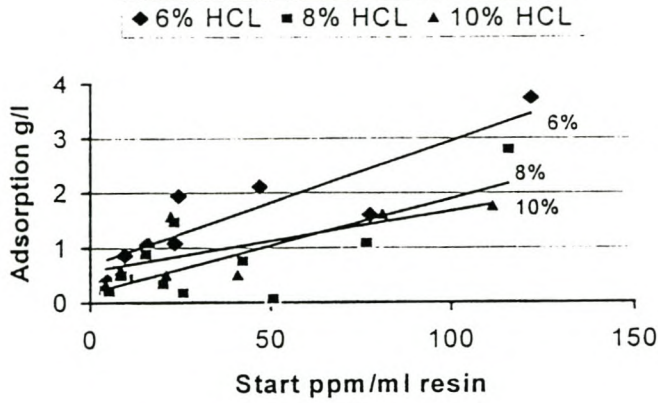


Fig.14 Base metals adsorption with acidity.

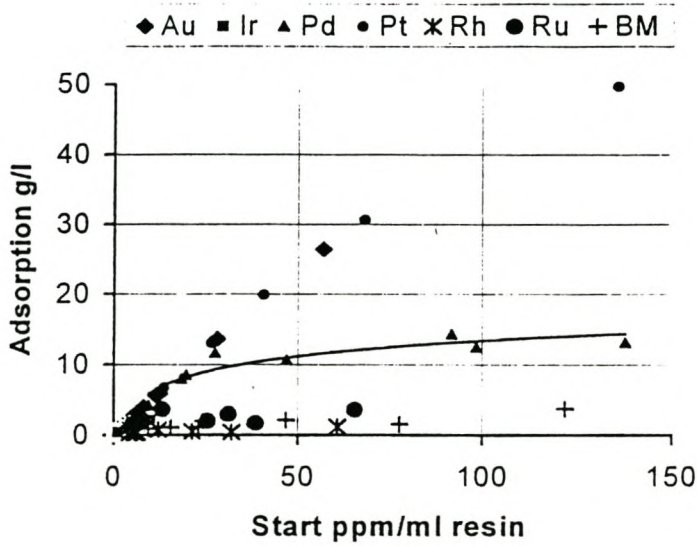


Fig.15 Pt, Rh, Ru, Au and base metals adsorption in 6% HCl.

The iridium adsorption can not be seen, as no additional iridium was added to the solution, only the iridium contained in the base metal solution was determined. The rhodium and iridium mixed solutions maintain the distinct preference for iridium at both 6 and 10% HCl, Figures 17 and 18. The adsorption of both rhodium and iridium decrease at higher chloride concentrations as to be expected.

The mixed iridium and base metal solution also maintain the preference for iridium, as to be expected as the base metals are by and large present in the solution as cations, Figures 19 and 20.

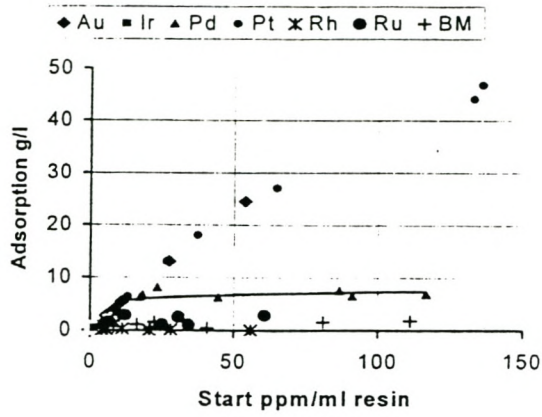


Fig.16 Pt, Rh, Ru, Au and base metals adsorption in 10% HCl.

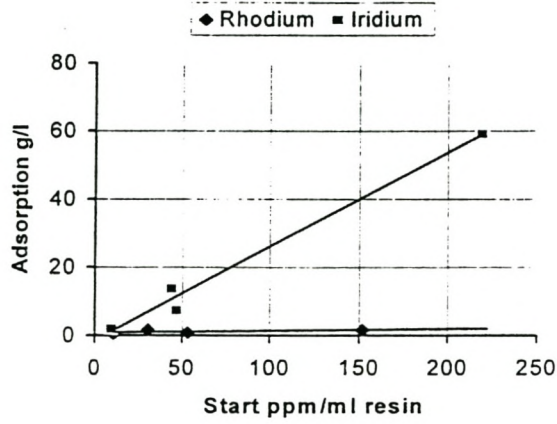


Fig.17 Rhodium and iridium adsorption in 6% HCl.

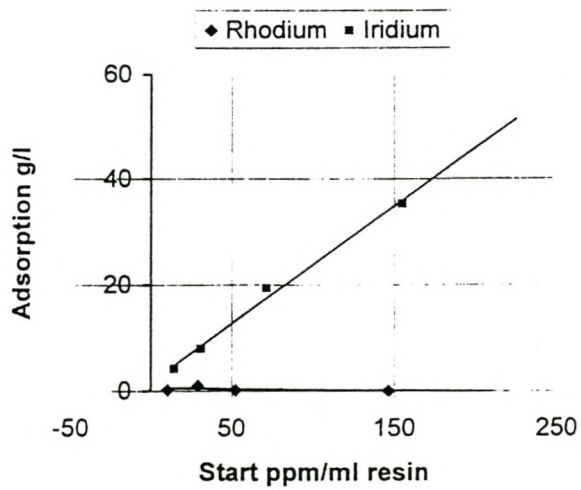


Fig.18 Rhodium and iridium adsorption in 10% HCl.



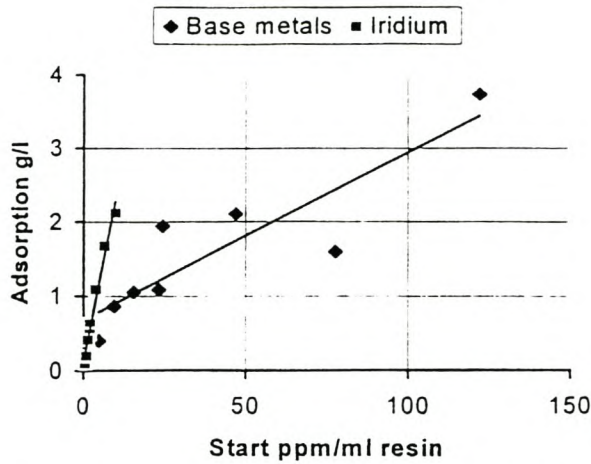


Fig.19 Iridium and base metals adsorption in 6% HCl.

