

https://dspace.org/

Investigation of the leaching of the platinum group metal concentrate in hydrochloric acid solution by chlorine

Asamoah- Bekoe, Yaw

2016
http://hdl.handle.net/10539/21348

Downloaded from a DSpace repository. https://dspace.org/



INVESTIGATION OF THE LEACHING OF THE PLATINUM-GROUP METAL CONCENTRATE IN HYDROCHLORIC ACID SOLUTION BY CHLORINE.

Yaw Asamoah-Bekoe

INVESTIGATION OF THE LEACHING OF THE PLATINUM-GROUP METAL CONCENTRATE IN HYDROCHLORIC ACID SOLUTION BY CHLORINE.

Yaw Asamoah-Bekoe

Degree awarded with distinction on 8 December 1998

A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg,

March, 1998.

DECLARATION

I declare that this dissertation is my own, unaided work, except where specific acknowledgement is made. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.



Yaw Asamoah-Bekoe

5TH day of APRIL 1998.

ABSTRACT

The dissolution of platinum-group metals (PGMs) requires a high chloride ion concentration in an acidic solution and a suitable oxidant. At Impala Platinum Refinery, the concentrate is leached in a hydrochloric acid solution using chlorine gas as the oxidant. The goal of this leaching step is a total dissolution of the PGMs and gold. The silver precipitates as silver chloride. The efficiency of this stage is crucial for the performance of the precious metals refinery.

The aim of this project is to investigate the factors that influence the efficiency of the PGM leaching operation and to model for the results obtained. In order to investigate and evaluate the total dissolution of the PGMs in HCl/Cl_2 leach system, it is necessary to establish the effective conditions for the dissolution of chlorine gas in hydrochloric acid solution. The results showed that the solubility of chlorine gas increases with an increase in the acid concentration and chlorine gas concentration but decreases as the temperature increases. The HCl solution is almost saturated with chlorine after about 50 minutes. The chlorine mass transfer coefficient is dependent on the temperature, the stirrer speed, the concentration of the HCl solution and that of the chlorine.

The dissolution rates of PGMs and gold were investigated in hydrochloric acid with chlorine at ambient pressure under various conditions in a bench-scale stirred reactor. The PGMs dissolution rates were found to depend on the temperature, the acid concentration, the chlorine concentration, the initial particle size, agitation speed and the pressure. The PGMs dissolution in the HCl solution without chlorine revealed the presence of acid soluble PGMs which do not require chlorine or any oxidant to dissolve them. The results for both the chlorine soluble and acid soluble PGMs dissolutions were fitted into the shrinking particle kinetic model and the activation energies were determined.

The activation energies of the chlorine soluble PGMs dissolution for the temperature

range of 30°C to 80°C was found to be 42.36 $kJmol^{-1}$ for Pt, 40.19 $kJmol^{-1}$ for Pd, Rh was 44.56 $kJmol^{-1}$, Ru was 46.62 $kJmol^{1}$, Ir was 47.60 $kJmol^{1}$ and Au was 40.44 $kJmol^{-1}$. The reaction mechanisms were found to be generally chemical reaction control in conditions of full suspension of the particles. The PGMs dissolution reactions had an average of 0.77 order of dependence on the HCl concentration in the range 1.00 M to 10.0 M and 0.65 order of dependence on the chlorine concentration. Passivation of the PGMs by AgCl was also found to be evident.

The mineralogy and physical characteristics of the sample together with the reaction mechanism, the surface area change during leaching and the primary factors that affect the rate of reaction were considered in the development of the overall rate expression for the PGMs dissolution. Based on the sample analysis, a shrinking-particle model combined with the activation energy is used to show the dissolution behaviour of the PGMs in a batch reactor that would be useful for the Precious Metals Refineries. A computer program is developed to run the overall PGMs conversion model from the energy balance and chlorine mass balance based on the Impala refinery reactor.

To

My dearly beloved wife ***DOROTHY*** and daughter ***ESI*** who have been a source of encouragement to me, a pillar of good counsel, and an unfailing well of love and dedication.

God bless You!

ACKNOWLEDGEMENTS

Firstly, I wish to thank the Impala Platinum Refinery Limited, Springs for sponsoring this research work. I also wish to thank Impala for the use of their Analytical services and for supplying the sample that was used in the leaching experiments.

I gratefully acknowledge the interest and assistance given to me by the following people:
Dr Frank K Crundwell, my Supervisor needs to be praised for his great guidance and excellent motivation throughout the duration of this work. I wish to express my sincere appreciation and thanks to Professor Mike J Nicol for supervising my work when Frank was away to USA on sabbatical.

Mr Mark W Godfrey, the Consulting Metallurgist of Impala Platinum Limited for his keen interest, assistance and several discussions which helped me to get on well with the research. The assistance and encouragement I received from Mark and Mr Malcolm Isles, the Impala Projects Manager served as a major stimulus for my test work. Many thanks go as well to Dr Dirk de Waal (R&D Manager), Dr Myles Smith, Mr Ashok Jheelan, Mrs Ilani Hattingh (Senior Analytical Chemist) and all the Impala Platinum staff both at the Plant and Projects, not fogetting Wendy and Elrina at Impala Library for their invaluable assistance throughout the various stages of the research.

Mr Eugene Louwrens, Gencor Laboratory, deserves credit for his assistance in the chemical and mineralogical analysis of the sample.
I am thankful to all at the School of Process and Material Engineering, particularly my friends Paul Holmes, Douglas Mughogho, Kofi Gyabaah, Samuel Eshun and family and all the Ghanaian community in Johannesburg for making me feel very much at home.

My dear wife Dot, for her great support and motivation when I needed it most.

Lastly, I wish to express my gratitude to the Almighty GOD, without whom nothing is possible. I will forever remember His word to me - Gen.28[15].

LIST OF ABBREVIATIONS

Abbreviation	Full expression
A	Ampere
A	Acid soluble Platinum group metals
AES	Atomic Emission Spectrometry
aq	Aqueous
BMR	Base Metals refinery
C	Chlorine soluble Platinum group metals
Cl_2	Chlorine gas
C_M	weight % of the PGM in sample into leach
Cor.	Corrosion potential
conc.	Concentration
EDAX	Energy dispersive analysis of X-rays
EDS	Energy dispersive spectroscopy
ener.	Energy
exp	exponential function
Fig.	Figure
g	gramme
Gr	Group
HCl	Hydrochloric acid
ICP	Inductively Coupled Plasma
INCO	International Nickel Company
K	degree Kelvin
KI	Potassium iodide
ln	Natural logarithm
m	mass of solid sample

Abbreviation	Full expression
M	Molarity (=mol l^{-1})
M^*	Metal
MIBK	Methyl isobutyl ketone
min	minute
org	Organic
PGE	Platinum-group elements
PGM	Platinum-group metal
pH	hydrogen ion exponent
PMR	Precious Metal Refinery
ppm	parts per million
red.	Redox potential
rpm	revolutions per minute
SEM	Scanning Electron Microscope
Spd	Speed
Stir.	Stirrer
TBP	Tributyl phosphate
Temp.	Temperature
V	Volts
V	Volume of solution
vol.	Volume
vs	versus
XRD	X-ray diffraction

CONTENTS

Declaration
Abstract
Acknowledgements
List of Abbreviations
Contents
List of Figures
List of Tables
Nomenclacture

CHAPTER 1: INTRODUCTION 1

1.1 Literature Survey.....2
1.1.1 Description of Processes for the recovery of PGMs.....3
1.1.1.1 Leaching of PGM concentrate using Aqua regia.....4
1.1.1.2 Leaching of PGM concentrate using chlorine gas as oxidant.....7
1.1.2 Chemistry of the dissolution of PGM concentrates.....11
1.1.3 Dissolution reactions.....18
1.2 Aims and Scope of this Research work.....22
1.2.1 Research Objective.....22
1.2.2 Motivation and Scope of the Study.....23

CHAPTER 2: THEORETICAL ANALYSIS AND MODELLING 24

2.1 Modelling of the Leaching kinetics of the PGMs.....25
2.1.1 Shrinking Particle model.....26
2.1.1.1 Chemical Reaction Control.....26
2.1.1.2 Solution Film Diffusion Control.....27
2.2 Proposed Kinetic Model describing the PGM dissolution.....28

CHAPTER 3: EXPERIMENTAL APPARATUS AND PROCEDURE 30

3.1 Concentrate Sample Preparation.....30
3.1.1 Chemical Analysis of the bulk concentrate sample.....30
3.1.2 Mineralogical Analysis of the Concentrate sample.....31
3.1.3 Particle Size Analysis of the concentrate sample.....32
3.1.4 Chemical Composition of the Concentrate Sample.....35
3.2 Apparatus.....37
3.3 Chemical Reagents.....39
3.4 Experimental Procedure.....39
3.4.1 Procedure for the Chlorine Dissolution in HCl.....40
3.4.1.1 Chemical Analysis: Titration method for the Cl_2 concentration.....40
3.4.2 Procedure for Leaching the PGM concentrate sample.....42
3.4.2.1 Sample Analysis.....44
3.4.2.2 Calculations of extractions during the leaching.....44
3.4.3 Procedure for the PGM Leach Tests in Autoclave.....45
3.5 Etch Tests.....46
3.6 SEM Analysis of the Leach Residue samples.....49
3.7 Procedure for the Impala Refinery Plant Tests.....52

CHAPTER 4: RESULTS OF THE EXPERIMENTAL WORK 54

4.1 Experimental Results for the Chlorine dissolution.....54
4.1.1 Reproducibility of the Chlorine dissolution.....54
4.1.2 Effect of Temperature on Rate of Chlorine dissolution in HCl.....55
4.1.3 Effect of HCl concentration on Saturated Chlorine concentration.....61
4.1.4 Effect of Chlorine flowrate on the Rate of Cl_2 dissolution in HCl.....63
4.1.5 Effect of Agitation Speed on the Rate of Cl_2 dissolution in HCl.....64
4.2 Experimental results for the leaching of the PGMs.....66
4.2.1 Reproducibility of the PGMs leaching.....66

4.2.2 Effect of Temperature on the PGMs dissolution rate.....67
4.2.3 Effect of HCl concentration on the PGMs dissolution rate.....71
4.2.4 Effect of Chlorine flowrate on the PGMs dissolution rate.....75
4.2.5 Effect of Initial Particle size on the rate of PGMs dissolution.....79
4.2.6 Effect of Agitation speed on the rate of PGMs dissolution.....82
4.2.7 Effect of Reactor Pressure on the rate of PGMs dissolution.....86
4.2.8 Redox potentials measurement during the Leach test.....89
4.3 Results for the Impala plant reactor test 91
4.3.1 Heat Transfer Coefficient of the Impala plant Reactor.....91
4.3.2 Mass Transfer Coefficient of the Impala plant Reactor.....93
4.3.3 PGM dissolution with the Impala plant reactor.....95

CHAPTER 5: ANALYSIS OF THE EXPERIMENTAL RESULTS 96

5.1 Applications of the Model to the Experimental results.....96
5.2 The Leaching Rate Model.....103
5.3 Analysis of the Rate of Cl_2 soluble PGMs dissolution with Temperature.....108
5.4 Analysis of the Rate of Cl_2 soluble PGMs dissolution with HCl conc.....113
5.5 Analysis of the Rate of PGMs dissolution with Chlorine concentration.....117
5.6 Effect of Initial particle size on the Rate of Cl_2 soluble PGM dissolution.....127
5.7 Analysis of the Acid soluble PGMs to the Fit of the shrinking particle model..132
5.8 Comparison between Experimental results and the Plant test results for the fit of the proposed model.....143
5.9 Overall Leaching rate model for the PGMs dissolution.....146
5.10 Combined model for the Plant Reactor.....148

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS 152

6.1 Conclusions.....152
6.2 Recommendations.....157

BIBLIOGRAPHY 158

APPENDIX 164

Appendix A.....164
- Some Physical properties of the Platinum-group metals.

Appendix B.....166
- Raw data for the Chlorine dissolution tests.

Appendix C.....173
- Results for the Leaching experiments of the PGMs
  - Experimental measurements,
  - Mass balances,
  - Extractions versus time and redox potential data.

Appendix D.....286
- Raw data for the Heat transfer coefficient for the Impala reactor 2101,
- Raw data for the Mass transfer coefficient of the Impala reactor 2101,
- Raw data for the Impala plant leach test.

Appendix E.....291
- Derivation and calculation of the overall Heat transfer coefficient for the Impala reactor 2101.
- Derivation of the equation of the Mass transfer coefficient.

Appendix F.....297
- C++ computer program for solving 14 differential equations for
  - Energy balance,
  - Chlorine mass balance
  - PGMs leaching reactions,

  to calculate the PGMs dissolution conversion from the Chlorine soluble and acid soluble PGM fractions for the Impala reactor

LIST OF FIGURES

Figure Page

1.1 Aqua regia leaching of PGM concentrate process flow.....6
1.2 Process flow for PGM concentrate leach with HCl/Cl_2 gas followed by solvent extraction.....9
1.3 E_h-pH diagram for Pt-Cl-H_20 system at $[Pt]=10^{-6}M$, $[Cl^-]=1.00M$.....12
1.4 E_h-pH diagram for Pd-Cl-H_20 system at $[Pd]=10^{-6}M$, $[Cl^-]=1.00M$.....13
1.5 E_h-pH diagram for Au-Cl-H_20 system at $[Au]=10^{-6}M$, $[Cl^-]=1.00M$.....13
1.6 E_h-pH diagram for Ag-Cl-H_20 system at $[Ag]=10^{-6}M$, $[Cl^-]=1.00M$.....14
3.1 Cummulative Particle size distribution graph for the Malvern and dry screen analysis.....33
3.2 Percentage Particle size distribution graph for the Malvern analysis.....33
3.3 Percentage Particle size distribution for the Dry screen analysis.....35
3.4 Schematic diagram of the Leach Reactor.....37
3.5 Schematic diagram of the Constant-temperature Bath Leach equipment.....38
4.1 Reproducibility of Chlorine dissolution in hydrochloric acid results.....54
4.2 Effect of Temperature on the rate of Chlorine dissolution in 11.50 M hydrochloric acid solution.....55
4.3 Effect of Temperature on the rate of Chlorine dissolution in 6.00 M hydrochloric acid solution.....56
4.4 Effect of Temperature on the rate of Chlorine dissolution in 2.00 M hydrochloric acid solution.....56
4.5 Variation of $\ln(1-C/C_s)$ with time to determine mass transfer coefficient at different temperatures in 11.50 M hydrochloric acid.....57
4.6 Variation of $\ln(1-C/C_s)$ with time to determine mass transfer coefficient at different temperatures in 6.00 M hydrochloric acid.....59

4.7 Variation of ln(1-C/C_s) with time to determine mass transfer coefficient at different temperatures in 2.00 M hydrochloric acid.....59
4.8 Arrhenius plot for the Chlorine dissolution in HCl solution at different acid concentrations.....60
4.9 Effect of HCl concentration on the saturated Chlorine concentration.....61
4.10 Relationship between the Mass transfer coefficient and HCl concentration at different temperatures 62
4.11 Effect of Chlorine concentration on the rate of dissolution in HCl.....63
4.12 Effect of Agitation on the rate of Chlorine dissolution in 6.00 M hydrochloric acid solution.....64
4.13 Variation of ln(1-C/C_s) with time to determine mass transfer coefficient at different agitation speeds 65
4.14 Relationship between the Mass transfer coefficient and stirrer speeds.....65
4.15 Reproducibility of the Leaching results - Platinum.....66
4.16 Reproducibility of the Leaching results - Rhodium.....67
4.17 Effect of Temperature on Platinum dissolution rate.....68
4.18 Effect of Temperature on Palladium dissolution rate.....68
4.19 Effect of Temperature on Rhodium dissolution rate.....69
4.20 Effect of Temperature on Ruthenium dissolution rate.....69
4.21 Effect of Temperature on Iridium dissolution rate.....70
4.22 Effect of Temperature on Gold dissolution rate.....70
4.23 Effect of HCl concentration on Platinum dissolution rate.....72
4.24 Effect of HCl concentration on Palladium dissolution rate.....72
4.25 Effect of HCl concentration on Rhodium dissolution rate.....73
4.26 Effect of HCl concentration on Ruthenium dissolution rate.....73
4.27 Effect of HCl concentration on Iridium dissolution rate.....74
4.28 Effect of HCl concentration on Gold dissolution rate.....74
4.29 Effect of Chlorine concentration on Platinum dissolution rate.....75
4.30 Effect of Chlorine concentration on Palladium dissolution rate.....76
4.31 Effect of Chlorine concentration on Rhodium dissolution rate.....76