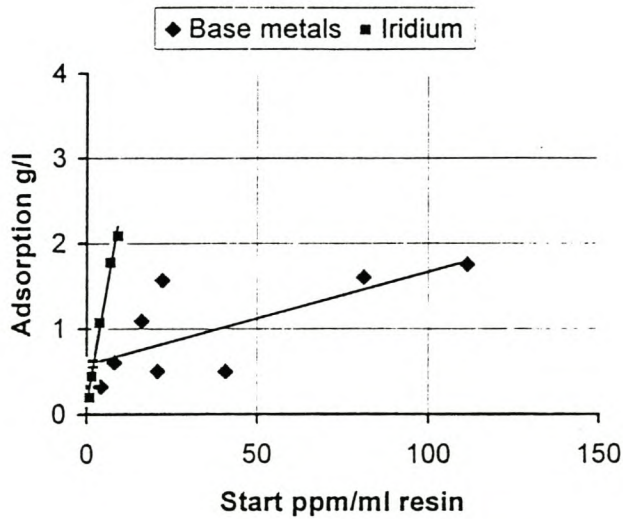


Fig.20 Iridium and base metals adsorption in 10% HCl.

### CONCLUSIONS

The resin uptake of precious metals is in the order of Au>Pt>Pd>Ru>Ir>Rh. Some sorption of base metals do also occur. The effect of additional components in the solution on the equilibrium adsorption is very small, mostly simply lowering the adsorptive capacity of a specific ion. The effect of chloride strength on the adsorption in the 6 to 10% free HCl range is small.

### ACKNOWLEDGEMENTS

The authors wish to express their sincere thanks to Mrs H Tan for her help with the experimental work. The contribution from Impala Platinum Refineries is also highly appreciated.

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## THE ADSORPTION OF BASE METALS AND PRECIOUS METALS ON IR200 ION EXCHANGE RESIN

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### 1 INTRODUCTION

Selective recovery of precious group metals (PGMs) from chloride solutions has always been a major challenge to chemists trying to isolate single metal compounds of high purity. Recently the focus has moved towards ion exchange technology and the use of active groups on a resin which can selectively extract specific species from a solution. Due to confidentiality reasons very little relevant literature is available on the separation of industrial precious metal solutions with ion exchange resins.

Due to the tendency of PGM ions to form anionic complexes, the focus for PGM recovery with ion exchange is more towards anion exchange resins. The PGM industry are refining of chloride complexes of the precious metals as this is the solution product after aqua-regia leaching, used for dissolution of the metal sulphides in the ore. The dissolved PGMs form anionic complexes with the general formula  $[MCl_x]^{n-}$ . The base metals tends to dissolve as cations in these solutions. The thermodynamics and kinetics of aqueous solution containing PGMs and base metals are not always well understood and therefore, remained tenaciously elusive<sup>1</sup>. The removal of base metals from precious metal solutions are very important to extract pure PGM's. It is essential that no precious metals are lost in the removal of base metals.

Study of the adsorption of PGM ions in an industrial solution containing a variety of PGM and base metal ions will therefore be difficult as there are too many species interacting in the solution. For this reason, single component solutions of the precious metals were prepared by using pure metal, or in some cases pure metal salts. These solutions served as a stock solution from which further dilutions to test concentrations was done. A synthetic base metal solution, including the PGMs, was prepared by adding all the individual components to match an industry based metal solution composition.

The adsorption characteristics of single metals were established and thereafter adsorption from a solution was studied to determine the effect of other ions competing for the adsorption sites on the resin. The effect of chloride strength on equilibrium adsorption was determined for 2, 5, and 8% free HCl in the solution.

### 2 RESIN USED

#### 2.1 Resin Description



The resin is a strong acid macroreticular cation exchange resin based on sulfonic acid exchange groups, the  $\text{SO}_3^-$  functional group, on a polystyrenic matrix. It has a high degree of crosslinking which imparts superior stability to the macroreticular structure of the resin. The resin is widely used for demineralisation and mixed bed units, hot process softeners, chemical processing and systems involving appreciable oxidative potential or high temperatures. Due to confidentiality the name of the resin will not be disclosed.

## 2.2 Resin Preparation

The resin was supplied in the sodium ionic form. The resin was prepared by contacting it in glass columns with upward flow of solution. The solution was pumped with a variable speed peristaltic pump. The upward flow of solution has to be very slow to allow displacement of the air from the resin bed and the connecting tubes as air pockets tend to lift the resin upwards and out of the column. The resin was initially washed with distilled water to remove all foreign ions entrapped from the factory floor. It was then washed with 14% HCl to displace the sodium. This was followed by a rinse with 5% HCl. The resin was then taken out of the column and put in a 5 litre plastic drum from where small amounts were taken for adsorption tests.

## 3 SOLUTION PREPARATION

### 3.1 PGM Dissolution

Platinum, palladium and gold solutions were prepared by dissolution of the pure metals in aqua-regia. Ruthenium, iridium, and rhodium were dissolved from pure salts. The salts were used because the dissolution of the metals is very difficult. Ruthenium was dissolved from the  $(\text{NH}_4)_2(\text{RuNOCl}_5)$  salt, iridium from  $(\text{NH}_4)_2(\text{IrCl}_6)$ , and rhodium from the DETA salt  $(\text{DETAH}_3)(\text{RhCl}_6)$ . DETA being the  $\text{C}_4\text{N}_3\text{H}_{10}$  chain. The mass required for a 2000 ppm stock solution was weighed out and boiled in aqua-regia until dissolved. More HCl was added, and the solution was boiled further to drive off all the nitric acid as  $\text{NO}_x$  fumes. The resulting free HCl in the solution was determined by titration. The solution was then diluted with the correct amounts of water and acid to achieve the desired final free acid and metal concentrations. From these 2000 ppm stock solutions, further dilutions to the actual test concentrations, ranging from 25 to 300 ppm and 2 to 8% HCl, were done.

### 3.2 Base Metal Solution

The composition of an industrial base metal solution was matched by adding all the required components in the correct quantities. The composition and reagents used for preparation of the base metal solution can be seen in Table 1. Ruthenium, rhodium and iridium were added from the previously prepared pure stock solutions.

Aqua-regia was added to dissolve all the solid components. All nitric acid was boiled off from the solution. The solution was then diluted to the required acid concentration and 2000 ppm PGM plus base metal concentration.



## 4 EXPERIMENTAL

For the determination of equilibrium points at a specific PGM concentration, the adsorption from the solution was determined by varying the amount of resin added to the solution. The volume of solution used for each test was either 500 or 1000 mL. Seven different quantities of resin were added to a specific solution concentration ranging between 0.5 mL to 100 mL resin. The amount of resin added to the solution was varied to achieve a low, as well as a high, total loading on the resin. In batch experimentation, the final solution concentration is unknown and it is therefore difficult to predict the eventual equilibrium concentration beforehand.

	Stock Individual ppm	Stock Individual Gram	Reagent Used	Metal MM	Reagent MM	Gram Reagent Required
Pt	845.1	9.1	Pt	195.09	195.09	9.1
Pd	422.5	4.6	Pd	106.4	106.4	4.6
Au	28.2	0.3	Au	196.967	196.967	0.3
Rh	98.6	1.1	2764 ppm stock		ml required	385
Ru	126.8	1.4	2620 ppm stock		ml required	523
Ir	42.3	0.5	7408 ppm stock		ml required	62
Ag	70.4	0.8	AgNO <sub>3</sub>	107.87	169.87	1.2
Ni	28.2	0.3	Ni(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	58.71	290.8	1.5
Cu	56.3	0.6	Cu(NO <sub>3</sub> ) <sub>2</sub> ·3H <sub>2</sub> O	63.54	241.6	2.3
Fe	56.3	0.6	Fe(NO <sub>3</sub> ) <sub>3</sub> ·9H <sub>2</sub> O	55.847	404	4.4
Pb	84.5	0.9	Pb(NO <sub>3</sub> ) <sub>2</sub>	207.19	331.2	1.5
As	14.1	0.2	As <sub>2</sub> O <sub>3</sub>	74.922	197.84	0.4
Se	42.3	0.5	Se	78.96	78.96	0.5
Te	84.5	0.9	Te	127.6	127.6	0.9
Total	2000.0	21.6				
Non PGM	436.6	4.7				

**Table 1** Preparation and composition of base metal solution

Although the PGMs form anionic complexes in chloride media, the adsorption tests were done for the PGMs to verify the adsorption. The resin was measured out in a small plastic measuring cylinder which was tapped against the bench for settlement of the resin beads. The test solution was prepared by dilution from the 2000 ppm stock solution to the required metal and free acid concentrations. A sample of the test solution was taken as reference before addition of the resin beads. All analyses were done by inductively coupled plasma spectrophotometry (ICP). The reference sample was titrated to check that the targeted free HCl concentration was correct. The resin was added to the solution and rolled in bottles for 24 hours to ensure equilibrium was attained. The bottles were rolled on a roller bench which facilitated multiple simultaneous tests. After exposure, a sample of the solution was taken and analysed by ICP. The adsorption was calculated by difference to the reference sample concentration. The solution potentials are reported for comparative purposes.



The following equilibrium adsorption tests were conducted:

1. Single component PGMs
2. Base metal solution
3. Effect of additional PGMs in the solution on adsorption
4. Effect of different  $\text{Cl}^-$  concentration (pH) on adsorption

IUPAC recommendations on ion exchange nomenclature define “theoretical specific capacity” as the milliequivalents of ionogenic group per gram of dry ion exchanger<sup>2</sup>. The ionogenic group in this instance is the  $\text{SO}_3^-$  functional group, it holds the ions capable of exchanging for other ions in the external solution. The actual uptake will not reach the theoretical capacity, for example, when there are exchange sites to which various ions have different accessibilities. Some sites may be entirely inaccessible to larger ions. The IUPAC recommendations also include the “practical specific capacity” of an ion exchanger. This is the total amount of ions expressed in milliequivalents taken up per gram of ion exchanger under specific conditions, which should always be given. The usual way to present adsorption isotherms is to plot on the Y axis the amount of say x adsorbed/capacity of the resin for x against the concentration of x in the solution/total concentration of x. In this case x will be one of the PGMs or base metals. From the above definition it is evident that the practical capacity depends on the experimental conditions. All the experimental work done was done by batch experimentation. To determine the maximum resin uptake of an specific ion, the practical capacity, the counter ion which is displaced from the resin must be continuously removed, such as in a column. The batch equivalent would be a large number of successive batch equilibrations in series.

From the experimental data analysis, it became evident that effective visualisation of the quantitative adsorption data can be obtained by combining the variable parameters such as solution concentration and quantity of resin used into a single ratio and to plot this ratio against the weight adsorbed per litre of resin. It is also evident that for each solution concentration the adsorption, expressed as gram/litre resin, increased as the amount of resin used decreased. This is due to the ratio of exchangeable ions in solution divided by the number of potential adsorption sites on the resin. Therefore the ratio used for the graphs is the initial concentration of precious metal in solution (which determines the potential quantity of ions to be adsorbed onto the resin) divided by the volume of resin used (which determines the total amount of adsorption sites available for adsorption). The graphs presented are therefore presented as such. It is evident that where the resin has a high preference for the ion to be exchanged, the initial slope of the graph will be high. This indicates that the resin has a high affinity for the ion to be exchanged and that high loading will be attained in dilute solutions.

## 5 RESULTS

### 5.1 Single Component PGM Adsorption

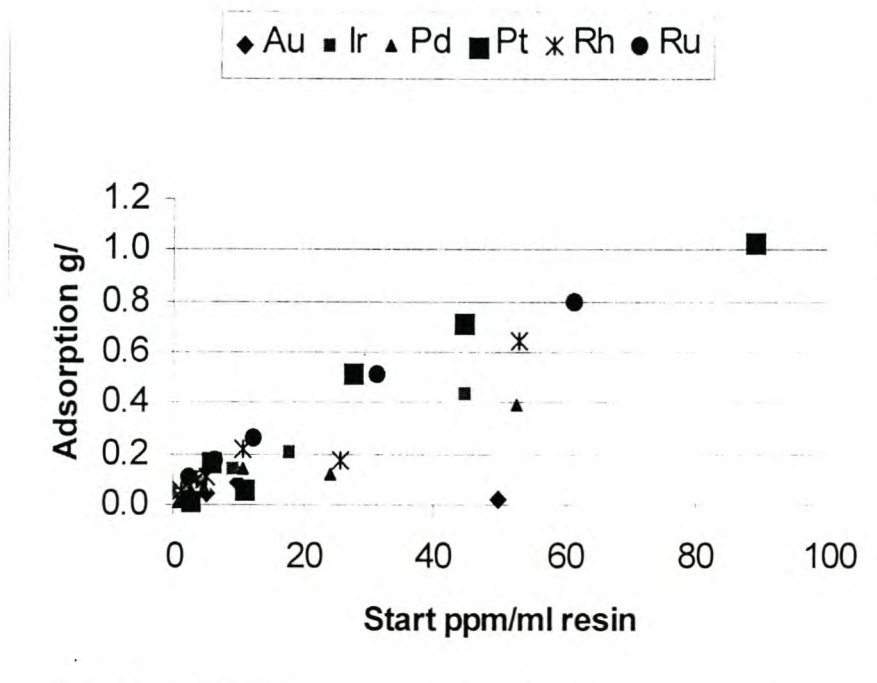
Two adsorption data points were determined for each test solution concentration used to establish the adsorption characteristics. It should be noted that inaccuracies occur for very small resin volumes, that is, where the ratio “Start ppm/mL resin” is large. Solution potential was measured with a platinum redox electrode with reference to Ag/AgCl. All results were determined at 2% free HCl concentration. It is important to note that although the adsorption graphs, presented in Figure 1, are all presented in a single figure



they were determined individually from single precious metal solutions. The initial PGM concentrations used for the adsorption tests ranged between 50 to 100 ppm as metal.