4.32 Effect of Chlorine concentration on Ruthenium dissolution rate.....77
4.33 Effect of Chlorine concentration on Iridium dissolution rate.....77
4.34 Effect of Chlorine concentration on Gold dissolution rate.....78
4.35 Effect of Initial Particle size on Platinum dissolution rate.....79
4.36 Effect of Initial Particle size on Palladium dissolution rate.....80
4.37 Effect of Initial Particle size on Rhodium dissolution rate.....80
4.38 Effect of Initial Particle size on Ruthenium dissolution rate.....81
4.39 Effect of Initial Particle size on Iridium dissolution rate.....81
4.40 Effect of Initial Particle size on Gold dissolution rate.....82
4.41 Effect of Agitation speed on Platinum dissolution rate.....83
4.42 Effect of Agitation speed on Palladium dissolution rate.....83
4.43 Effect of Agitation speed on Rhodium dissolution rate.....84
4.44 Effect of Agitation speed on Ruthenium dissolution rate.....84
4.45 Effect of Agitation speed on Iridium dissolution rate.....85
4.46 Effect of Agitation speed on Gold dissolution rate.....85
4.47 Effect of Reactor pressure on Platinum dissolution rate.....86
4.48 Effect of Reactor pressure on Palladium dissolution rate.....87
4.49 Effect of Reactor pressure on Rhodium dissolution rate.....87
4.50 Effect of Reactor pressure on Ruthenium dissolution rate.....88
4.51 Effect of Reactor pressure on Iridium dissolution rate.....88
4.52 Effect of Reactor pressure on Gold dissolution rate.....89
4.53 Redox potential measurements during the leach test with temperature.....90
4.54 Comparison of Redox and Corrosion potentials during No Cl_2 leach test....90
4.55 Heating and Cooling curves for the Impala PMR reactor 2101.....91
4.56 Overall Heat transfer coefficient for the Impala reactor 92
4.57 Chlorine dissolution in 6.00 M HCl solution in the Impala PMR reactor.....94
4.58 Determination of the Mass transfer coefficient of the Impala PMR reactor....94
4.59 Dissolution of the PGMs in the Impala PMR reactor with 6.00 M HCl.....95
5.1 Plot of $1-(1-X)^{1/3}$ vs time for Platinum on total HCl/Cl_2 leach.....97
5.2 Dissolution of the 5th stage PGM concentrate material without chlorine.....98
5.3 Dissolution of the 4th stage PGM concentrate material without chlorine.....99

5.4 Dissolution of the Dry chlorinated PGM concentrate without chlorine.....99
5.5 Comparison of Acid soluble, Chlorine soluble and Total Pt. Extraction.....102
5.6 Product layer diffusion control model plot for Chlorine soluble Platinum...103
5.7 Film layer diffusion control model for large particles plot - Platinum.....104
5.8 Film layer diffusion control model for small particles plot - Platinum.....104
5.9 Chemical reaction control model plot for Chlorine soluble Pt. dissol.....105
5.10 Chemical reaction control model plot for Acid soluble Pt. dissolution.....107
5.11 Dependence of temperature on the rate of Cl_2 soluble Pt. dissolution.....109
5.12 Dependence of temperature on the rate of Cl_2 soluble Pd. dissolution.....109
5.13 Dependence of temperature on the rate of Cl_2 soluble Rh. dissolution.....110
5.14 Dependence of temperature on the rate of Cl_2 soluble Ru. dissolution.....110
5.15 Dependence of temperature on the rate of Cl_2 soluble Ir. dissolution.....111
5.16 Dependence of temperature on the rate of reaction of Au. dissolution.....111
5.17 Arrhenius plot for the dissolution of the Cl_2 soluble PGMs and gold in the HCl/Cl_2 system.....112
5.18 Effect of HCl concentration on the rate of Cl_2 soluble Pt. dissolution.....113
5.19 Effect of HCl concentration on the rate of Cl_2 soluble Pd. dissolution.....114
5.20 Effect of HCl concentration on the rate of Cl_2 soluble Rh. dissolution.....114
5.21 Effect of HCl concentration on the rate of Cl_2 soluble Ru. dissolution.....115
5.22 Effect of HCl concentration on the rate of Cl_2 soluble Ir. dissolution.....115
5.23 Effect of HCl concentration on the rate of total Au. dissolution.....116
5.24 Reaction order with respect to HCl conc. for the Cl_2 soluble PGMs and gold.....117
5.25 Relationship between chlorine concentration and redox potential with time in 6.00 M HCl at 30°C.....119
5.26 Relationship between chlorine concentration and redox potential with time in 6.00 M HCl at 50°C.....121
5.27 Relationship between chlorine concentration and redox potential with time in 6.00 M HCl at 60°C.....121
5.28 Relationship between the redox potential and the chlorine dissolution.....122
5.29 Variation of the leaching rate with chlorine conc. for Cl_2 soluble Pt.....124

5.30 Variation of the leaching rate with chlorine conc. for Cl_2 soluble Pd.....124
5.31 Variation of the leaching rate with chlorine conc. for Cl_2 soluble Rh.....125
5.32 Variation of the leaching rate with chlorine conc. for Cl_2 soluble Ru.....125
5.33 Variation of the leaching rate with chlorine conc. for Cl_2 soluble Ir.....126
5.34 Variation of the leaching rate with chlorine concentration for Au.....126
5.35 Reaction order with respect to chlorine conc. for the
Cl_2 soluble PGMs and gold.....127
5.36 Variation of the leaching rate with initial particle size for Cl_2 soluble Pt.....128
5.37 Variation of the leaching rate with initial particle size for Cl_2 soluble Pd.....128
5.38 Variation of the leaching rate with initial particle size for Cl_2 soluble Rh.....129
5.39 Variation of the leaching rate with initial particle size for Cl_2 soluble Ru.....129
5.40 Variation of the leaching rate with initial particle size for Cl_2 soluble Ir.....130
5.41 Variation of the leaching rate with initial particle size for Au.....130
5.42 A plot of the reaction rate constant versus the inverse of the
initial particle diameter for the Cl_2 soluble PGMs and Au.....131
5.43 Chemical reaction control model plot for the Acid soluble Pt. dissol.....133
5.44 Chemical reaction control model plot for the Acid soluble Pd. dissol.....133
5.45 Chemical reaction control model plot for the Acid soluble Rh. dissol.....134
5.46 Chemical reaction control model plot for the Acid soluble Ru. dissol.....134
5.47 Chemical reaction control model plot for the Acid soluble Ir. dissol.....135
5.48 Arrhenius plot for the dissolution of the Acid soluble PGMs
in the HCl/Cl_2 system.....135
5.49 Effect of HCl concentration on the rate of Acid soluble Pt. dissolution.....136
5.50 Effect of HCl concentration on the rate of Acid soluble Pd. dissolution.....137
5.51 Effect of HCl concentration on the rate of Acid soluble Rh. dissolution.....137
5.52 Effect of HCl concentration on the rate of Acid soluble Ru. dissolution.....138
5.53 Effect of HCl concentration on the rate of Acid soluble Ir. dissolution.....138
5.54 Order of reation with respect to HCl conc. for the Acid soluble PGMs.....139
5.55 Effect of Initial particle size on dissolution rate for Acid soluble Pt.....140
5.56 Effect of Initial particle size on dissolution rate for Acid soluble Pd.....140
5.57 Effect of Initial particle size on dissolution rate for Acid soluble Rh.....141

5.58 Effect of Initial particle size on dissolution rate for Acid soluble Ru.....141
5.59 Effect of Initial particle size on dissolution rate for Acid soluble Ir.....142
5.60 A plot of the reaction rate constant versus the inverse of the initial particle diameter for the Acid soluble PGMs.....142
5.61 PGM dissolution in 6.00 M HCl solution with the Impala Reactor 2101....143
5.62 PGM dissolution in 6.00 M HCl solution with the Laboratory reactor.....144
5.63 Determination of the overall rate constant for the Chlorine soluble Pt.....147
5.64 A plot of the PGMs conversion from the computer program output for the Impala plant test results.....150

PHOTOS

3.1 Scanning electron micrographs of the initial PGM particles of the concentrate before leaching.....47
3.2 Scanning electron micrographs of the PGM particles of the fresh concentrate sample before leaching.....47
3.3 Scanning electron micrographs of the PGM sample after 1 hour leach in 6.00 M HCl solution at 30°C.....48
3.4 Scanning electron micrographs of the PGM sample after 2 hour leach in 6.00 M HCl solution at 30°C.....48
3.5 Scanning electron micrographs of a 6 hour leached residue from the laboratory leach test in 6.00 M HCl at 30°C.....50
3.6 Scanning electron micrographs of a 6 hour leached residue from the laboratory leach test in 6.00 M HCl at 30°C.....50
3.7 Scanning electron micrographs of a 6 hour leached residue from the laboratory leach test in 6.00 M HCl at 80°C.....51
3.8 Scanning electron micrographs of a 6 hour leached residue from the laboratory leach test in 6.00 M HCl at 80°C.....51

LIST OF TABLES

Table Page

3.1 Chemical analysis of the bulk concentrate sample.....30
3.2 Particle size analysis of the Sample by Malvern.....32
3.3 Particle size distribution of the PGM sample by Dry screening.....34
3.4 Chemical composition of the Size fractions of the sample.....36
4.1 Temperature influence on Mass transfer coefficient of Cl_2 dissolution in HCl solution.....58
5.1 Percentage PGM extraction of different stages material without chlorine.....98
5.2 Chlorine concentrations from redox potentials during PGM dissolution.....120
5.3 Comparison of the PGM dissolutions with the Laboratory reactor and the Impala plant reactor.....144
5.4 Ruthenium mass balance for the laboratory leach test 21.....145
5.5 Values of k_o for the Chlorine soluble and Acid soluble PGMs and Au.....147
6.1 Comparison of the dissolution of the PGMs with and without Chlorine.....153
6.2 A summary of activation energies, the order of reactions with respect to HCl and chlorine concentrations for the PGMs and Au.....154
6.3 A summary of the leaching rate expressions for the Chlorine soluble PGMs and gold.....155
6.4 A summary of the leaching rate expressions for the Acid soluble PGMs and gold.....156
A1 Some physical properties of the PGMs.....165
B1 Raw data for the Chlorine dissolutions.....167
C1.1 - C28.3:
C1.1 Raw Data for the Leaching Experiment 1.....175
C1.2 Assay values for Leach 1 solids.....176
C1.3 Mass balance values for Leach 1.....176
C1.4 Extraction vs Time data for Leach 1.....177

C27.1 Raw Data for the Leaching Experiment 27.....279
C27.2 Assay values for Leach 27 solids.....280
C27.3 Mass balance values for Leach 27.....280
C27.4 Extraction vs Time data for Leach 27.....281
C28.1 Evaluation of the Chlorine soluble Platinum (30°C).....283
C28.2 Evaluation of the Chlorine soluble Platinum (40°C).....284
C28.3 Evaluation of the Chlorine soluble Platinum (50°C).....285

D1.1 Raw data for the Heat transfer coefficient of the Impala reactor 2101.....287
D1.2 Raw data for the Chlorine mass transfer coefficient for the reactor.....288
D1.3 Raw data for the Impala plant Leach test.....289
D1.4 Extraction vs time data for the Impala plant Leach test.....290

NOMENCLACTURE

Symbol	Description	Dimensions
a	Reaction order with respect to HCl conc.	-
A	Heat transfer area	m^2
A	Particle surface area	m^2
A_o	Arrhenius pre-exponential factor	-
b	Reaction order with respect to Cl_2 conc.	-
C	Concentration of chlorine gas at time t	M
C_{pi}	Specific heat capacity of component i	kJs^{-1}
C_s	Saturated chlorine concentration	M
d_o	Initial particle diameter	m
e^-	Elementary charge (charge on proton)	-
E_a	Activation energy	$kJmol^{-1}$
E_h	Solution redox potential	V
E^o	Standard redox potential	V
f_A	Fraction of acid soluble PGM in sample	
f_C	Fraction of chlorine soluble PGM in sample	
F	Faraday's constant	$JV^{-1}\ mol^{-1}$
H	Heat of reaction	J
j	j^{th} sample taken during leaching	
J	Total number of samples taken	
k_o	Overall rate constant	cms^{-1}
k_d	Rate constant for diffusion control	cms^{-1}
k_m	Mass transfer coefficient	s^{-1}
$k_{m,o}$	Initial Mass transfer coefficient	s^{-1}
k_s	Rate constant for surface reaction control	cms^{-1}

NOMENCLACTURE

Symbol	Description	Dimensions
k_s'	Rate constant for surface reaction control	cms^{-1}
k_s^*	Rate constant for surface reaction	cms^{-1}
k_s^+	Rate constant for surface reaction	cms^{-1}
m	Amount of leachable metal in a particle	mol
m_{i_0}	Initial mass of metal in the particle	g
M	Molarity	$moll^{-1}$
n	Number of moles of chlorine	M
N_i	Number of moles of component I	M
q	Quantity of heat generation	kJs^{-1}
r	Reaction rate	$molm^{-2}min^{-1}$
R	Universal gas constant	$JK^{-1}mol^{-1}$
t	Time	min
T	Temperature	°C
T_j	Temperature of fluid in reactor jacket	°C
T_o	Initial temperature of the reactor fluid	°C
T_w	Temperature of the cooling water	°C
U_{ht}	Overall heat transfer coefficient	$W/m^{-2}K^{-1}$
X	Conversion of PGE or gold	-
X_A	Conversion of acid soluble PGM	-
X_C	Conversion of chlorine soluble PGM	-
[X]	Concentration of species X	M
Greek Letters		
ρ	Mass density	gm^{-3}

CHAPTER 1

1.0 INTRODUCTION

The platinum-group metals (PGMs) are finding increasing application in modern technology. The PGMs are important for their special chemical properties as catalysts and thus fill a special industrial need. The PGMs serve as electrocatalysts in fuel cells and batteries, as electrical conductors in the electronics industry and as catalysts in the petroleum refining industry. Their use in the motor industry as catalysts to reduce automotive exhaust emissions accounts for nearly 50% of the platinum and palladium consumption. The consumption of rhodium by the auto industry is 73% of production[1].

The utilization of the precious metals is likely to increase the future demand for the platinum-group metals. Therefore, the price of platinum-group metals will undoubtedly continue to experience a high increase with the demand. The metal extraction industry can take advantage of this opportunity by generating more efficient extraction schemes for precious metal extraction from ores and concentrates, as well as from scrap and waste materials. The scrap recovery is an essential economic activity, owing to the rarity of the metals and their elevated prices. Because of their noble character, the PGMs are not lost in most industrial uses and they can therefore be recycled by secondary refining. Hoffmann[2] and Vermaak[3] reported that the recycling and refining of scrap PGM materials account for approximately one third of the annual PGM production that enters the supply market, and constitutes a significant source of the PGM worldwide. With the escalating capital and running costs and decreasing ore grades, improved efficiencies have become essential. These factors have contributed to a new emphasis on the search for technological advances in the PGMs extraction process. The Republic of South Africa and Russia accounts for about 95% of the worlds platinum-group metals production[4].

Although many techniques exist for the leaching of platinum-group metals with

different lixiviants, the most successful method uses chlorine gas. This has been shown by different investigators[5 - 10]. The leaching efficiencies that have been reported are quite different and their dissolution rates have not been properly established. In addition, there has been little systematic work to establish the dissolution mechanism. For instance, the platinum-group metals' extraction from this concentrate is claimed to be more than 98% in a test work conducted at the Impala Platinum refinery while in some cases the reported recovery of PGMs is between 80 and 90%[11]. Therefore this research is intended to present an original contribution on the kinetics of the dissolution of PGMs and gold from the concentrate materials by determining factors that affect their leaching rates.

The PGM concentrate materials are normally leached in a hydrochloric acid solution using chlorine gas as an oxidant. The rate of PGM dissolution in hydrochloric acid solution with chlorine gas is greatly influenced by the temperature of the leaching system, the concentration of the hydrochloric acid, the chlorine gas concentration and the particle size. The agitation speed also has an effect on the reaction rate. This work monitored these factors in both the chlorine dissolution in hydrochloric acid and the concentrate leaching experiments to look at the way they affect the leaching efficiency of platinum-group metals.

In the remaining section of this chapter, the literature on the leaching of platinum-group metals and gold is reviewed and the aims and scope of this research are discussed.

1.1 Literature Survey

There is considerable interest in the oxidative leaching of platinum-group metals. Research on the dissolution and recovery of platinum-group metals from both concentrate materials obtained from mined platinum-group metals bearing copper-nickel sulphide ores and from scrapped automotive catalysts and electronic scrap using an acidic chloride medium with different oxidants has been reported[2, 5 - 10, 20].

1.1.1 Description of Processes for the Recovery of PGMs.

Several different processes for the recovery and refining of raw material source of platinum group metals have been practiced industrially. The method chosen depends on the physical form of the source, its precious metal content and the nature of the other elements present.

Normally, the platinum-group metals in the spent catalysts and the electronic scraps are brought into solution with aqua regia or hydrochloric acid solution with oxidizing agents like NaOCl, HOCl, H_2O_2 or Cl_2 gas. The respective metals are recovered by electrowinning or ion-exchange techniques.