Gold is in solution as the  $\text{AuCl}_4^-$  ion, the solution potential was 750 mV. The iridium ion is present as  $\text{IrCl}_6^{3-}$ , 980 mV. Palladium is in solution as the  $\text{PdCl}_4^{2-}$  ion, 550 mV. Platinum is in solution as the  $\text{PtCl}_4^{2-}$  ion, 460 mV. Rhodium is in solution as one of the following chlorocomplexes<sup>1</sup>,  $\text{RhCl}_4(\text{H}_2\text{O})^-$ ,  $\text{RhCl}_5(\text{H}_2\text{O})^{2-}$ , or the  $\text{RhCl}_6^{3-}$  ion, depending on the equilibrium between these species, the solution potential was 400 mV. Ruthenium is in solution as one of the following chlorocomplexes<sup>1</sup>,  $\text{RuCl}_5(\text{H}_2\text{O})^{2-}$ , or the  $\text{RuCl}_6^{3-}$  ion, depending on the rhodium equilibrium between these species, 780 mV.

It is evident that some sorption of platinum, ruthenium, rhodium, iridium, and palladium does occur. Being present as anions, these ions can still penetrate the resin, but are not necessary bonded by ion exchange to the resin. It is noted that the adsorption quantities are very low, that is below 1 g/litre resin.



**Figure 1** Individual PGM adsorption

## 5.2 Base Metal Adsorption

The base metal solution composition, Table 1, can be simplified as in Table 2. The concentrations are presented as ppm metal.

COMP	Pt	Pd	Au	Rh	Ru	Ir	Ag	Ni	Cu	Fe	Pb	As	Se	Te	Total	Non PGM
ppm	845	423	28	99	127	42	70	28	56	56	85	14	42	85	2000	437

**Table 2** Base-metal solution composition

Two adsorption curves were drawn, Figure 2, for both 1.6% and 2% free HCl concentrations. In this graph, the individual base metals are added together and plotted as

a total base metals curve. The solutions used to establish the adsorption ranged between 50 ppm to 110 ppm combined base metal concentration, the solution potentials were in the region of 750 mV.

In Figure 3 the adsorption of the individual base metal components can be seen, the adsorption of each base metal component is shown. The start concentration of an individual component is much smaller than for the combined value, Figure 2, as can be seen on the x axis of the graph.

The preference for Ag, which is present as an impurity in this process stream, and for Fe and Pb can be seen from the graph.

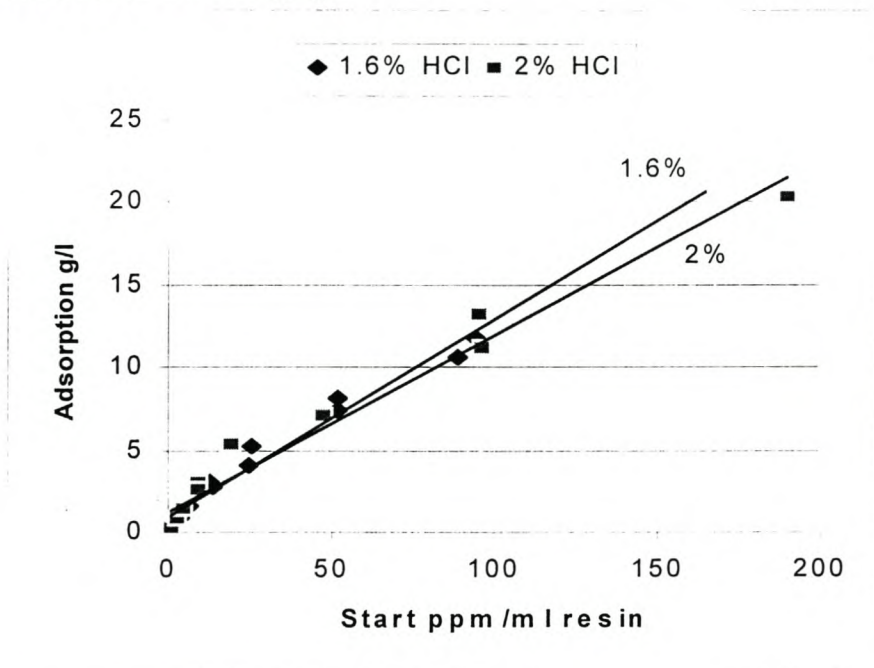


Figure 2 Total base metals adsorption

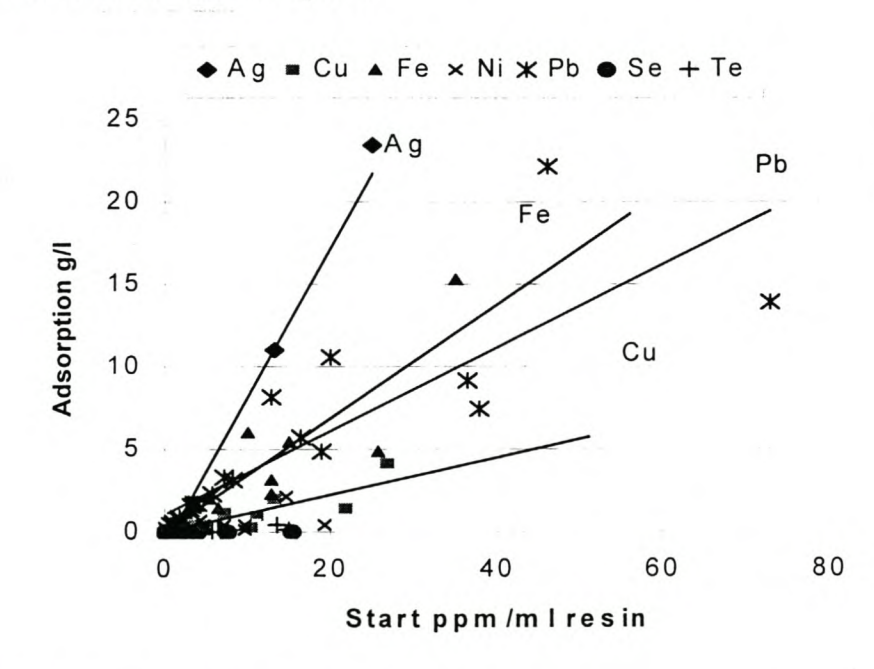


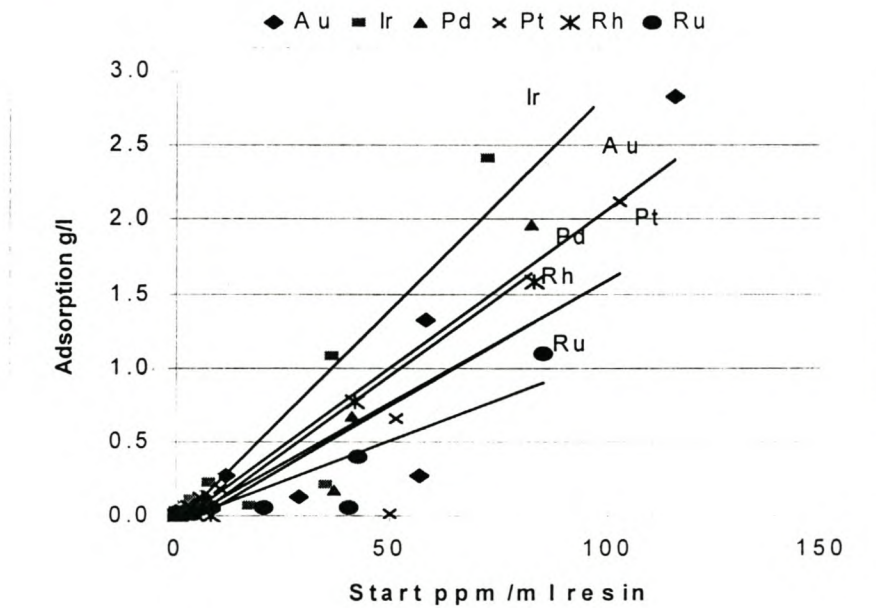
Figure 3 Individual base metal adsorption



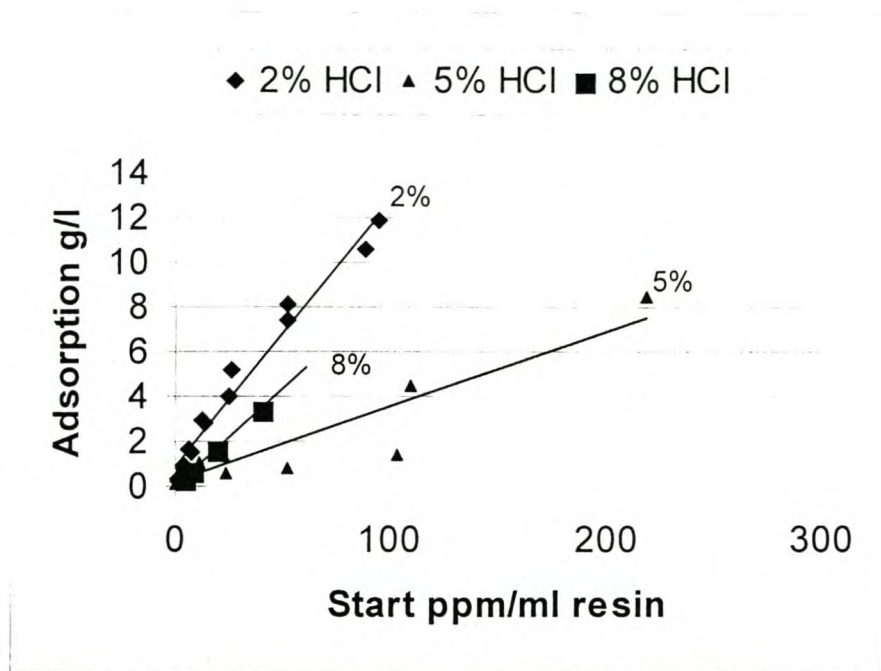
### 5.3 Effect of Additional PGMs in the Solution

A mixed solution containing all the PGMs, but excluding the base metals, was tested for adsorption for comparison to the single PGM adsorption characteristics, see Figure 4. Two mixed solutions with different concentrations of PGM were tested in 2% free HCl. The individual PGM concentrations ranged between 25 and 50 ppm, the solution potential was 790 mV.

It is interesting to note that in comparison to Figure 1- *Individual PGM adsorption*, gold which was not adsorbed at all individually is now the second most preferred ion. The iridium adsorption also improved for the mixed solution. The reason for the different equilibrium adsorption characteristics may be one of many, including the kinetics of adsorption in the resin particle.



**Figure 4** Adsorption of PGM from a mixed PGM solution



**Figure 5** Total base metals adsorption in different free HCl concentrations

#### 5.4 Effect of Different $\text{Cl}^-$ Concentration on Adsorption

The effect of HCl concentration on the adsorption was determined for 2, 5, and 8% free HCl in the solution. For each of the three chloride strengths, test solutions were prepared with base metal concentrations in the range of 50 to 110 ppm base metals only. The solution potential ranged from 650 to 750 mV. The adsorption characteristics can be seen in Figure 5.

The adsorption at 2% free chloride is the best, as to be expected as there is less protons in the solution competing for the adsorption sites on the resin.

## 6 CONCLUSIONS

From the above it is evident that some sorption of precious metals does occur, although in small quantities. Base metals are effectively adsorbed by the resin. It also became apparent that the preference of the resin for individual PGM ions changes when all the ions are together in solution. From the tests done, the best base metals adsorption was achieved at 2% free HCl.

### Acknowledgements

The authors wish to express their sincere thanks to Mrs H Tan for her help with the experimental work. The contribution from Impala Platinum Refineries is also highly appreciated.

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## THE ADSORPTION OF PRECIOUS AND BASE METALS ON XAD7 ION EXCHANGE RESIN

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### Abstract

The adsorption characteristics of XAD7 ion exchange resin has been established for precious metals and base metals. Synthetic single precious metal solutions as well as mixed solutions containing base metals were tested for adsorption. The effect of chloride strength on equilibrium adsorption was determined for 10.8, 14 and 17.2% free HCl in the solution.

*Keywords: Adsorption, resin, precious metals, base metals*

### Introduction

Selective recovery of precious group metals (PGM's) from chloride solutions has long been a major challenge to chemists trying to selectively isolate single metal compounds of high purity. Recently the focus has moved towards ion exchange technology and the use of active groups on a resin which can selectively extract specific species from a solution.