The conventional methods used for the recovery of platinum-group metals from the ores involves concentration, smelting and refining processing techniques. The ore is milled and a gravity concentrate is extracted. The valuable sulphides are concentrated by flotation. Vermaak[3] pointed out that this flotation concentrate has a PGM content of 100 to 400 gt^{-1}, depending on the original nature and concentration of the copper-nickel sulphides with which the platinum-group metals are associated in the ore. The flotation concentrate is smelted to produce a copper-nickel matte with an estimated PGMs content of 30%[3]. Other than concentrating the metal content, the ore minerals also loose their identity in the furnace at the smelting temperatures. Accordingly, the thermodynamics and the mass transfer kinetics are the main parameters which control the process. The PGMs are then recovered from the base metal matte by known hydrometallurgical techniques[8, 9, 14].

The traditional hydrometallurgical process of leaching and refining of PGMs is the treatment using aqua regia, followed by a series of precipitation and purification processes. However, due to numerous problems associated with the aqua regia process, considerable research and development effort has been directed towards the replacement of this traditional process with the use of chlorine in hydrochloric acid solution

followed by solvent extraction. Three commercial refineries, namely the INCO Acton Refinery, the Matthey Rustenburg Refinery and the Lonrho Refinery, have incorporated this technology into their operations, employing various newly developed solvent extraction processes[9].

These new processes use hydrochloric acid solution together with chlorine gas as the oxidising agent to totally dissolve the PGMs into solution. When this is achieved different separation and refining processes are employed to produce the pure metals. These processes are all based on the physico-chemical characteristics of the precious metals solution chemistry, such as the nature of the complex-ionic species and their redox potentials.

1.1.1.1 Leaching of PGM Concentrate using Aqua regia.

It is known that a mixture of hydrochloric acid (HCl) and nitric acid (HNO_3) which is commonly called aqua regia is an effective leachant for platinum group metals. The aqua regia is a mixture of concentrated hydrochloric and nitric acids in the proportion ([HCl] : [HNO_3]) of 3:1.

The raw material is attacked with aqua regia to dissolve platinum, palladium and gold. The secondary PGMs which are Rh, Ru, Ir and Os are left as an insoluble residue. The aqua regia solution is treated with ferrous sulphate. Gold is precipitated and separated for its recovery by reduction with oxalic acid and for further purification[8].

A saturated ammonium chloride solution is added to the gold-free solution to precipitate ammonium hexachloroplatinate. This precipitate is separated and calcined to form platinum metal sponge of 98% purity. This sponge is further refined by repeated dissolution and reprecipitation[9].

The filtrate from the ammonium hexachloroplatinate is treated with ammonium

hydroxide solution and hydrochloric acid is then added. Diammine palladium dichloride is precipitated, separated and calcined in a hydrogen atmosphere[8]. The crude palladium metal obtained is further purified by repeated dissolution and precipitation.

The original insoluble residue from the aqua regia attack is fused with fluxes composed of litharge, soda ash, borax and carbon. This is alloyed with lead, which collects all the precious metals including the secondary platinum group metals. The lead alloy is leached in hot nitric acid solution to dissolve silver and lead. The lead in the leach liquor is precipitated as lead sulphate, and the silver as silver chloride. The nitric acid insoluble residue is fused with sodium bisulphate at 500°C to form a water soluble rhodium sulphate salt. This salt is treated with an ammonium nitrite solution which precipitates ammonium rhodium nitrite, $(NH_4)_3Rh(NO_2)_6$. The nitrite salt is later treated with hydrochloric acid to form ammonium rhodium chloride, $(NH_4)_3RhCl_6$, which is further refined by formic acid reduction, or precipitated repeatedly as the $(NH_4)_3RhCl_6$ salt followed by a reduction with hydrogen gas at 1000°C to produce a pure rhodium metal powder[3].

The water-insoluble residue from the sodium bisulphate fusion is then fused with a mixture of sodium hydroxide and potassium nitrate. Osmium and ruthenium form water soluble potassium salts, potassium osmate and potassium ruthenate. Iridium forms an oxide that is soluble in aqua regia solution. After the potassium salts of osmium and ruthenium are dissolved in water, the solution is treated with hydrochloric acid and chlorine gas. The volatile tetroxides of osmium (OsO_4) and ruthenium (RuO_4) are evolved and they are absorbed into a mixture of dilute hydrochloric acid and methanol. When the hydrochloric acid/methanol solution is heated, only osmium tetroxide is evolved. This is absorbed into a solution of sodium hydroxide and methanol, from which ammonium osmium chloride is precipitated by the addition of ammonium chloride. This chloride salt is then calcined in a hydrogen atmosphere to produce crude osmium. This is further refined by repeated distillation and precipitation.

The ruthenium remains as ruthenium oxychloride in solution and is treated with

ammonium chloride to precipitate an ammonium ruthenium chloride salt. This is reduced by heating in a hydrogen atmosphere at 1000°C to obtain a crude ruthenium. This is also further treated for purification to obtain pure ruthenium metal.

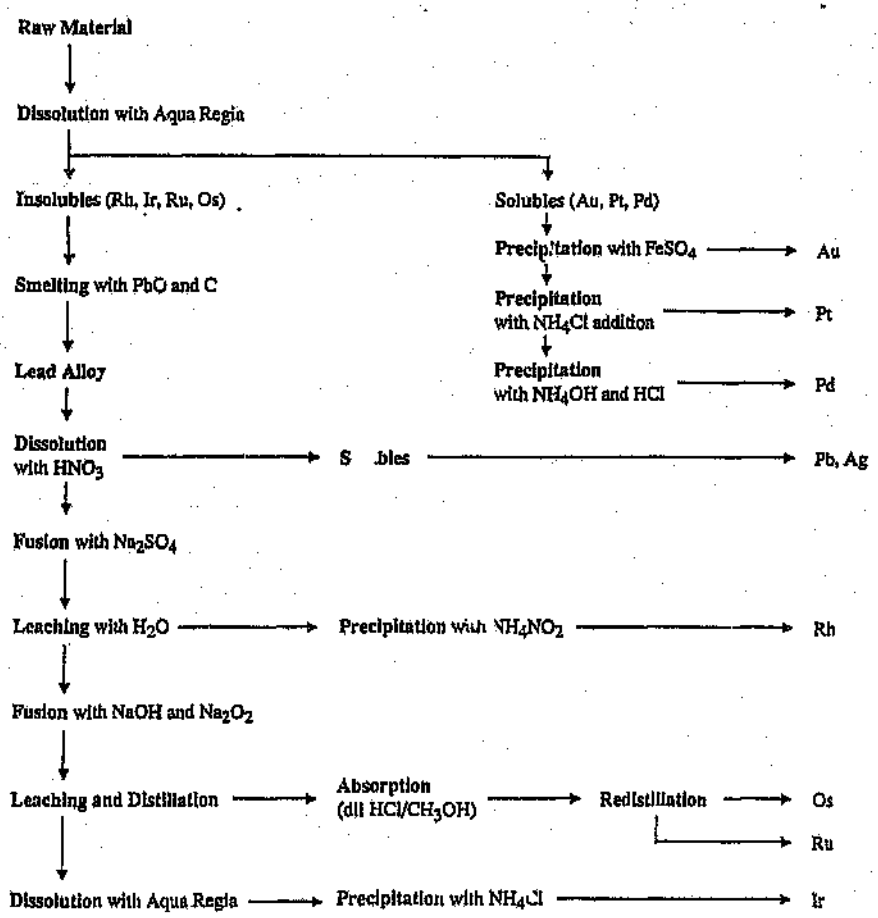


Fig. 1.1 Aqua regia leaching of PGM concentrate process flow.

The iridium oxide that is formed during the previous fusion treatment is dissolved in aqua regia and precipitated with ammonium chloride solution as ammonium hexa-chloroiridate. Crude iridium is obtained by calcining the ammonium iridium chloride

compound in a hydrogen atmosphere at 1000°C. Further purification of the crude iridium requires repeated dissolution and reprecipitation.

This process which is shown in Figure 1.1 is quite tedious, requiring a large number of steps together with recycles in order to achieve the desired degree of purity and even at a relatively low temperature of between 70°C and 90°C, leaching with aqua regia is extremely difficult. This is due to the instability of the solution which is characterised by a high partial pressure of gaseous hydrogen chloride ($HCl_{(g)}$) and substantial nitric acid decomposition resulting in evolution of gaseous nitrogen oxides[15]:

$$3HCl + HNO_3 \rightleftharpoons NOCl + Cl_2 + 2H_2O \qquad 1.1$$

The side reactions for the above equation are:

$$Cl_2 + H_2O \rightleftharpoons HCl_{(g)} + HClO \qquad 1.2$$

$$NOCl \rightleftharpoons NO_{(g)} + Cl \qquad 1.3$$

The main problem of leaching with aqua regia is the loss of the volatile source of chloride ions ($HCl_{(g)}$) which are essential for the formation of the soluble platinum group metal complex ions in solution. This loss of chlorine ions is detrimental to the leaching efficiency by reducing the leaching rate and the process requiring specialised installation of equipment to absorb these toxic gases from the reagent decomposition. As a result of these conditions, aqua regia leaching is an extremely expensive procedure which does not readily result in an acceptably high recovery of PGMs.

1.1.1.2 Leaching of PGM Concentrate using Chlorine as oxidant.

The degree of recovery attained with the aqua regia method cannot be considered to be efficient in terms of the yields, the complexity of the operation and the labour

expended. Many precious metal refineries have switched to the hydrochloric acid and chlorine gas leaching of PGMs followed by solvent extraction process. This switch is due to the fact that leaching with hydrochloric acid and chlorine gas effectively bring all the PGMs into solution and reduces the processing time[9].

In this process which is shown in Figure 1.2, the precious metal raw materials are leached in hydrochloric acid solution with chlorine gas to dissolve all the PGMs. The silver forms insoluble silver chloride which is separated and recovered.

The gold in the form of $AuCl_4^-$ in solution is extracted by either the solvent extraction with tributyl phosphate (TBP) or with methyl isobutyl ketone (MIBK), into the organic phase. The extraction reaction may be described as[8]:

$$[H^+(AuCl_4^-)]_{aq} + [TBP]_{org} \rightleftharpoons [HAuCl_4][TBP]_{org} \qquad 1.4$$

The other impurities like Fe and Te are also extracted, so that the organic phase is next scrubbed with hydrochloric acid for impurity removal. The gold is reduced and recovered from the organic phase with iron powder. Kahn and Morris[22] have shown in laboratory experiments that the recovery of gold from PGM-containing solutions is almost quantitative and that the gold metal produced is 99.99% pure.

Palladium can be extracted by beta-hydroxyoxime by the ligand exchange reaction:

$$[PdCl_4^{2-}]_{aq} + 2[RH]_{org} \mapsto [PdR_2]_{org} + 2[H^+]_{aq} + 4[Cl^-]_{aq} \qquad 1.5$$

Since the extraction rate (ie, the ligand exchange rate) is small, an organic amine reagent is added to accelerate the extraction. After the organic phase has been scrubbed with weak hydrochloric acid to remove base metal impurities, palladium is stripped with aqueous ammonium hydroxide solution. The palladium is precipitated as $(NH_4)_2PdCl_6$ with hydrochloric acid[8].

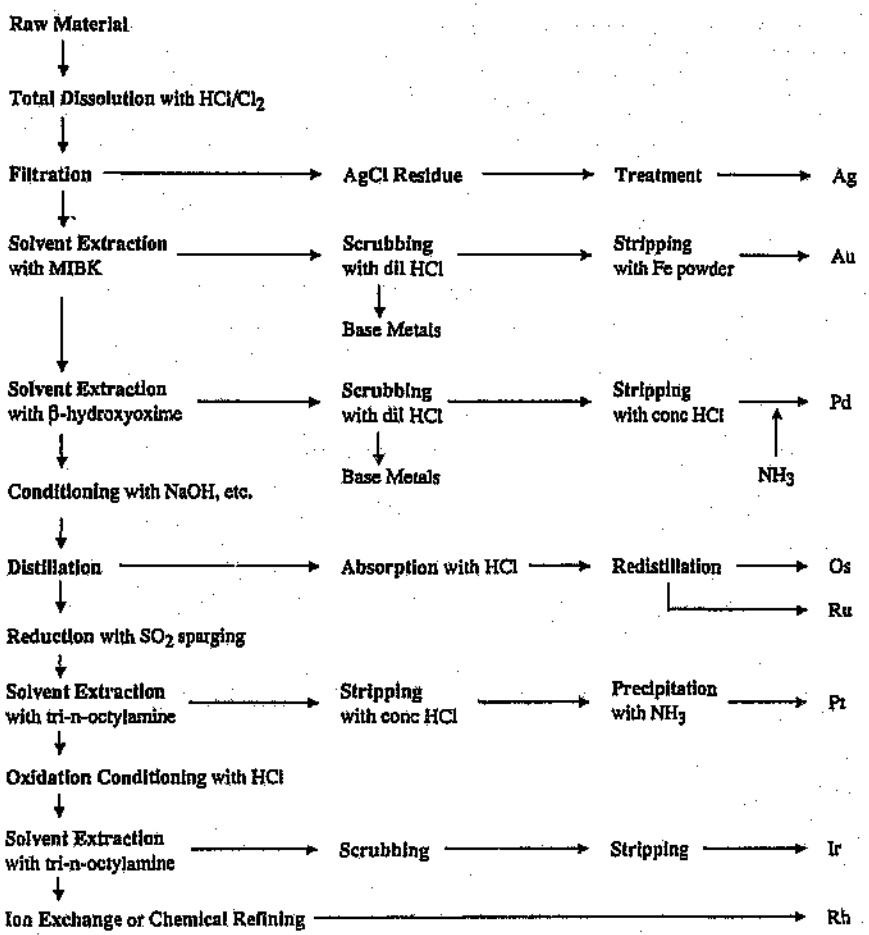


Fig. 1.2 Process flow for PGM concentrate leach with HCl/Cl_2 gas followed by solvent extraction

Osmium and ruthenium are then separated as their volatile tetroxides after the solution has been neutralised with alkaline hydroxide. The tetroxides are absorbed into a dilute

hydrochloric acid solution. This solution is redistilled for separation of osmium from ruthenium.

After reducing the iridium (IV) to its (III) state, platinum is extracted by the tertiary amine, tri-n-octyl amine into the organic phase as[9]:

$$[PtCl_6^{2-}]_{aq} + 2[RH^+]_{org} \mapsto [(RH)_2PtCl_6]_{org} \qquad 1.6$$

The platinum is stripped from the organic phase with 10.00 M to 12.00 M hydrochloric acid. The platinum is precipitated as $(NH_4)_2PtCl_6$ with ammonium chloride.

After oxidising iridium (III) back to its (IV) state and adjusting the acid strength to about 4 mole per litre, iridium is extracted into the organic phase of the tri-n-octyl amine phase in the same way as the platinum. The organic phase is scrubbed with dilute acid. The iridium is stripped into the aqueous phase after reducing it to its (III) valency state and recovered.

Finally, rhodium is separated and recovered from the solution containing other element impurities.

The commercial and industrial operation of solvent extraction processes are established with respect to efficiency and the rate of stripping, the degradation and loss of extractants, flexibility and versatility of the process. Depending on the differences in the forms of the raw materials, the contents and grade of precious metals and the pretreatment procedures, the respective commercial refineries have developed and applied different solvent extraction technologies and processes based on the influences of the thermodynamic and kinetic behaviour. The major advantages of these solvent extraction processes are the fact that the overall processing time is reduced, the separation efficiency and the product purity is higher and yields are improved[8, 9].

1.1.2 Chemistry of the Dissolution of PGM Concentrates

The platinum-group metals comprise of platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os). Platinum and palladium are the major constituents and are referred to as the primary platinum group metals; rhodium, ruthenium, iridium and osmium in smaller amounts, and are called the secondary platinum group metals. Their nobility is shared to a large extent with gold and silver, and are characterised by their reluctance to dissolve in media that will corrode any base metal[14].

Mishra[5] and Bautista *et al*[7] reviewed the available literature for the dissolution of PGM from automobile catalytic converters by hydrometallurgical methods and reported on the chemistry of the dissolution process. Platinum-group metals, in general, are very resistant to acid dissolution and only a very strong hydrochloric acid solution is able to slowly dissolve them under non-oxidizing conditions. Therefore, a high chloride ion concentration in acidic medium strongly promotes the rate of PGMs dissolution[15].

Based on this fact, almost all process chemistry of PGMs involves the use of a chloride and an oxidant. The most common oxidants are chlorine and aqua regia. Chlorine is provided by sparging a solution of hydrochloric acid with chlorine gas, and aqua regia is provided by the reaction of nitric acid and hydrochloric acid. The platinum-group metals are solubilised as $PtCl_6^{2-}$, $PdCl_6^{2-}$, $RhCl_6^{3-}$, $RuCl_6^{2-}$, $IrCl_6^{2-}$ and $AuCl_4^{2-}$ in the chloride solution[16].