Due to the tendency of PGM ions to form anionic complexes, the focus for PGM recovery with ion exchange is more directed towards anion exchange resins. The PGM industry is refining the chloride complexes of the precious metals as these are the solution products resulting from aqua regia leaching, used for dissolution of the metal sulphides in the ore. The dissolved PGM's form anionic complexes with the general formula  $[MCl_x]^{n-}$ . The base metals tends to dissolve as cations in these solutions. The thermodynamics and kinetics of aqueous solutions containing PGM's and base metals are not always well understood and therefore, remained tenaciously elusive [Dhara, 1993].

To study the adsorption of PGM ions in an industrial solution containing a variety of PGM and base metal ions will therefore be difficult as there are too many species interacting in the solution. For this reason single component solutions of the precious metals were prepared by using pure metal, and in some cases pure metal salts. These solutions served as mother solution from which further dilution to test concentrations were done. A base metal solution, including the PGM's, was prepared by adding all the individual components to match an industry base metal solution composition.

The adsorption characteristics of a single metal were established and thereafter adsorption from a solution was studied to determine the effect of other ions



competing for the adsorption sites on the resin. The effect of chloride strength on equilibrium adsorption was determined.

### **XAD7 Resin**

The resin used was Amberlite XAD7. The resin is a polymeric adsorbent. It is a non-ionic aliphatic acrylic polymer which derives its adsorptive properties from its patented macroreticular structure (containing both a continuous polymer phase and a continuous pore phase). The adsorption is therefore not ion exchange as such. The macroreticular structure of the resin gives it excellent physical and thermal stability. Due to its aliphatic nature the resin can adsorb non polar compounds from aqueous systems, and can also adsorb polar compounds from non-polar solvents. It has been reported that the resin is ion specific towards gold [Fritz, 1973].

The resin was supplied wetted with NaCl and Na<sub>2</sub>CO<sub>3</sub> salts to prevent bacterial growth. The resin was prepared in glass columns with upward flow of solution. The solution was pumped with a variable speed peristaltic pump. The upward flow of solution has to be very slow to allow displacement of the air from the resin bed and the connecting tubes as air pockets tend to lift the resin upwards and out of the column. The resin was firstly washed with distilled water to remove all foreign ions entrapped from the factory floor. The resin was then washed with 14% HCl to prepare the resin for adsorption. The resin was then taken out of the column and put in a 5 litre plastic drum from where small amounts were taken for adsorption tests.

### **Solution Preparation**

Platinum, palladium and gold solutions were prepared by dissolution of the pure metals in aqua-regia. Ruthenium, iridium, and rhodium were dissolved from pure salts. The salts were used in instances where the dissolution of the metals are very difficult. Ruthenium was dissolved from the (NH<sub>4</sub>)<sub>2</sub>(RuNOCl<sub>5</sub>) salt, iridium from (NH<sub>4</sub>)<sub>2</sub>(IrCl<sub>6</sub>) salt, and rhodium from the DETA salt (DETAH<sub>3</sub>)(RhCl<sub>6</sub>). DETA being the C<sub>4</sub>N<sub>3</sub>H<sub>10</sub> chain. The mass required for a 2000 ppm stock solution was weighed off and boiled in aqua-regia until dissolved. More HCl was added, and the solution was boiled further to drive off all the nitric acid as NO<sub>x</sub> fumes. The resulting free HCl in the solution was determined by titration. The solution was then diluted with the correct amounts of water and acid to achieve the desired final free acid and metal concentration. From this 2000 ppm stock solutions further dilution to the actual test concentrations, ranging from 25 to 300 ppm and 10.8 to 17.2% HCl, were done.

#### *Base Metal Solution*

The composition of an industrial base metal solution was matched by adding all the required components in the correct quantities. Ruthenium, rhodium and iridium were added from the already prepared pure stock solutions. The composition of the base metal solution can be seen in Table I. The concentration is reported as ppm metal.



Table I: Base-metal solution composition

COMP	Pt	Pd	Au	Rh	Ru	Ir	Ag	Ni	Cu	Fe	Pb	As	Se	Te	Total	Base Metals
PPM	845	423	28	99	127	42	70	28	56	56	85	14	42	85	2000	437

Aqua-regia was added to dissolve all the solid components. All nitric was boiled off from the solution. The solution was then diluted to the required acid concentration and 2000 ppm PGM plus base metal concentration.

## Experimental

To determine equilibrium points at a specific PGM concentration the adsorption from the solution was established by varying the amount of resin added to the same solution concentration. The volume of solution used for each test was either 500 or 1000 ml. Seven different quantities of resin were added to a specific solution concentration ranging between 0.5 ml to 100 ml resin. The amount of resin added to the solution was varied to achieve a low as well as a high total loading on the resin. In batch experimentation the final solution concentration is unknown and it is therefore difficult to predict the eventual equilibrium concentration beforehand.

The resin was measured out in a small plastic measuring cylinder which was tapped against the bench for settlement of the resin beads. The test solution was prepared by dilution from the 2000 ppm stock solution to the required metal and free acid concentrations. A sample of the test solution was taken as reference before addition of the resin beads. All analysis were done by inductively coupled plasma (ICP). The reference sample was titrated to check that the targeted free HCl concentration was correct. The resin was added to the solution and rolled in bottles for 24 hours to ensure equilibrium was attained. The bottles were rolled on a roller bench which facilitate multiple simultaneous tests. After exposure a sample of the solution was taken and analysed by ICP. The adsorption was calculated by difference to the reference sample concentration.

IUPAC Recommendations on ion exchange nomenclature define “theoretical specific capacity” as the milliequivalents of ionogenic group per gram of dry ion exchanger [Lehto, 1995]. The ionogenic group holds the ions capable of exchanging for other ions in the external solution. The IUPAC recommendations also include the “practical specific capacity” of an ion exchanger. This is the total amount of ions expressed in milliequivalents taken up per gram of ion exchanger under specific conditions, which should always be given. The actual uptake will not reach the theoretical stated capacity, for example, when there are exchange sites to which various ions have different accessibility’s. Some sites may be entirely inaccessible to larger ions.

The usual way to present adsorption isotherms is to plot on the Y axis the amount of say  $x$  adsorbed / capacity of the resin for  $x$  against the concentration of  $x$  in the solution / total concentration of  $x$ . In this case  $x$  will be one of the PGM’s or base metals. For this graph the maximum capacity must be known. From the above definition it is evident that the practical capacity depends on the experimental conditions. All the experimental work done was done by batch experimentation. To



determine the maximum resin uptake of an specific ion, the practical capacity, the counter ion which is displaced from the resin must be continuously removed, such as in a column. The batch equivalent should be a large number of successive batch equilibration's in series.