Considerable attention has been focussed on the thermodynamic basis of the stability domains of the platinum-group metals. In 1986, Osseo-Asare[17] presented a number of stability diagrams for process design and analysis to link a solid PGM material and the product aqueous solutions to the overall chemical reactions which represents the reaction path for the dissolution process of platinum-group metals and gold.

In order to ascertain the feasibility of the PGM dissolution, each solid metal can be compared with the stable chlorocomplex formed in the various solubility regions. Osseo-Asare and Luo[18] prepared the Eh-pH diagrams for the systems Au-, Ag-, Pt-, Pd-Cl-H_2O at a condition $[M^+]=10^{-6}$ M, $[Cl^-]=$ 1.00 M. In this systems which involve a higher chlori to metal activity ratio show chlorocomplex solubility region for the PGMs. This is presented in Figures 1.3 to 1.6. The relatively high solubility of Pd compared with Pt is indicated by the larger Pd chlorocomplex stability domain and the stability field of the neutral hydrocomplex, $Pd(OH)_{2\,(aq)}$. The relative positions of the metal chlorocomplex stability boundaries show that a solution containing chlorides of Au(III), Pt(IV), and Pd(IV) can be treated with a reductant to selectively precipitate metallic gold and platinum will remain unchanged in solution as $PtCl_6^{2-}$, whereas palladium will undergo reduction from $PdCl_6^{2-}$ to $PdCl_4^{2-}$.

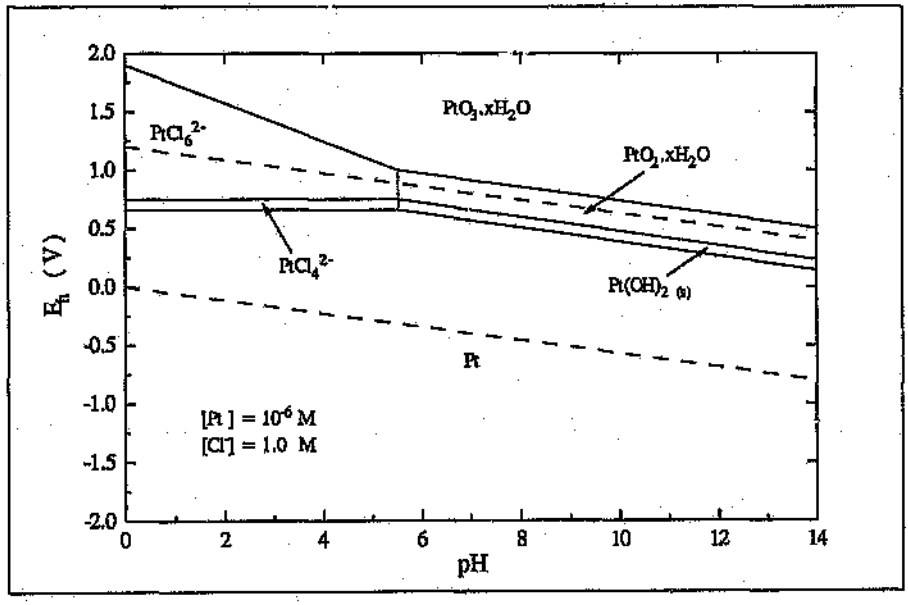


Fig. 1.3 E_h - pH diagram for Pt-Cl-H_2O system. $[Pt]=10^{-6}$ M, $[Cl^-]=$ 1.00 M.

Figures 1.5 and 1.6 show Eh-pH diagrams for the Au-Cl-H_2O and Ag-Cl-H_2O systems for $[Au]=[Ag]=10^{-6}$ M and $[Cl^-]=1.00$ M. The gold system shows a small $AuCl_4^-$

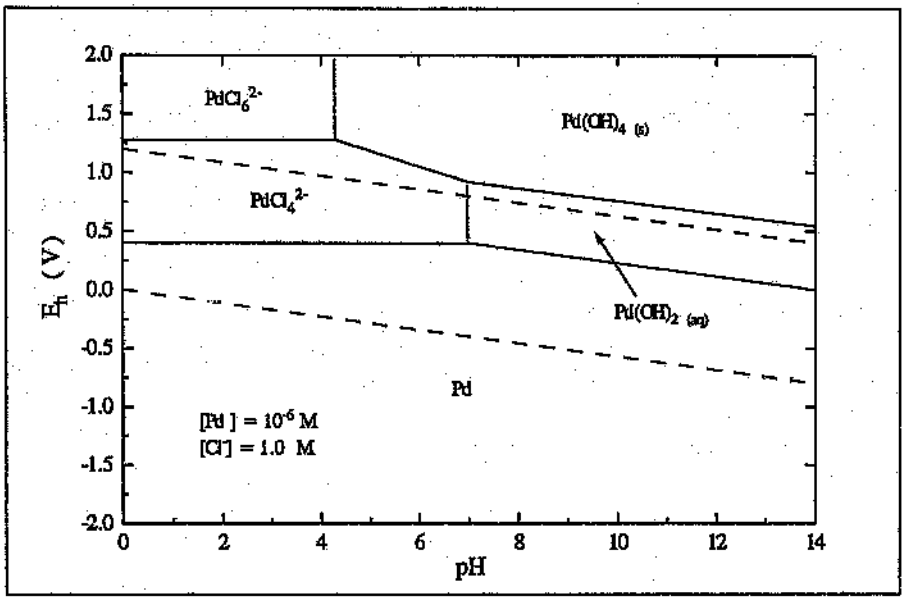


Fig. 1.4 E_h - pH diagram for Pd-Cl-H_2O system at [Pd]= 10^{-6} M, [Cl]= 1.00 M.

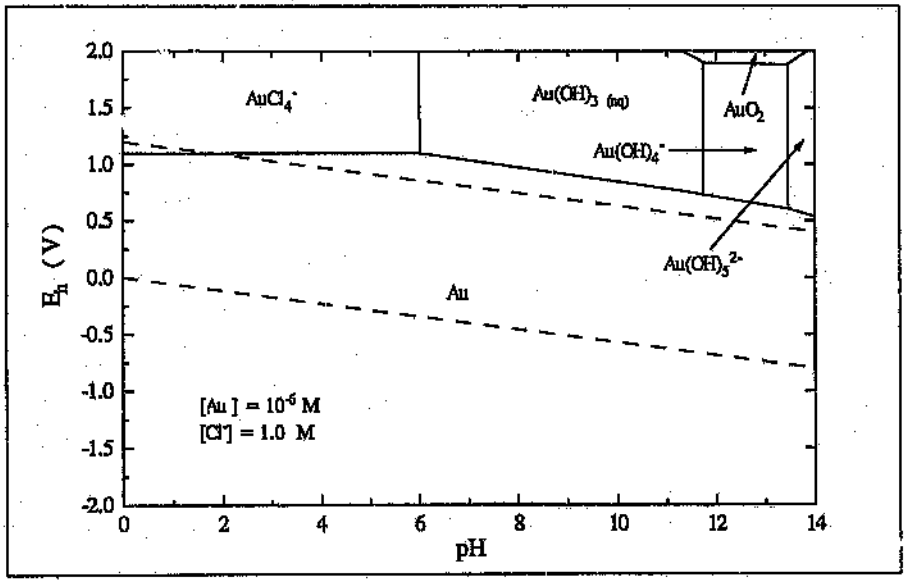


Fig. 1.5 E_h - pH diagram for Au-Cl-H_2O system at [Au]= 10^{-6} M, [Cl]= 1.00 M.

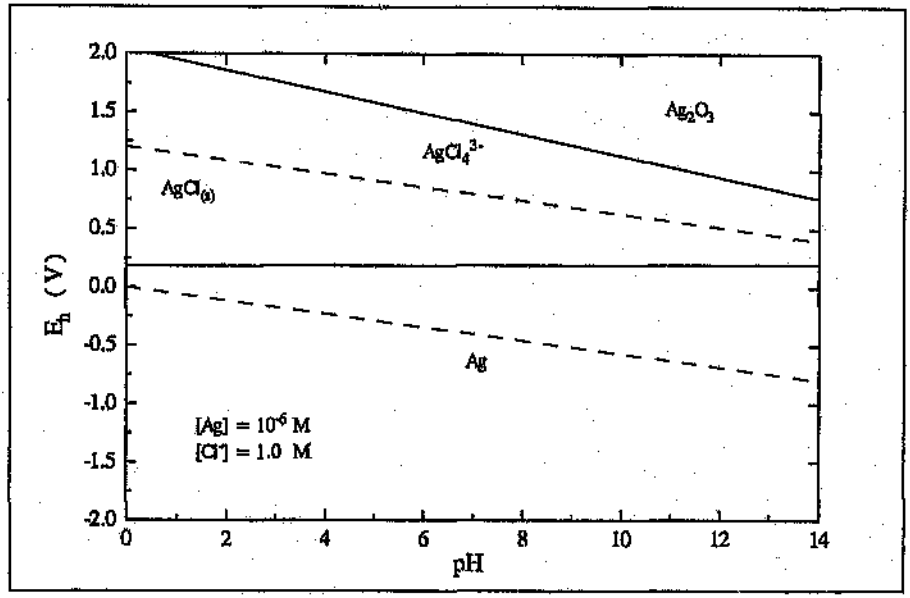


Fig. 1.6 E_h - pH diagram for Ag-Cl-H_2O system at [Ag]= 10^{-6} M, [Cl^-]= 1.00 M.

stability field under highly oxidizing and acidic conditions. In contrast, there is a wider stability field for $AgCl_{(s)}$. This difference in Au and Ag behaviour is exploited when high gold alloys (<8% Ag) are refined by treatment with aqua regia[18].

Basically, the chemical leaching of platinum group metals like any other metal depends on the thermodynamics of the dissolution and the kinetics of the leaching. The thermodynamic information are used to predict the general conditions that enhance the dissolution of the metals. This shows the tendency of the reaction to occur in a particular direction but provides no information on the rate of the reaction nor the mechanism that governs it. From the Eh-pH diagrams, the presence of chlorine creates a stability region for the chlorocomplexes of platinum-group elements which are formed at lower pHs and higher oxidation potentials above 740 mV as illustrated clearly in the Figure 1.3.

In 1989, Mishra[5] reported that, for a mixture of platinum-group elements, the standard potential for the formation of the chlorocomplexes requires an oxidizing agent with a reduction potential of greater than 0.74V which agrees with the PGMs phase diagrams given above. The standard reduction potential of commonly used oxidants are[5]:

$ClO_3^- + 6H^+ + 6e^- \rightleftharpoons Cl^- + 3H_2O$	$E^o = +1.45V$	1.7
$HOCl + H^+ + 2e^- \rightleftharpoons Cl^- + H_2O$	$E^o = +1.49V$	1.8
$Cl_2 + 2e^- \rightleftharpoons 2Cl^-$	$E^o = +1.35V$	1.9
$H_2O_2 + 2H^+ + 2e^- \rightleftharpoons H_2O$	$E^o = +1.77V$	1.10
$BrO_3^- + 6H^+ + 6e^- \rightleftharpoons Br^- + 3H_2O$	$E^o = +1.44V$	1.11
$NO_3^- + 4H^+ + 3e^- \rightleftharpoons NO + 2H_2O$	$E^o = +0.96V$	1.12

Examination of the above reduction potentials indicate that any of the above oxidants are thermodynamically capable of oxidizing platinum-group metals provided the kinetics of dissolution is favourable. The choice of a lixiviant and an oxidant must be determined by balancing increases in the reaction speed or the efficiency of metal extraction with the additional costs and downstream processing difficulties incurred by their use.

The dissolution of PGMs by aqua regia in reality is not as simple as presented by the NO_3^- reduction potential since the HNO_3 decomposes to release NO gas therefore bringing the potential down. The HCl gas produced as a result of the aqua regia reaction which is the source of chloride ions also escape during the leaching[5]. Bradford[10] studied various oxidants for the leaching of PGMs and found chlorine gas to be the most effective oxidant which is more capable to totally dissolve and bring all the PGMs into solution.

The dissolution of metallic platinum-group metals in hydrochloric acid solution and chlorine gas system is generally straight-forward. The chlorine gas is used solely as an oxidizing agent which dissolves into solution to oxidise and convert the PGMs to their chlorocomplexes. There is no intermediary side reaction for the chlorine and the hydrochloric acid solution.

The reaction can be generally presented as:

$$M^* + 4HCl \rightleftharpoons M^*Cl_4^{2-} + 4H^+ + 2e^- \qquad 1.13$$

$$M^*Cl_4^{2-} + 2Cl^- \rightleftharpoons M^*Cl_6^{2-} + 2e^- \qquad 1.14$$

(where M^* can be Pt, Pd, Rh, Ru, Ir or Au.)

$$Cl_2 + 2e^- \rightleftharpoons 2Cl^- \qquad 1.15$$

The oxidizing agent is not only important for dissolving the PGEs but to convert and maintain any PGE ions from the +2 to the +4 oxidation state which is the requirement for the next processing step.

For solubilization of the platinum-group metals, the standard potentials in aqueous chloride media are shown for some of the PGMs as[16]:

$$Pt + 4Cl^- \rightleftharpoons PtCl_4^{2-} + 2e^- \qquad E^\circ = -0.73V \qquad 1.16$$

$$PtCl_4^{2-} + 2Cl^- \rightleftharpoons PtCl_6^{2-} + 2e^- \qquad E^\circ = -0.74V \qquad 1.17$$

$$Pd + 4Cl^- \rightleftharpoons PdCl_4^{2-} + 2e^- \qquad E^\circ = -0.62V \qquad 1.18$$

$$PdCl_4^{2-} + 2Cl^- \rightleftharpoons PdCl_6^{2-} + 2e^- \qquad E^\circ = -1.29V \qquad 1.19$$

$$Rh + 6Cl^- \rightleftharpoons RhCl_6^{3-} + 2e^- \qquad E^o = -0.44V \qquad 1.20$$

The first reaction is the dissolution reaction whereas the second is the oxidation reaction which occurs in solution. The oxidation reactions are able to take place because of the high enough potentials of these reduction reactions. D'Aniello[20] postulated that a high chloride concentration and a value of the pH less than one must be maintained in the leach solution in order to prevent the monochlorocomplexes of PGMs (PtCl, PdCl, RhCl, RuCl and IrCl) from forming which sometimes hydrolyse to create hydroxo complexes.

The dissolution of platinum-group metals can also be considered to occur through an electrochemical mechanism in which the anodic oxidation of the PGE is coupled to cathodic reaction of the chlorine on the surface. In 1952, Llopis and Tordesillas[12] studied extensively on the anodic dissolution of platinum in hydrochloric acid and expressed the corrosion product as $PtCl_6^{2-}$. Hawkins and Nicol[13] in 1976 investigated the electrochemical dissolution and passivation of platinum in acid solutions. These researchers found out that a high overpotential is required to accomplish the anodic corrosion of platinum. The attack on platinum by direct current is enhanced by increasing temperature, high chloride concentration and high acidity.

Palladium dissolves relatively easily as an anode in acidic solutions unless the electrode potential is sufficiently positive that palladium is passivated by an oxide layer. Corrosion is practically zero under passivation conditions. In chloride solutions, palladium dissolves at low anodic potentials or by passing chlorine gas through the solution.

The anodic dissolution of rhodium occurs at very high overpotentials even in concentrated HCl solutions; therefore a very low current density is required to avoid passivation. Under these conditions, anodic corrosion leads to the formation of Rh (III) complexes and is enhanced by increasing the HCl concentration at 'gher temperatures.[21]

1.1.3 Dissolution Reactions.

Most of the mineral acids do not readily attack platinum-group metals. The resistance of PGMs to acid dissolution is due to the thermodynamic stability of their crystal lattice which is of low concentration of free electrons[21]. Another possibility is the effect of protective mono-atomic oxide films which further passivate the surface of the metal during dissolution[21] . The part played by oxygen in the reaction of the platinum-group metals with hydrochloric acid solution without an oxidant could be attributed to the fact that it oxidises the acid and liberates chlorine[21]. This free chlorine then oxidises the PGMs into solution. This possibly explains why some PGMs partially dissolves in hydrochloric acid solution without chlorine oxidant. The hydrated oxides of the PGMs readily dissolve in hydrochloric acid solution to form their stable chlorocomplexes.

The dominant mechanism of dissolution of platinum-group metals depends on the relative concentrations of oxidant and the acid. The reactivity of the PGMs in acidic medium is largely determined by the degree of their dispersity and the formation of intermetallic compounds with other elements that are present in the concentrate or the metal as alloy[21]. This depends most of the time on the presence of foreign impurities, normally base metals which probably have a catalytic effect on the dissolution process. For instance, when the PGMs are alloyed with zinc or tin, they can then be dissolved in acids in which they are insoluble under ordinary conditions[21]. This may be due to galvanic interactions where the PGMs and zinc or tin placed in the acid facilitates charge transfer which results in the rate of PGMs dissolution being enhanced and that of zinc or tin being retarded[37] . This may be one of the most important electrochemical factors which governs the dissolution rate of platinum- group metals and some minerals in hydrometallurgical systems.

Platinum:

Most acids do not attack platinum. Chlorine generated by aqua regia or from gaseous

chlorine reacts with platinum as[8]:

$$Pt + 2HCl + 2Cl_2 \rightleftharpoons H_2PtCl_6 \qquad 1.21$$

Platinum is usually soluble in aqua regia which combines the oxidising action of HNO_3 with the complexing ability of HCl to form platinum hexachloride salt [16].

$$3Pt + 18HCl + 4HNO_3 \rightleftharpoons 3H_2PtCl_6 + 4NO + 8H_2O \qquad 1.22$$

Palladium:

Palladium is readily soluble in aqua regia and partially soluble in hydrochloric acid containing no oxidizing agents. It is soluble in chlorine and is also the only PGM that is readily soluble in nitric acid. The reactions are[8]:

$$Pd + 2HCl + 2Cl_2 \rightleftharpoons H_2PdCl_6 \qquad 1.23$$

$$3Pd + 18HCl + 4HNO_3 \rightleftharpoons 3H_2PdCl_6 + 4NO + 8H_2O \qquad 1.24$$

$$Pd + Cl_2 \rightleftharpoons PdCl_2 \qquad 1.25$$

It is apparent from the above reactions that the stable state for platinum is tetravalent while that of palladium is divalent[21]. Palladium metal is slightly attacked in HCl solution in the presence of oxygen and the attack is enhanced by increasing the hydrochloric acid concentration and temperature. In contrast, palladium is not acted upon by alkaline solutions even in the presence of an oxidizing agents.

Rhodium:

The dissolution of rhodium is an extremely difficult task since it is a very noble metal. The general rhodium dissolution methods are as follows[8]:

(i) Rhodium is first fused with potassium bisulphate to produce water soluble rhodium sulphate.

$$4Rh + 12KHSO_4 + 3O_2 \rightarrow 6K_2SO_4 + 6H_2O + 2Rh_2(SO_4)_3 \qquad 1.26$$

(ii) After alloying this sulphate salt with a ten-fold excess of zinc or lead, this alloy is treated with hydrochloric or nitric acid. After removing the solution, the residue is dissolved easily in aqua regia to yield rhodium chloride.

$$Rh + 6HCl + HNO_3 \rightarrow H_3RhCl_6 + NO + 2H_2O \qquad 1.27$$

Rhodium is insoluble in nitric acid but when alloyed with zinc dissolves in a mixture of boiling hydrochloric and nitric acids[21]. Rhodium partially dissolves in HCl solution bubbled with air at high pressure at ambient temperature. It also dissolves in HCl with H_2O_2 present as oxidant[21]. The presence of dissolved palladium in HCl solution under a strong oxidizing conditions has been shown to enhance rhodium dissolution at temperatures around 60°C[21]. Rhodium sponge has the tendency of forming an oxide layer at the metal surface (probably Rh_2O_3) when heated at 100°C. This oxide is highly insoluble and renders rhodium insoluble for all practical purposes[21].

Other Platinum-group Metals:

Ruthenium and iridium are partially soluble in HCl in the presence of atmospheric oxygen. Ruthenium and iridium are hardly attacked by aqua regia even when they are finely divided. Alloys of iridium with platinum and palladium are soluble in aqua regia. The dissolution of the alloy decreases remarkably when it contains over 10% of iridium[21]. The iridium, ruthenium and osmium cannot be directly dissolved in acids so alkaline peroxide fusion with NaOH, KNO_3 or KCl; or chlorination in the presence of chlorine gas and NaCl is used[21]. The oxidative roasting of osmium to produce its vapour which is absorbed into hydrochloric acid is used[21]. Ruthenium and Osmium are dissolved readily by alkaline hypochlorite solution which is not effective towards the

other PGMs as they form protective layers at high potentials and pH.

Osmium reacts more rapidly with chlorine than any other platinum-group metal even at a lower temperature. The most aggressive reagent for the PGMs are fluorine and chlorine at elevated temperature.

The dissolution reactions for the other platinum group metals and some base metals with hydrochloric acid and chlorine gas that occur in the leaching vessel are the following:

$$Au + 3/2Cl_2 + HCl \rightleftharpoons H^+ + AuCl_4^- \quad 1.28$$

$$Ru + 2Cl_2 + 2HCl \rightleftharpoons 2H^+ + RuCl_6^{2-} \quad 1.29$$

$$Ir + 2Cl_2 + 2HCl \rightleftharpoons 2H^+ + IrCl_6^{2-} \quad 1.30$$

$$Ag + 1/2Cl_2 \rightleftharpoons AgCl \quad 1.31$$

$$Ni + Cl_2 \rightleftharpoons Ni^{2+} + 2Cl^- \quad 1.32$$

$$Cu + Cl_2 \rightleftharpoons Cu^{2+} + 2Cl^- \quad 1.33$$

$$Fe + 3/2Cl_2 \rightleftharpoons Fe^{3+} + 3Cl^- \quad 1.34$$

The silver and the base metals also consume some of the dissolved chlorine in the reactor so the concentration of chlorine must be in excess to account for this.

1.2 Aims and Scope of this Research Work.

The main aim of this research goes beyond the academic level into the industrial operations to achieve the goals set for it. While the industrial processes intermingle with the academic works, more research is needed to come out with an improved processing operations for the metal refineries. This will make the total recovery of metals from ores a reality in our days.

1.2.1 Research Objective.

The present research work was undertaken with a view to systematically investigate and evaluate the dissolution efficiencies of the PGMs and gold from the concentrate material to uncover new knowledge so as to provide a better understanding of the mechanisms and kinetics of reaction involved in the PGM dissolution in hydrochloric acid and chlorine gas. It was also structured to investigate the applicability of the shrinking particle model to the leaching kinetics of PGM concentrate and to model the kinetics of PGMs dissolution in HCl/Cl_2 leach system to fit the experimental data obtained. A general model to scale up the plant results to industrial scale is also established.

Bearing in mind the importance attached to the improvement of the leaching process, imperative for the economical recovery of PGM from the concentrate, it is natural that a greater amount of theoretical and practical study be carried out in this field. The contribution of this research to improve the platinum-group metals extraction process is to provide detailed information on the leaching behaviour of the platinum-group metals in hydrochloric acid solution with chlorine. The results of this studies serve as a building block which can be used to obtain improved understanding of the more complex natural systems at the PGM refineries.

The project was split into two separate phases. The first phase consisted of a very thorough study of chlorine gas solubility in hydrochloric acid solution under different

conditions to establish an effective concentration of chlorine gas for a total dissolution of the platinum-group metals and gold with the intention of bringing an understanding to the medium for the dissolution processes. The second phase of the work concentrated on the practical leaching test of the PGMs with the view to substantiate and further develop the existing knowledge.

1.2.2 Motivation and Scope of the Study.

With the Impala Precious Metal Refinery in mind, the present study is designed to investigate and ascertain the dissolution efficiencies of platinum, palladium and gold which have been shown by researchers[5, 6, 10] to be good whereas those of rhodium, ruthenium and iridium were lower. The dissolution process at most precious metal refineries are empirical process which is based on experience.

The leaching efficiencies of these platinum-group metals are crucial to the operating performance of the Precious Metal Refineries since poor leaching efficiencies result in increased recycle loads and increase lock-up of PGMs within the refineries. Thus leaching problems bring about high operational costs to the production of the PGMs and gold and therefore bringing down the profits of these companies.

In view of this, the economic situation in the precious metal industry has called for more research into these areas to improve the dissolution of PGMs and gold since their leaching operations have been in use for many years but the kinetics and mechanisms involved in this process are not fully understood. A good understanding of the kinetics and mechanisms of the dissolution of PGMs would aid in the choice of flowsheet for the precious metal plants and in the design and the operation of the plants. When a better leaching conditions are uncovered, the new knowledge of the leaching efficiencies together with the kinetics of reaction for the leaching of the PGMs will enable Plant Operators to optimize the dissolution operation.

CHAPTER 2

2.0 THEORETICAL ANALYSIS AND MODELLING

The leaching of the platinum-group metal concentrate in hydrochloric acid solution with dissolved chlorine is a three-phase system. It consists of solid PGMs, hydrochloric acid solution and chlorine in gaseous and dissolved forms in the stirred reactor as shown for platinum by the leaching equation

$$Pt_{(s)} + 2HCl_{(l)} + 2Cl_{2\,(g)} \rightleftharpoons H_2PtCl_{6\,(aq)} \qquad 2.1$$

The PGM leach reaction complexes with chloride ions to produce chloro-complexes of the PGEs in solution. The dissolved chlorine oxidises the PGMs.

Levenspiel[23] stated that the factors controlling the rate of solid-fluid reactions can be broadly classified into three groups:

1. The mass transport between the bulk of the solution and the solid surface. This involves the rate of supply of the chlorine to the solid PGE surface and the reverse process where the dissolved solids are transported into the bulk solution. This is a diffusion (mass transfer) process which is determined by:
   - Surface area of the solid particle,
   - Hydrodynamics (rate of mixing of the solid and liquid),
   - Diffusion through the boundary layer, governed by the Fick's law.
   - Pressure which contributes to the dissolution of chlorine gas in the hydrochloric acid solution.

   There is no product layer in this particular case to offer any resistance to the transport of reactants to and products from the surface.
2. The formation of coatings of insoluble products like silver chloride on the surface of the platinum-group elements.
3. The control by the rate of chemical reaction at the mineral surface or in the

solution. This is a chemical process and is affected by:

- Surface area of the solid particle,
- Temperature from which the activation energy can be determined,
- Concentration of the reagents and the stoichiometry of the reaction.

Any one of these factors may be the rate-determining step.

If a suitable mathematical model of a leaching process is to be a useful tool for a full-scale process design, it must account for a mineralogical and physical characteristics of the feed. Therefore the minerals present in the sample material must be known. The mineralogy and physical characteristics of the concentrate sample were considered. The sample particle size distribution must also be known along with the distribution of the various minerals and the alloy phases between the particle sizes.

2.1 Modelling of the Leaching Kinetics of the PGMs

The kinetic model considered must be able to describe the simultaneous leaching of different minerals. The leaching model must be based on the correct fundamental reaction mechanism which must describe the effect of changes in the leaching solution on the leaching rate. The appropriate rate-controlling step should be used. These basic factors were greatly considered as the background for the kinetic modelling of the leaching rate of PGMs in this work.

The changing effect of the size of the PGE particle during dissolution is described by the shrinking-particle model. This kinetic model can be used to describe the leaching behaviour of PGMs dissolution in the hydrochloric acid solution with chlorine and to determine which parameter affects the dissolution rate. This mathematical model assumes that the reaction rate is proportional to the mineral surface area. It also accounts for the change in the metal surface area as the reaction proceeds. The rate controlling step may be either chemical (surface) reaction or film diffusion.

2.1.1 Shrinking-Particle Model

When the reaction product does not form a layer around the unreacted solids but instead flakes off or forms a fluid product which becomes part of the bulk solution, the process is expressed as shrinking particle model. If the effect of temperature on the leaching rate is high, then the leaching rate is controlled by chemical reaction at the interface. If, on the other hand, the effect of temperature is low, then the leaching rate is controlled by film transport of fluid reactants or product to or from the reacting interface which is referred to as diffusion control of the shrinking particle model.

The leaching of a PGE particle in the sample occurs at the particle surface. The reaction zone moves towards the centre of the particle, leaving behind reaction products and inert materials such as AgCl. The reacting particle shrinks in size as the reaction proceeds and finally disappears.

2.1.1.1 Chemical Reaction Control

In the case of chemical reaction control, the rate determining (limiting) step is the reaction at the interface. The dissolution rate expression for this is[2,1]:

$$1-(1-X)^{1/3} = k_s t \qquad 2.2$$

where,

k_s = overall reaction rate constant for the surface controlled reaction, and is dependent on the temperature, concentrations of HCl and Cl_2 and the particle size.

t = time of dissolution,

$X = (m_0 - m)/m_0$, the degree of dissolution,

and

m = undissolved mass of the metal in the solid phase,

m_o = initial mass of metal in solid phase

If a plot of [1 - (1 - X)$^{1/3}$] against t gives a straight line then the chemical or surface reaction is the rate determining step and the reaction is thus chemically or surface reaction controlled. Therefore, the products of the reaction do not inhibit the reaction.

2.1.1.2 Solution Film Diffusion Control

In the case of the film diffusion control, the rate may be controlled either by diffusion of reactants to or reaction products from the surface of the solid through the film into the bulk fluid. There is no product layer here to contribute any resistance. The film diffusion controlled reaction is expressed as[23]:

$$1-(1-X)^{2/3} = k_d t \qquad 2.2$$

for small particles in the Stokes regime, and

$$1-(1-X)^{1/2} = k_d t \qquad 2.3$$

for large particles

where,

k_d = overall reaction rate constant for the film diffusion controlled reaction,

t = time of dissolution,

X = $(m_o - m)/m_o$, the fraction of the PGE extracted from the sample.

If a plot of [1 - (1 - X)$^{2/3}$] or [1 - (1 - X)$^{1/2}$] against t gives a straight line then the film diffusion reaction is the rate determining step. The reactant then has to pass through a film into the metal surface for the dissolution to occur.

2.2 Proposed Kinetic Model describing the PGM dissolution

The PGMs dissolution process involves a reacting chloride solution which penetrates through the silica matrix of the concentrate sample to the spherical particle of the reacting platinum-group metal surface for a chemical reaction to take place. Since the PGMs dissolution reaction leaves no solid product on the surface of the attacked metals, the leaching process is entirely chemical or surface reaction control. Therefore, the leaching rate should be linear in a well agitated system.

If the leaching rate from the experiment is established to be temperature dependant, then the reaction would be confirmed to be chemically controlled as opposed to diffusion control. In view of this, the rate equation of the shrinking-particle model which would be used to describe the PGMs dissolution is:

$$1-(1-X)^{1/3} = k_s t \qquad 2.4$$

The whole process is regulated by an overall reaction rate coefficient k_s which is a function of temperature, particle size and the concentrations of the HCl and Chlorine. Therefore,

$$k_s = k_o d_o^{-1}[HCl]^a[Cl_2]^b \exp\left[\frac{-E_a}{RT}\right] \qquad 2.5$$

where,

k_o = the overall constant determined from the product of the constants of initial particle size, [HCl], [Cl_2] and temperature relationships;

d_o^{-1} = the reciprocal relationship between the initial particle size and the reaction rate constant, ie, the larger the surface area per unit volume of solids (small particle size) the larger the rate of reaction;

$\exp\{-E_a/RT\}$ = the relationship between the temperature and the reaction rate constant which is determined from an Arrhenius plot, and

a, b. = the reaction orders with respect to [HCl] and [Cl_2] respectively.

When a chemical reaction at the mineral surface is the rate determining factor, the dissolution rate then depends on the temperature of the reaction. The dissolution values obtained for different leaching temperatures are used to calculate the activation energy, E_a of the reaction from an Arrhenius plot.

It is also known that the smaller the particle size, d_o, the higher the rate of dissolution. Therefore, particle size has an important role in the modelling of the rate of dissolution of the platinum-group metals.

CHAPTER 3

3.0 EXPERIMENTAL APPARATUS AND PROCEDURE

3.1 Concentrate Sample Preparation

A single sample of platinum-group metal concentrate, dried and blended was obtained from Impala Platinum Refinery (Springs) for the test work. This sample was thoroughly characterized, using chemical and mineralogical analyses. Particle size analysis was also performed on the sample and each of the size fractions were chemically analysed.

3.1.1 Chemical Analysis of the Bulk concentrate Sample

The concentrate sample was analysed chemically and the results are given below.

Table 3.1 : Chemical analysis of the bulk concentrate sample.

Elements	%	Elements	%
Pt	24.60	Fe	2.60
Pd	13.30	Pb	1.90
Au	1.12	SiO_2	12.90
Rh	4.12	As	0.43
Ru	5.03	Se	1.20
Ir	1.49	Te	2.40
Ag	2.20	Ba	<2000ppm
Ni	1.20	Na	1.70
Cu	3.00		

This analysis indicates that Pt and Pd are the major platinum-group metals in the concentrate sample. There is a significant component of silica in this sample.

3.1.2 Mineralogical Analysis of the Concentrate Sample

A number of polished sections of the concentrate sample were prepared and mineralogical analyses were investigated using the scanning electron microscope (SEM) utilising back-scattering electron microscopy and energy dispersive analysis (EDS). The mineralogy of the crystalline phases was determined by X-ray diffraction (XRD) analysis.

In the identification of the various phases by the EDS, the electron beam not only excites the atoms of the elements of the target grain but also the surrounding minerals. The XRD, EDS and the relative brightness of the back-scattering image were used to differentiate between the phases.