## Results

From the experimental data analysis it became evident that instead of the usual representation, effective visualisation of the quantitative adsorption data can be obtained by combining the variable parameters like solution concentration and quantity of resin used into a single ratio and to plot this ratio against the gram adsorbed per litre of resin. It is also evident that for each solution concentration the adsorption, expressed as gram/litre resin, increase as the amount of resin used decrease. This is due to the ratio of exchangeable ions in solution divided by the number of potential adsorption sites on the resin. Therefore the ratio used for the graphs is the initial concentration of precious metal in solution (which determine the potential quantity of ions to be adsorbed onto the resin) divided by the ml of resin used (which determine the total amount of adsorption sites available for adsorption). The graphs presented are therefore presented as such. It is evident that where the resin has a high preference for the ion to be exchanged the initial slope of the graph, that is for small ppm / ml resin, will be high. This indicates that the resin has a high affinity for the ion to be exchanged and that high loading will be attained in dilute solutions.

### *Single Component PGM Adsorption*

Adsorption data points were determined for each test solution concentration used to establish the adsorption characteristics. It should be noted that inaccuracies occur for the very small resin volumes, that is where the ratio "Start ppm / ml resin" is large. Solution potential was measured with a platinum redox electrode with reference to Ag/AgCl. All single component graphs were determined at 14% free HCl concentration. It is important to note that although the adsorption graphs, presented in Figure 1, are all presented in a single figure they were determined individually from single precious metal solutions. The start PGM concentrations used for the adsorption tests ranged between 50 to 100ppm as metal. Gold is in solution as the  $\text{AuCl}_4^-$  ion, the solution potential was 670 mV. The iridium ion is present as  $\text{IrCl}_6^{3-}$  at 890 mV. Palladium is in solution as the  $\text{PdCl}_4^{2-}$  ion at 930 mV. Platinum is solution as the  $\text{PtCl}_4^{2-}$  ion at 900 mV. Rhodium is in solution as one of the following chlorocomplexes [Dhara, 1993],  $\text{RhCl}_4(\text{H}_2\text{O})^-$ ,  $\text{RhCl}_5(\text{H}_2\text{O})^{2-}$ , or the  $\text{RhCl}_6^{3-}$  ion, depending on the equilibrium between these species, the solution potential was 910 mV. Ruthenium is solution as one of the following chlorocomplexes [Dhara, 1993],  $\text{RuCl}_5(\text{H}_2\text{O})^{2-}$ , or the  $\text{RuCl}_6^{3-}$  ion, depending on the equilibrium between these species at 929 mV.

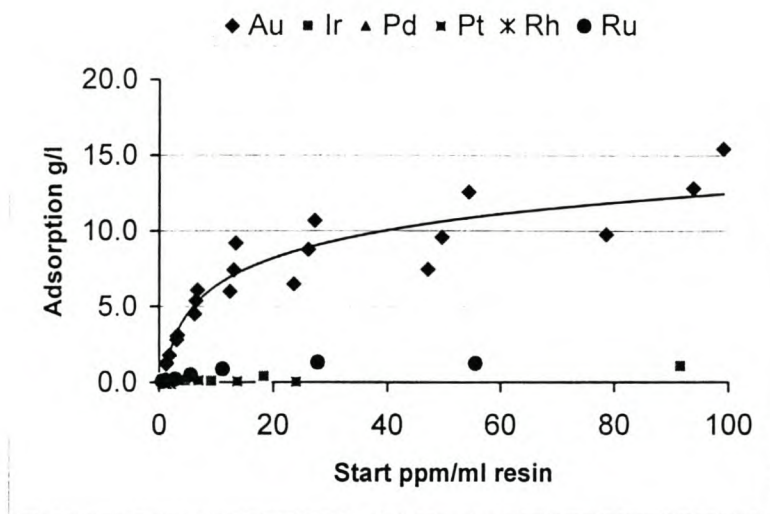


Figure 1: Individual PGM adsorption

Many data points were determined for gold at various solution strengths as it is known that the resin is selective towards gold. The PGM's not seen in the graph is due to negligible adsorption. It is evident that some sorption of ruthenium and iridium does occur. These ions can penetrate the resin, but are not necessarily adsorbed by the resin. It is noted that the adsorption quantities for PGM's other than gold are very low.

#### *Effect of Additional PGM's in the solution*

A mixed solution containing all the PGM's, excluding gold, was tested for adsorption. The mixed solution also included the base metals solution. The base metals are added together and treated as a total base metals content. The purpose of this test was to determine the next strongest binder to gold. From Figure 2 it is evident that very little adsorption of any of the other ions in solution occur.

Ruthenium was selected as the next strongest binder to gold. A mixed solution containing gold and ruthenium was tested to establish the selectivity of the resin for gold, see Figure 3. It is evident that hardly any adsorption of ruthenium is noticeable. The resin is very specific for gold.