The sample consisted mainly of a porous silicate matrix in which the platinum-group elements (PGE) and other minerals were embedded. These silicate particles have a size range up to about 0.5 mm. A number of particles of Rh and Ru sulphide were detected in the silicate matrix and some of the Si present is alloyed to Pt and Ru. Alloys of PGE are disseminated in the silicate matrix. Pt is generally alloyed in varying proportions with other PGE and Se (also with Te to a limited extent). The predominant alloy is an alloy of Pt and Pd with some Rh and Ru. This phase typically occurs as particles less than 5 microns in size.

Within the matrix are large (up to 70 μm) particles of Pt-Cu, Pd-Rh-Ru and Ru-Si-Pt phases. There are round inclusions of Pd-Sb, Rh-Pd-Sb, and Rh-Pt-Fe found in the matrix together with Ru-Ir and Pt-Ru-Te alloys. Pd-Te and Os metals were also present. Minor quantities of oxides of the PGMs were identified. The PdO which was found seems to form the matrix in which the PGMs occur as very small particles. The concentration of PdO varies from particle to particle. The oxides (excluding SiO_2) observed in minor quantities are Fe-Ni oxides with varying proportions of Fe and Ni ("ferrites"), Cr-Fe oxides (Cr spinel) and Fe-Al-Si oxides (rare phase).

3.1.3 Particle Size Analysis of the Concentrate Sample

The concentrate sample was sized into fractions using the Malvern (MasterSizer) and the results are presented below.

Table 3.2 : Particle size analysis of the sample by the Malvern.

Upper size		Lower Size	% In	% Under
600	-	492	26.3	73.7
492	-	404	22.5	51.2
404	-	332	17.9	33.3
332	-	272	9.0	24.3
272	-	224	5.0	[illegible]5
224	-	183	1.9	[illegible]4
183	-	151	1.0	[illegible]3.4
151	-	124	0.5	15.9
124	-	101	0.3	15.6
101	-	83.3	0.2	15.4
83.3	-	68.3	0.2	15.2
68.3	-	56.1	0.2	15.0
56.1	-	46.0	0.2	14.8
46.0	-	37.8	0.2	14.6
37.8	-	31.0	0.3	14.3
31.0	-	25.5	0.3	14.0
25.5	-	20.9	0.4	13.5
20.9	-	17.1	0.5	13.0
[illegible]7.1	-	14.1	0.7	12.3
14.1	-	11.6	0.8	11.6
11.6	-	9.48	0.9	10.6
9.48	-	7.78	1.0	9.6
7.78	-	6.39	1.1	8.5
6.39	-	5.24	1.2	7.3
5.24	-	4.30	1.1	6.2
4.30	-	3.53	1.1	5.1
3.53	-	2.90	1.0	4.1
2.90	-	2.38	0.9	3.2
2.38	-	1.95	0.8	2.3
1.95	-	1.60	0.7	1.6
1.60	-	1.32	0.7	0.9

The results indicated that 90% of the concentrate sample is below 556.75 microns, 50% is below 396.62 microns and 10% is below the size of 8.41 microns.

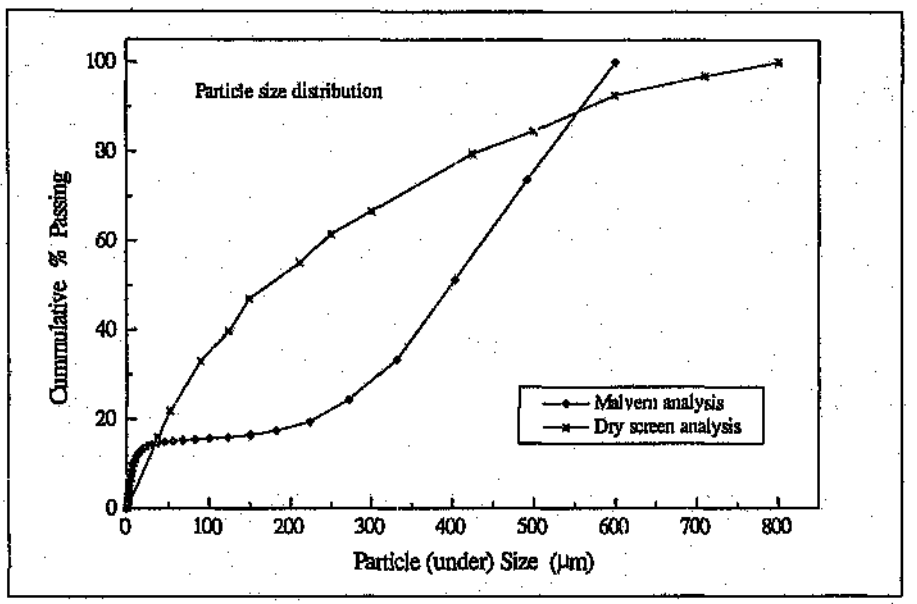


Fig. 3.1 Cummulative Particle-size distribution for Malvern and dry screen analysis.

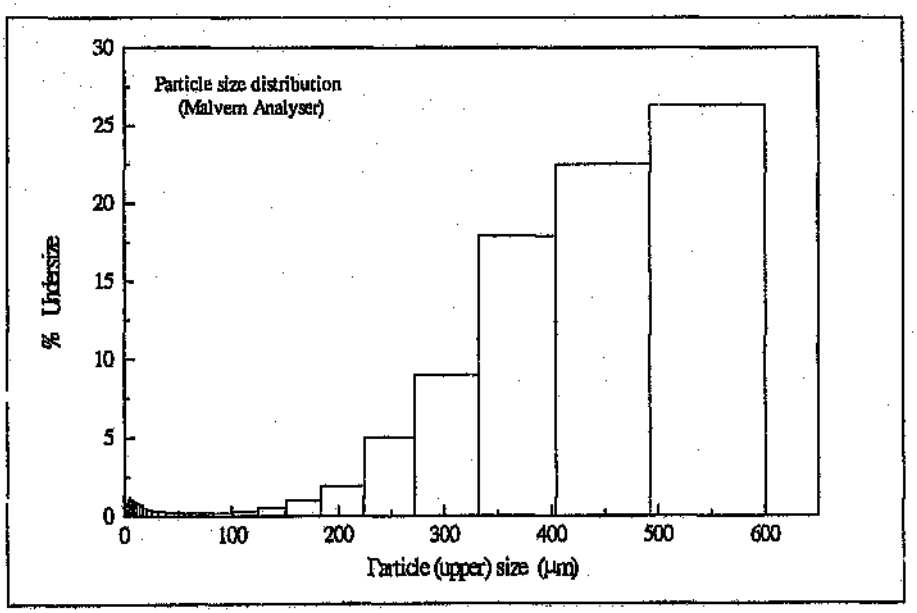


Fig. 3.2 Percentage Particle-size distribution for Malvern analysis.

The particle size distribution for the Malvern analysis is shown in Figures 3.1 and 3.2.

The bulk concentrate sample was also split into thirteen fractions by dry screening using ASTM standard sieves and a selected size fractions were leached separately. The relative amount of each fraction size is presented in Table 3.3 and the distribution is shown in Figures 3.1 and 3.3.

Table 3.3: Particle size distribution of the PGM sample (Dry screening)

Fractions	Size (μm)	% Mass retained	Cummul. % retained
0	850	-	-
1	710	3.17	100.00
2	600	4.27	96.85
3	500	8.08	92.58
4	425	5.06	84.50
5	300	12.88	79.44
6	250	5.09	66.56
7	212	6.44	61.47
8	150	8.09	55.03
9	125	7.24	46.94
10	90	6.90	39.70
11	53	11.03	32.80
12	38	5.92	21.77
13	-38	15.85	15.85
	Total	100	

From the dry screening, the results indicate that 90% of the sample is below 500 microns, 50% is below 150 microns and 10% of the sample is below the size of -38 microns.

The particle size distribution from the dry screening results as shown in Figure 3.3 differs from that obtained from the Malvern. The Malvern measures individual particle sizes optically (ie, a laser beam), while the screens separates particles of differing sizes or density by means of shaking them. Since there is a possibility of a particle missing a hole on the screen, these results show that the screening was satisfactorily done because the results are quite close as shown in Tables 3.2 and 3.3. The difference in particle size measurements for 90% of the concentrate sample by Malvern and dry screen analysis is 56.75 microns.

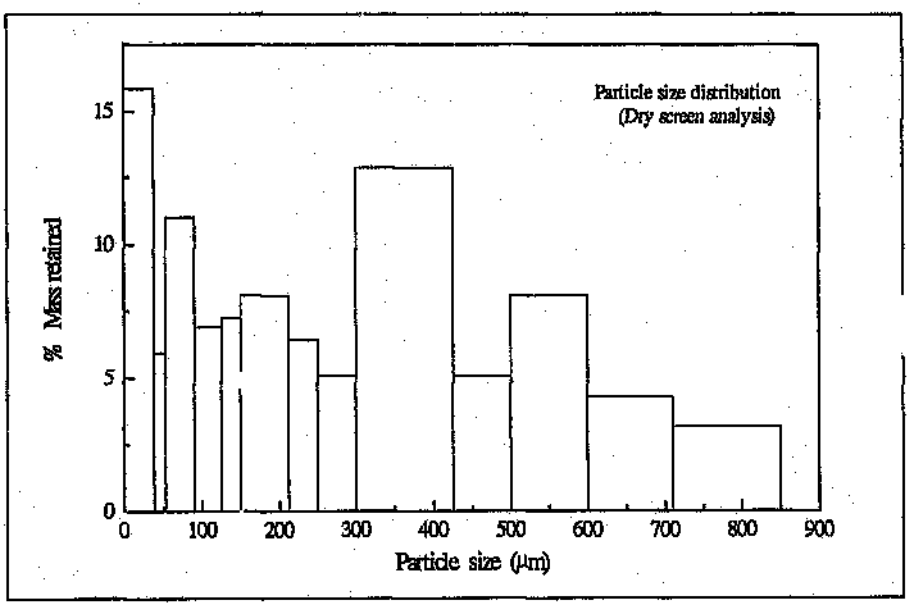


Fig. 3.3 Percentage Particle-size distribution for the Dry screen analysis.

3.1.4 Chemical Composition of the Concentrate Sample

The chemical composition of each size fraction was analysed by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP) and are presented in Table 3.4 below.

Table 3.4: PGM Sample - Chemical composition of the size fractions.

Size Fractions (μm)	Composition: Mass %										
	Pt	Pd	Rh	Ru	Ir	Au	Ag	Ni	Cu	Fe	Pb
710	24.1	13.0	3.9	4.8	1.4	1.1	3.3	0.94	1.9	2.0	1.7
600	23.9	12.9	3.8	4.7	1.4	1.1	3.3	0.92	1.9	1.9	1.7
500	24.4	13.2	4.0	4.8	1.4	1.1	3.4	0.93	1.9	1.9	1.7
425	24.3	13.2	3.9	4.8	1.4	1.1	3.4	0.91	1.9	1.9	1.7
300	23.3	12.6	3 8	4.6	1.4	1.1	3.1	0.88	1.9	1.9	1.7
250	24.0	13.0	4.0	5.0	1.4	1.1	3.3	1.00	1.9	2.3	1.7
212	23.9	12.9	4.0	5.1	1.5	1.1	3.3	1.00	1.9	2.4	1.7
150	23.3	12.6	4.0	5.0	1.5	1.1	3.0	1.00	2.0	2.4	1.6
125	23.5	12.6	4.0	5.1	1.5	1.1	3.2	1.00	1.9	2.6	1.7
90	22.8	12.2	4.3	5.6	1.8	1.1	3.0	1.30	1.9	3.9	1.6
53	23.3	12.4	4.4	5.6	1.8	1.1	3.1	1.30	1.9	3.7	1.7
38	23.2	12.4	4.4	5.7	1.8	1.1	3.1	1.30	1.9	3.8	1.7
-38	20.1	11.2	4.2	5.3	1.6	1.03	2.6	1.80	1.7	3.8	1.5
Bulk	23.0	12.5	4.1	5.1	1.5	1.1	3.1	1.20	1.5	2.7	1.6

Table 3.4 indicates that the mineral proportions in the bulk sample is almost the same as each size fractions with an average deviation of $\pm 0.75\%$ from the bulk sample.

Among the size fractions, the percentage mass of Rh, Ru and Ir increases as the particle size decreases, whereas the trend reverses for Pt and Pd. The percentage mass of Au remained the same for all the size fractions. The limits of measurement is $\pm 0.01\%$ for all the elements.

Therefore, it is concluded that the chemical composition of the size fractions is about the same for all the PGMs in the concentrate sample.

3.2 Apparatus:

The leaching experiments were conducted in a 2-litre glass vessel equipped with an overhead stirrer (Heidolph RZR 50) in a thermostatically controlled water bath with a constant temperature circulator. Figures 3.4 and 3.5 are the diagrams of the reaction vessel and its internals.

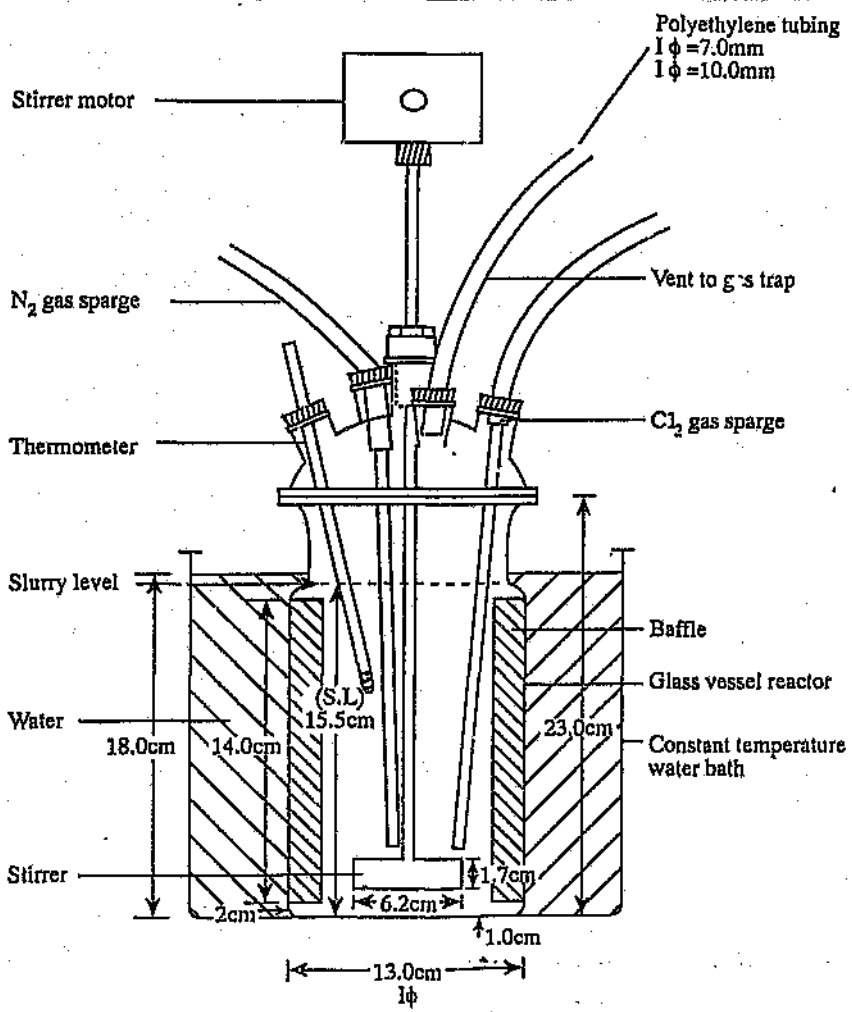


Fig. 3.4 Schematic diagram of the Leach Reactor.

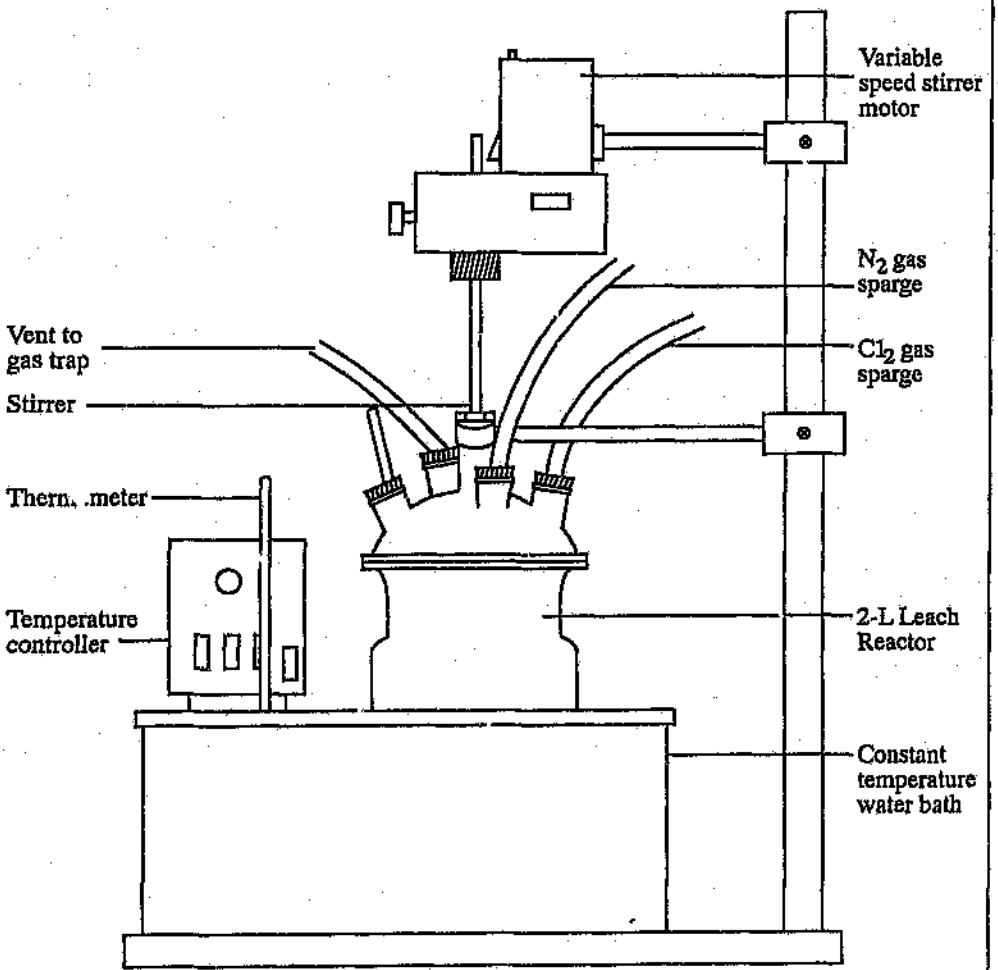


Fig. 3.5 Schematic diagram of the Constant-temperature batch Leach equipment.

Two glass baffles were attached to the inside of the leaching vessel. The lid of the vessel has 5 ports. The central port is for the stirrer and one port for a thermometer and also for withdrawing samples. The other ports are for nitrogen gas sparge and the redox electrode together in one port, chlorine gas sparge and the reference electrode in one and the last port for the gas exhaust. The gas exhaust passes through a series of vessels

containing NaOH solution in which the excess chlorine gas is absorbed.

The agitation was supplied by a flat two-bladed stirrer of teflon coated stainless steel (6.20 cm blade length). The stirrer was driven by a variable speed motor, and the speed was set by a tachometer.

An Orion platinum combination redox electrode (ATI type) of Ag/AgCl (3 M KCl) was used to measure the corrosion potential of the leaching solution, which was read on an Orion 420 pH/mV meter. The pH of the leaching solution was measured by an Orion pH triode. For the tests during which redox potential measurements were taken, a glassy carbon electrode and a double junction Ag/AgCl reference electrode were immersed to a sufficient depth in the leaching solution. The redox potentials were measured on a Copenhengen Radiometer PHM84 pH/mV meter. All the experimental tests were conducted at ambient pressure and a constant chlorine flowrate of $825 cm^3 min^{-1}$ except when chlorine concentration and pressure effects were being monitored.

3.3 Chemical Reagents

For each group of the leaching experiments, analytical grade of hydrochloric acid of 32.0 % purity were used. Deionised water was used to prepare all the HCl solutic and reagents to their desired concentrations.

3.4 Experimental Procedure

The experimental work can be divided into two parts, namely, the chlorine solubility tests and the PGMs leaching experiments. The chlorine solubility investigation was planned specifically to establish the effective conditions for the application of the leaching solution. The batch leaching tests were also designed to investigate the factors that affect the dissolution of PGMs and also to test the applicability of some

mathematical models. The redox potentials were also measured together with the leaching.

3.4.1 Procedure for the Chlorine Dissolution in HCl solution

The dissolution of Cl_2 gas in hydrochloric acid solution was determined by bubbling chlorine gas through the hydrochloric acid solution under different temperatures, hydrochloric acid concentrations, chlorine flowrates and agitation speeds. The agitation speed was set at 125 rpm for all the chlorine dissolution tests except when the effect of agitation was investigated.

Two litres of the hydrochloric acid solution of a particular concentration was poured into the leaching vessel in a constant temperature bath. The bath was set at the required temperature and controlled to within $\pm 0.5^{\circ}C$. The temperature of the solution was allowed to rise and once it had stabilised, the chlorine gas purge was supplied from a high pressure cylinder through a pressure regulator and a rotameter to the hydrochloric acid solution. The stop-watch was started.

Solution samples of 10 ml were extracted using a pipette at a regular intervals of 10 minutes. The samples were titrated for chlorine gas concentration. The chlorine concentrations were determined by iodometric titration with sodium thiosulphate ($Na_2S_2O_3$) solution.

3.4.1.1 Chemical Analysis: Titration method for Chlorine Concentration

The total chlorine concentration in solution was determined by iodine and sodium thiosulphate titration method.

The titration involved the addition of a stoichiometric excess of I^- (typically in the form of KI) to the solution sample to be analysed[36, 37]. The OCl^- in the solution then oxidises

the I^- to I_3^-.

$$NaOCl^- + 3I^- + 2H_3O^+ \rightleftharpoons NaCl + I_3^- + 3H_2O \qquad 3.1$$

The I_3^- was then reacted with the $S_2O_3^{2-}$ during which a colour change occurs from a dark black (due to the I_3^-) to an almost colourless solution [36]. The determination of the equivalence point was simplified by the addition of a starch indicator to the solution.

$$I_3^- + 2S_2O_3^{2-} \rightleftharpoons 3I^- + S_4O_6^{2-} \qquad 3.2$$

A standard 0.100 M sodium thiosulphate solution and starch indicator were prepared.

The standardisation was performed by titrating the thiosulphate solution against a known mass of potassium dichromate according to the reactions[37]:

$$Cr_2O_7^{2-} + 9I^- \rightleftharpoons 2Cr^{3+} + 3I_3^- + 7H_2O \qquad 3.3$$

$$3I_3^- + 6S_2O_3^{2-} \rightleftharpoons 9I^- + 3S_4O_6^{2-} \qquad 3.4$$

About 1 g of pure potassium dichromate ($K_2Cr_2O_7$) in a watch glass was placed into an oven at 170°C for an hour and three 0.2 g portions of the dried potassium dichromate were accurately weighed into 500 ml flasks [37]. A volume of 100 ml distilled water was added to the content of each flask.

The three solution samples were treated separately from now on. A freshly prepared solution containing 4 gms of potassium iodide, 2 ml of HCl and 50 ml of distilled water was added to the dichromate solution. The solution was gently swirled and left to stand in a dark place for about 5 minutes. This was necessary to allow for the complete oxidation of the I^- to I_3^-.

A clean 50 ml burette was filled with the standardised solution. The thiosulphate

solution was titrated with the I_3^- solution until the dark yellow-orange colour of the I_3^- ion had almost disappeared. A starch solution of 5 ml was added and the solution darken immediately.

The titration was continued until the deep purple colour of the starch-tri-iodide complex had changed to a light blue colour. The end point to the nearest 0.05 ml was recorded. The other two samples were titrated in the same manner with the average standard deviation not more than 2 ppt.

Determination of the total concentration of chlorine in HCl solution was then determined by pipetting the solution sample to be analysed into a 500 ml Erlenmeyer flask. The burette was filled with the standardised thiosulphate solution. A prepared solution containing 3 gms of potassium iodide, 10 ml of distilled water was added to the solution sample and swirled to mix. Glacial acetic acid of 10 ml was added to the sample.

The sample was titrated with the sodium thiosulphate solution until the dark yellow-orange colour of the tri-iodide ion had almost disappeared and 5 ml of starch solution was added. The solution immediately darkens due to the formation of a starch-tri-iodide complex. The titration was continued until the solution became colourless and the end point volume was recorded to the nearest 0.05 ml.

3.4.2 Procedure for Leaching the PGM concentrate sample

For each leaching experiment, 2.0 litres of the hydrochloric acid solution of a particular concentration was poured into the leaching vessel in the constant temperature water bath. The bath heater and the leach vessel stirrer were switched on and when the temperature of the leach solution had stabilised at the required temperature, the chlorine gas sparge was started from the same high pressure cylinder through the pressure regulator system into the HCl solution and the stop-watch was started. A stirrer speed

of 150 rpm was used for all the experiments unless otherwise stated.

The chlorine gas was allowed to pass through the hydrochloric acid solution for 30 minutes to ensure that the solution is saturated with chlorine after which a 10 ml solution sample was taken for iodometric titration to determine the initial chlorine concentration. The initial pH and corrosion potential were measured. The chlorine gas was continually supplied to the leaching system throughout the experimentation.

Twenty grams of the PGM concentrate sample was weighed out on a plastic sheet to within ± 0.01 g accuracy on an electronic balance. This sample was poured into the leaching system immediately after taking the sample and the stop watch was started. It took about 5 to 10 seconds to pour all the sample into the leach vessel. Time zero was taken as the start of pouring the sample into the vessel.

Solution samples of 15 ml were drawn with a pipette at selected time intervals and immediately filtered under pressure in a Millipore filter using 0.44 micron teflon filter membranes. The filtered liquid samples were divided into two. One was bottled for analysis of the platinum-group elements and the other was used to determine the pH and the corrosion potential of the leaching solution at that dissolution time. Every time a solution was taken, redox potential measurements were also read on the Radiometer PHM84 and recorded. The solids from the filter membrane were combined for assay for the overall material balance.

The Millipore filter system was washed with water and dried for the next sample draw. The samples were taken at 10 minute intervals for the first 2 hours and thereafter at 30 minute intervals for the rest of the 6 hour leaching period.

At the end of the leach, the leach vessel was removed from the hot water bath and the contents were filtered hot in the Millipore filter system with the 0.44 micron teflon filter membrane. The last sample was also taken for the pH, corrosion potential analysis and 10 mls of it for analysis of the platinum-group elements.

The leach vessel was thoroughly rinsed with a known volume of deionised water. The wash water from this was used for the first residue wash and filtered. This leach residue was washed again by deionised water, filtered, dried and then weighed for analysis. These wash liquor were bottled and added to the solution samples for analysis.

3.4.2.1 Sample Analysis

The leach solution samples taken during and after the leaches were analysed for Pt, Pd, Rh, Ru, Ir and Au concentrations. This analysis of the leach solutions for the platinum-group elements was done by Inductively Coupled Plasma - Atomic Emission Spectrometry (ICP-AES) at Impala Analytical laboratory (Springs). The wash water samples were also analysed for Pt, Pd, Rh, Ru, Ir and Au in the same way. Solid samples were fused with peroxide prior to HCl/Cl_2 leach before analysed in the same way as the solution samples.

3.4.2.2 Calculations of extractions during the leaching

The extraction of Pt, Pd, Rh, Ru, Ir and Au during any given time of the leach were calculated as follows:

(i) % Extractions during leaching = $X_{M(t)}$

$$X_{M(t)} = \frac{\left(V - \sum_{j=1}^{j-1} V_j\right) C_{M(t)} + \sum_{j=1}^{j-1} V_j C_{M(t)}}{mc_M} \times 100 \qquad 3.5$$

where,

V = Initial volume of the solution into leach (litres)

V_j = Volume of solution sample j drawn at time t (litres)

$C_{M(t)}$ = Concentration of Pt, Pd, Rh, Ru, Ir or Au in the solution sample j drawn at time t (g/l)

m = Mass of the solid concentrate sample added into the reactor (g)

c_M= Weight % of the Pt, Pd, Rh, Ru, Ir or Au in the solids into leach.

j = the jth sample taken during leaching

J = Total number of samples taken

(i) Overall % Extraction = X_f

$$X_f = \frac{V_f C_{M(f)}}{mc_M} \times 100 \qquad 3.6$$

where,

V_f = Volume of pregnant liquor out (litres)

$C_{M(f)}$ = Concentration of the sample after leach (g/l)

3.4.3 Procedure for PGM Leach Tests in Autoclave

The autoclave used for the pressure variation experiments was a 2 litre PARR series 4520 bench top reactor. This autoclave was equipped with a stirring system for agitating the leaching solution system vigorously under pressure. It had an electric heater with automatic temperature controller, a spout for withdrawing solution samples in the course of the leaching, a pressure gauge and an LCD temperature monitor. The autoclave was constructed from 316 stainless steel and titanium. The leaching was done in the glass bottle inside the autoclave. The areas where serious corrosion would affect the autoclave were covered with teflon.

The autoclave was filled with 2.00 litres of 6.00 M hydrochloric acid solution and 20 grammes of the PGM concentrate sample was carefully weighed out on a plastic sheet to within ± 0.01 g accuracy on an electronic balance and was poured into the autoclave. The autoclave was covered tightly and the connection to the chlorine gas cylinder was fitted. The leaching system in the autoclave was heated to 50°C and the

stirrer speed was adjusted to 150 rpm to offer an excellent gas dispersion into the mixture. The start of the stirrer and heater was taken for time zero.

Solution samples were withdrawn from the autoclave at selected time intervals and immediately filtered with the Millipore filtration system. The samples were bottled for analysis of the platinum-group elements and the gold using the ICP-AES.

3.5 Etch Tests

A number of polished sections were prepared by cementing the PGM concentrate sample in an Araldite epoxy resin. The specimens surface were fine wet ground with emery paper and polished with 1 μm alumina.

The exposed surface areas were photographed and leached in hydrochloric acid solution of 6.00 M concentration for 1 hour and 2 hours. Chlorine gas flow of 750 cm^3min^{-1} was allowed to pass through the solution at a temperature of 30°C. The agitation of the solutions were accomplished with a magnetic stirrer at a speed of 140 rpm.

Two polished sections were leached for 1 hour and another two sections were also leached for 2 hours and photographs of the small circle on each section were taken. The attacked sections were analysed using XRD analytical techniques. The morphology of the leached surface of the polished PGM sections were examined by SEM. Photomicrographs 3.1 to 3.4 show the morphology of the polished PGM surface before and after leaching for 1 hour and 2 hours in 6.00 M hydrochloric acid solution at 30°C.

Photomicrographs 3.1 and 3.2 show the distribution of the PGM particles in a fresh concentrate sample. The central particle focussed in photo 3.1 is Pt-Pd alloy which is about 0.5 mm in size. Most of the identified particles are described in section 3.1.2. This can be compared with the photomicrographs 3.3 and 3.4 which were leached for 1 hour and 2 hours respectively. The mineralogical studies of these leached sections



Photo 3.1 Scanning electron micrographs of the initial PGM particles of the concentrate before leaching.

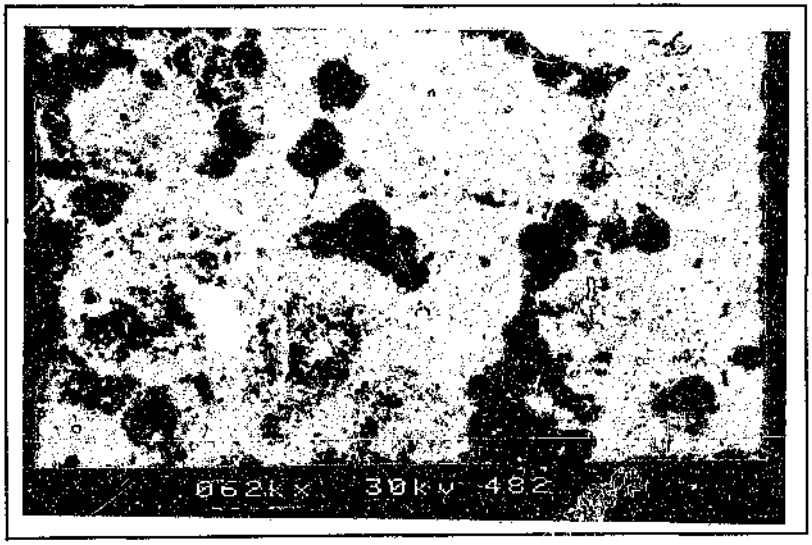


Photo 3.2 Scanning electron micrographs of the PGM particles of fresh concentrate sample before leaching.

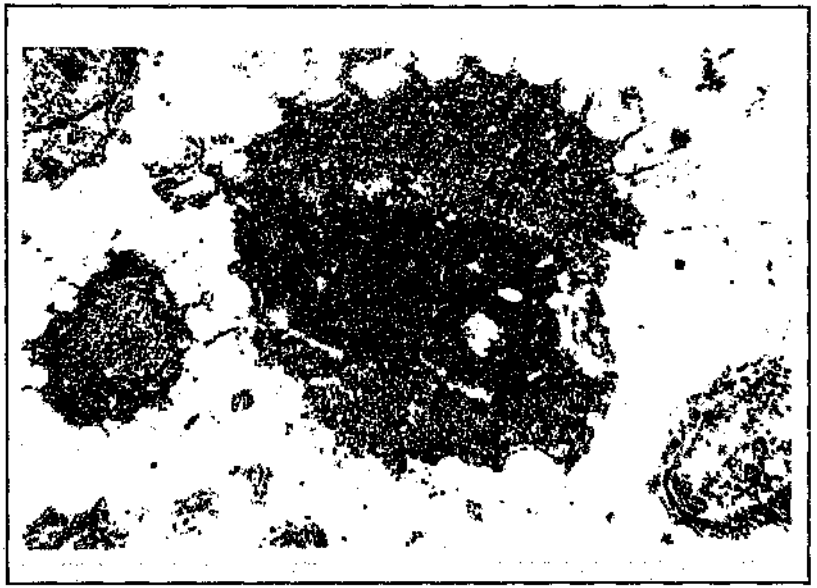


Photo 3.3 Scanning electron micrograph of the PGM sample after 1 hour leach in 6.00 M hydrochloric acid solution at 30°C.