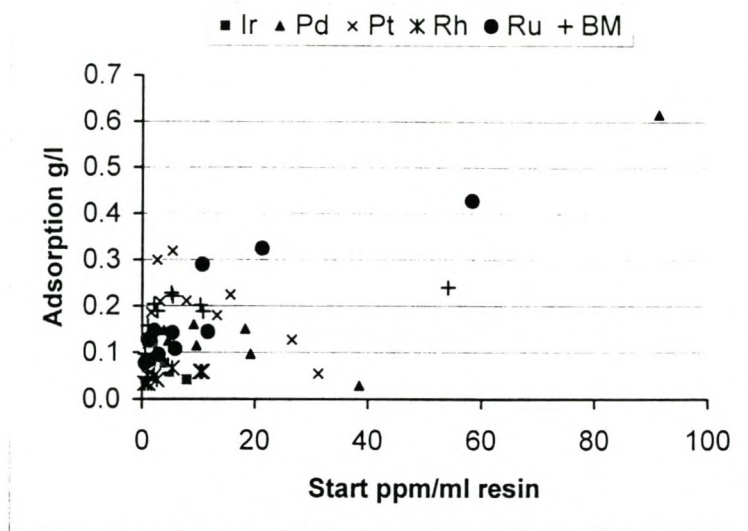


Figure 2: Adsorption from mixed solution excluding gold

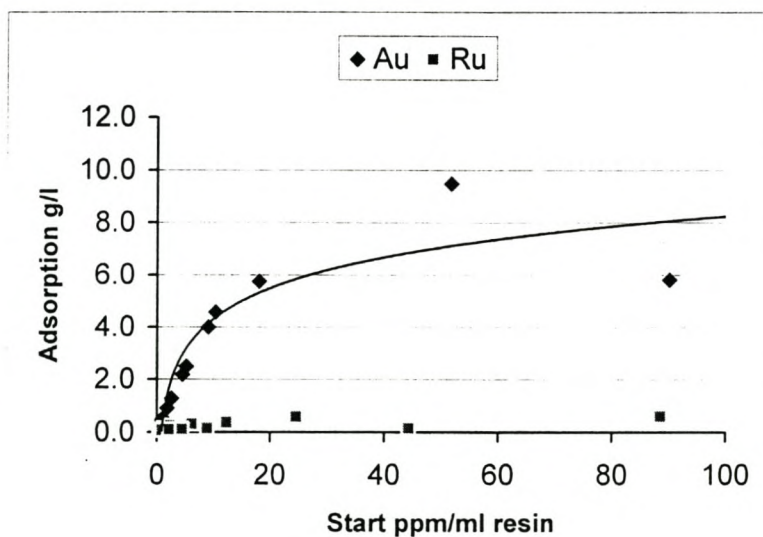


Figure 3: Adsorption from a gold plus ruthenium solution

*Effect of Different Cl<sup>-</sup> Concentration (pH) on Adsorption*

The effect of HCl concentration on the adsorption was determined for 10.8, 14, and 17.2% free HCl in the solution. For each of the three chloride strengths test solutions were prepared with gold concentrations in the range of 50 to 100 ppm. The solution potential ranged from 630 to 680 mV. The adsorption characteristic can be seen in Figure 4.

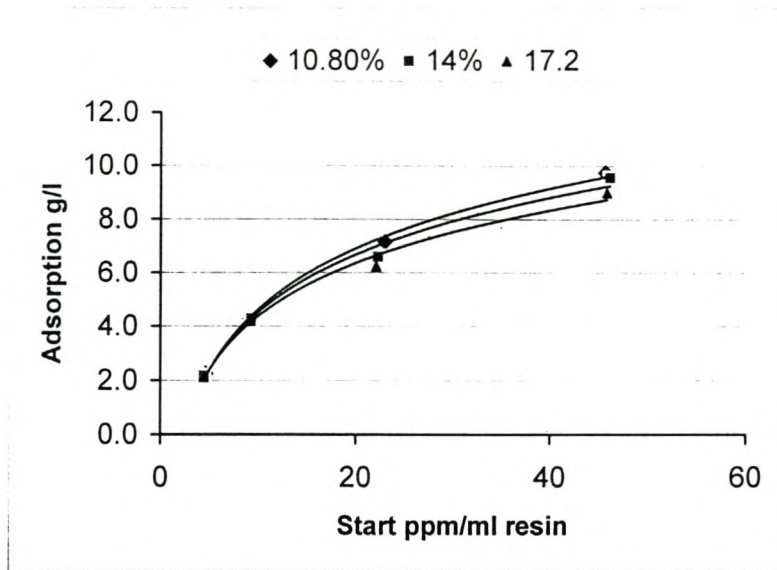


Figure 4: Gold adsorption with different acidity

The free HCl concentration has very little effect on the adsorption of gold. Lower acid concentrations tend to improve the adsorption quantity. To investigate the effect of different free chloride concentrations on the adsorption of other ions from a mixed solution the adsorption was tested for mixed solutions at 10.8% as well as for 17.2% free HCl, see Figures 5 and 6.

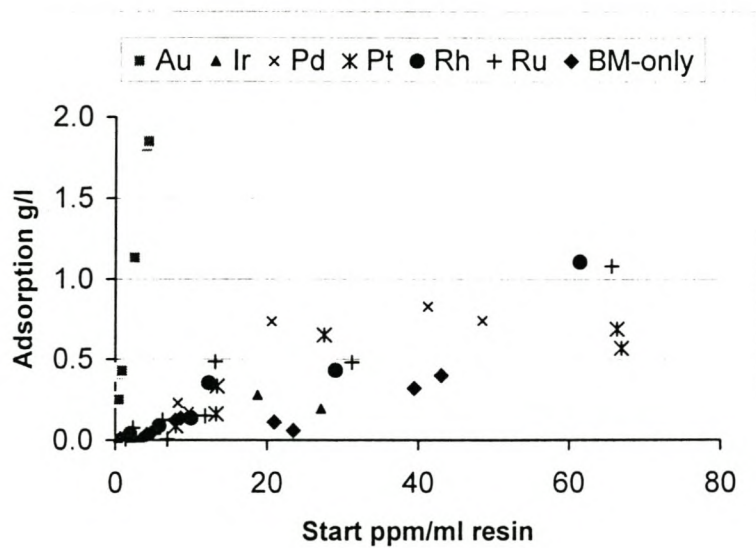


Figure 5: Adsorption from a mixed solution at 10.8% HCl



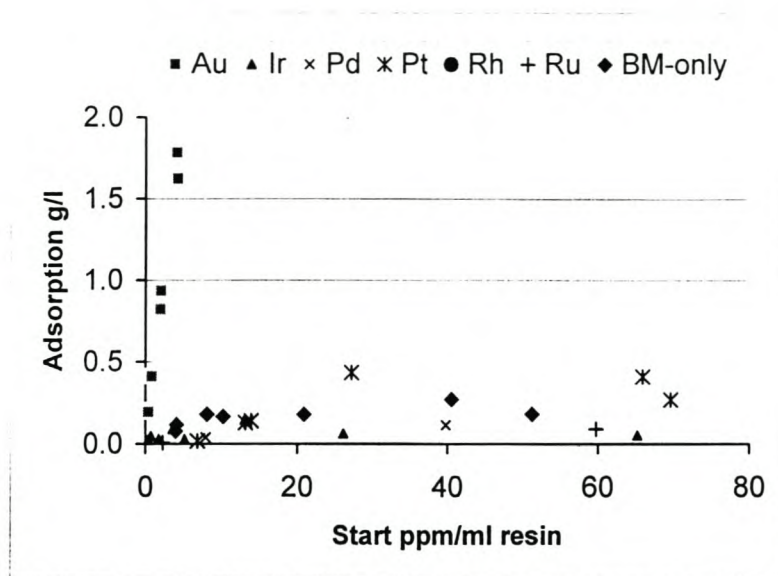


Figure 6: Adsorption from a mixed solution at 17.2% HCl

It is evident from Figures 5 and 6 that sorption of ions other than gold is very little. The sorption of other ions decrease with increased free chloride concentration.

## Conclusions

From the above it is evident that very little sorption of base metals and precious metals other than gold occur. The resin is very specific for gold even from mixed solutions. The concentration of free chloride in the solution does not effect the adsorption much.

## Acknowledgements

The authors wish to express their sincere thanks to Mrs H Tan for her help with the experimental work. The contribution from Impala Platinum Refineries is also highly appreciated.

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