Photo 3.4 Scanning electron micrograph of the PGM sample after 2 hour leach in 6.00 M hydrochloric acid solution at 30°C.

indicated that the sample consists mainly of silicate material with AgCl particles disseminated in them which might coat some of the PGM particles to hinder them from dissolving in the HCl leach solution. The investigated surfaces also show that most of the Pt and Pd occur together as alloys and dissolved quite fast during the etching. The Pt-Pd alloy particle (Photo 3.1) which was selected for observation was leached out completely (Photo 3.3). The particles which remained were identified to be Rh-Ir-Fe, Ru-Pt and Ru-Fe alloys. These particles ranged in size from 100 μm to 200 μm. Ru and Ir are the more abundant elements in both alloys. To a lesser extent, particles of Pt-Ru-Fe alloys were found. The proportion of Fe and Pt varied in these samples, but Ru was always the most abundant element in the alloys. Some of these Pt-Ru-Fe alloy particles are extremely large in size, up to 300 μm and 400 μm in some cases.

A few amounts of Pt, Rh and Ir were also detected in the leached sections. The Rh is not abundant and is present as either Rh-As alloy or Rh sulphide.

3.6 SEM Analysis of the Leach Residue Samples

Three polished sections of the leach residue sample from the experimentation work were also prepared and a small circle inscribed on each section was investigated using the scanning electron microscope (Cambridge Instrument - Stereoscan 360). The general composition of the residue samples is shown with the SEM photo-micrographs in Photos 3.5 to 3.8 below. Photomicrograph 3.5 and 3.6 are from the residue of the dissolution of unscreened sample with 6.00 M HCl solution at chlorine flowrate of 825cm^{3}min^{-1} at 30℃. The residue from the leaching test at a higher temperature of 80 ℃ was used for the sections from which the photomicrographs 3.7 and 3.8 were taken.

The particles that were photographed are from samples with different types of particles present. It is interesting to note that most of the particles present on the sections were Rh-Fe-Ir, Ru-Fe-Pt-Rh and Fe-Rh-Ru-Si alloys. Few particles of Pt alloys were identified. There was no Pd particle found in photo 3.7 and 3.8. A large number of

particles of AgCl were identified to be disseminated in the silicate matrix in all of the sections.

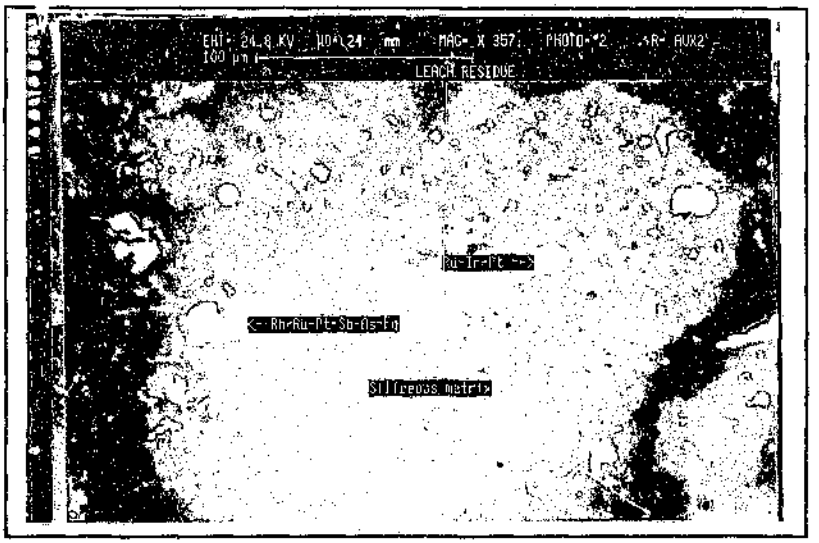


Photo 3.5 Scanning electron micrograph of a 6 hour leached residue from the laboratory leach test in 6.00 M HCl at 30°C.

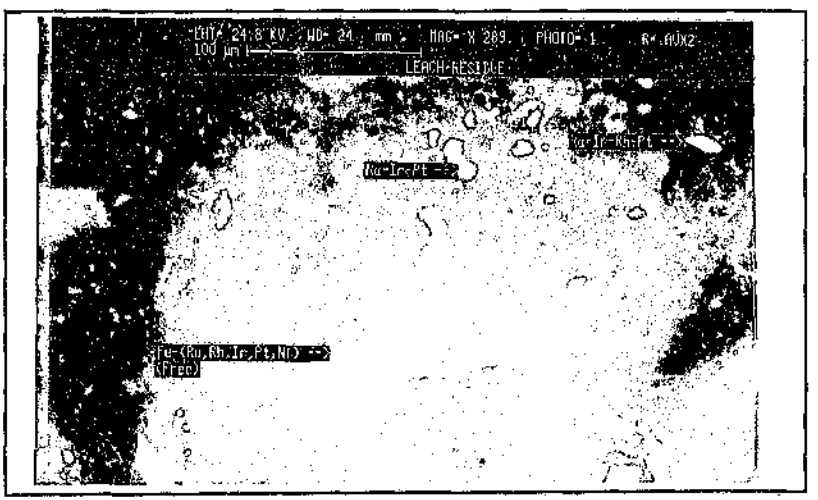


Photo 3.6 Scanning electron micrograph of a 6 hour leached residue from the laboratory leach test in 6.00 M HCl at 30°C.

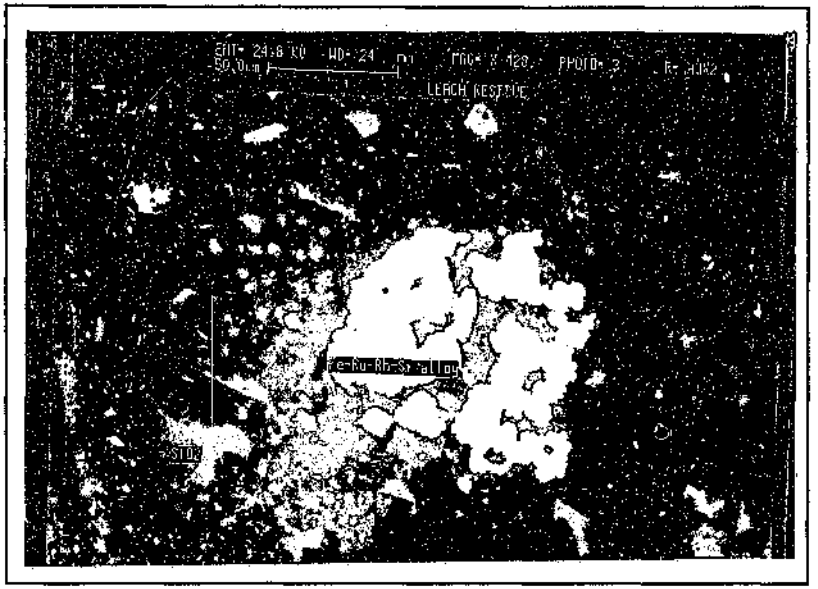


Photo 3.7 Scanning electron micrograph of a 6 hour leached residue from the laboratory leach test in 6.00 M HCl at 80°C.

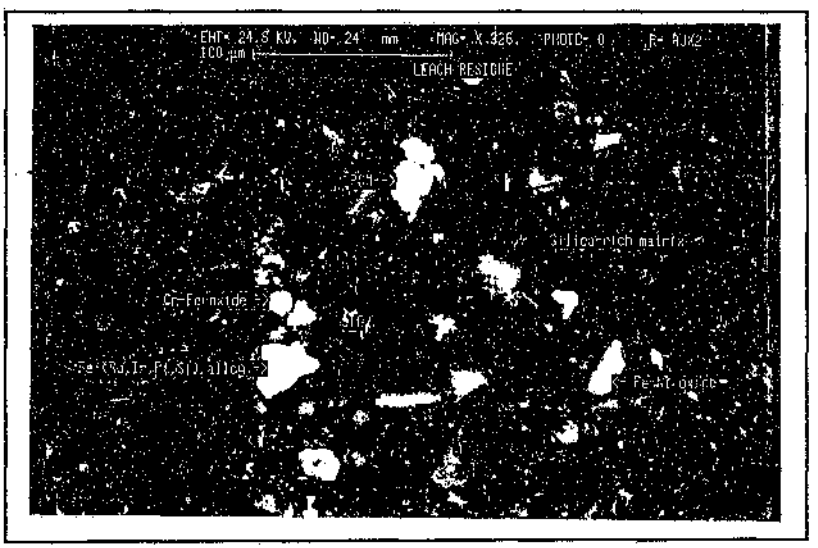


Photo 3.8 Scanning electron micrograph of a 6 hour leached residue from the laboratory leach test in 6.00 M HCl at 80°C.

3.7 Procedure for the Impala Refinery Plant Tests

The plant leach test was conducted using the Impala Precious Metal Refinery (PMR) reactor 2101. The reactor is made of titanium and is equipped with instrumentation and sampling device for accurate determination of temperature, pressure, agitation speed and flowrate of the cooling water. The reactor has a fluid capacity of 1500 litres with a diameter of 1.20 m, a height of 1.705 m and has a jacket for heating and cooling. The same jacket is used for both operations. A solution agitation speed of 140 rpm was considered for all the plant tests.

(i) Determination of Mass Transfer Coefficient Test.

The chlorine dissolution test was conducted using this plant reactor to determine the mass transfer coefficient of the reactor 2101. The temperature of the reactor was set at 50°C and controlled to within ± 2.5°C at an ambient pressure. The hydrochloric acid solution used for this test work was 6.00 M. The solution samples were withdrawn at 10 minutes intervals by the automatic sampler attached to the reactor.

The chlorine dissolution profile in the hydrochloric acid solution in the reactor is plotted and the mass transfer coefficient is determined.

(ii) Determination of Heat Transfer Coefficient Test

The heat transfer coefficient of the PMR reactor 2101 was also determined by heating the reactor from the initial temperature of 15°C to 85°C and was cooled to 32°C. The reactor was charged with 1200 litres of 6.00 M hydrochloric acid solution and ambient pressure was considered for this test. The average temperature of the steam was 116.8°C and the cooling water temperature was 11.8°C. The average flowrate of the cooling water was 13.4 m^3hr^{-1}.

The heating and cooling curves were measured in order to obtain values for the overall heat transfer coefficients for the reactor.

(iii) Plant Leach Test

The reactor was filled with 1200 litres of 6.00M hydrochloric acid solution and 320 kg of the dried PGM concentrate was charged into the reactor. Chlorine gas was sparged into the vessel at an average massflow of 1.20 $kgmin^{-1}$. As soon as the chlorine gas was allowed into the reactor, the watch was started for time zero for the leaching process. The temperature used for this test was 70°C which was controlled to within ±4.0 °C and the pressure was set at 80 kPaG.

The first sample was taken after 10 minutes of leaching when the reactor pressure was enough for sampling through the automatic sampler. The samples were taken at time intervals of 20 minutes for 2 hours and 30 minutes interval thereafter for the other 4 hours. The solution samples were filtered immediately they were taken using the Millipore filtration system and were bottled. The solution samples together with the residue samples were sent for ICP-AES analysis of PGEs and gold.

The laboratory leach test conducted at the same condition as the plant leach test was used to scale-up the laboratory results to the plant level. This assists in intepretation of the overall results so that they can be applied at the industrial scale. A scale-up model is developed to simulate the results to optimise the conditions for the refinery.

CHAPTER 4

4.0 RESULTS OF THE EXPERIMENTAL WORK

The observations made in the experiments are reported here. The deductions and applications made from these results are reported in subsequent chapters. The procedures outlined in Section 3.4 were followed and the raw data are presented in the Appendix B.

4.1 Experimental Results for the Chlorine dissolution

4.1.1 Reproducibility of the Chlorine dissolution

The first three experiments for the dissolution of chlorine in HCl were used to test the reproducibility of the experimental results.

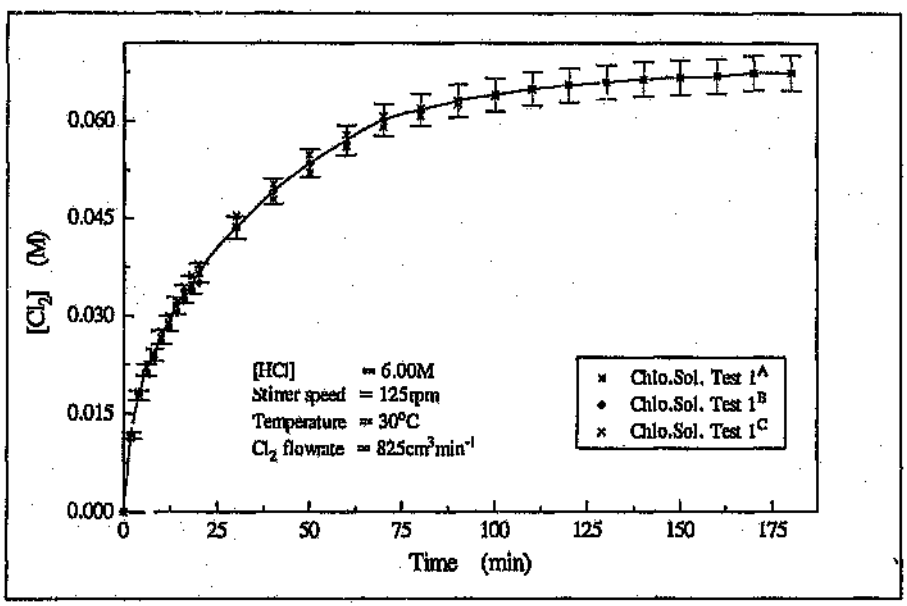


Fig. 4.1 Reproducibility of Chlorine dissolution in Hydrochloric acid results.

These three tests used the same experimental conditions and the results show the degree of reproducibility obtained in the experiments. Figure 4.1 shows that the experimental technique is reproducible.

The experimental factors studied were the effect of temperature, concentration of the hydrochloric acid solution, concentration of total chlorine and agitation speed. The chlorine dissolution tests were conducted over a period of 180 minutes by which time the hydrochloric acid solution was fully saturated with chlorine.

4.1.2 Effect of Temperature on the Rate of Chlorine dissolution in HCl

The effect of temperature was tested and the results are shown in Figures 4.2, 4.3 and 4.4 which indicate that the solubility of chlorine gas in hydrochloric acid solution decreases as the temperature increases from 30°C to the boiling point of the acid.

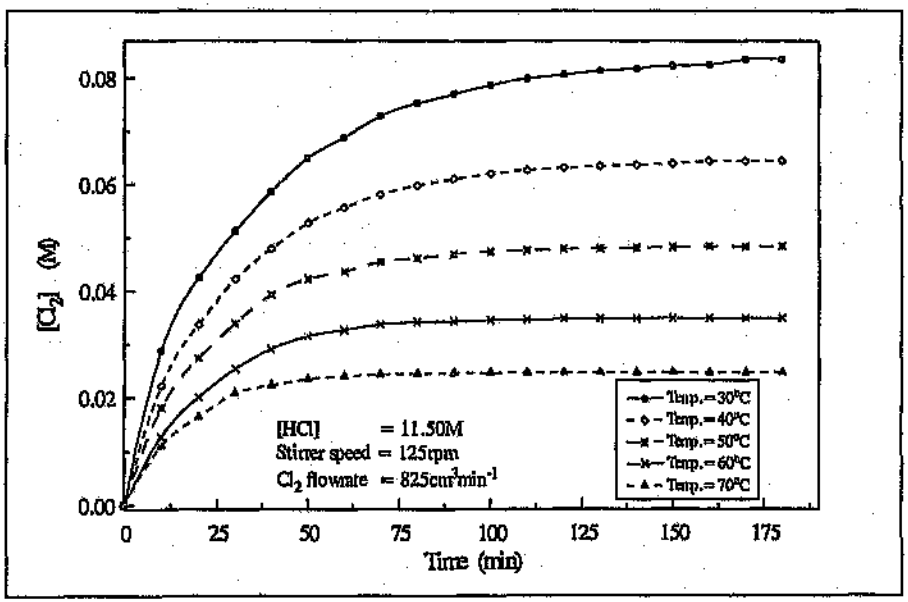


Fig. 4.2 Effect of Temperature on the rate of Chlorine dissolution in 11.50 M Hydrochloric acid solution.

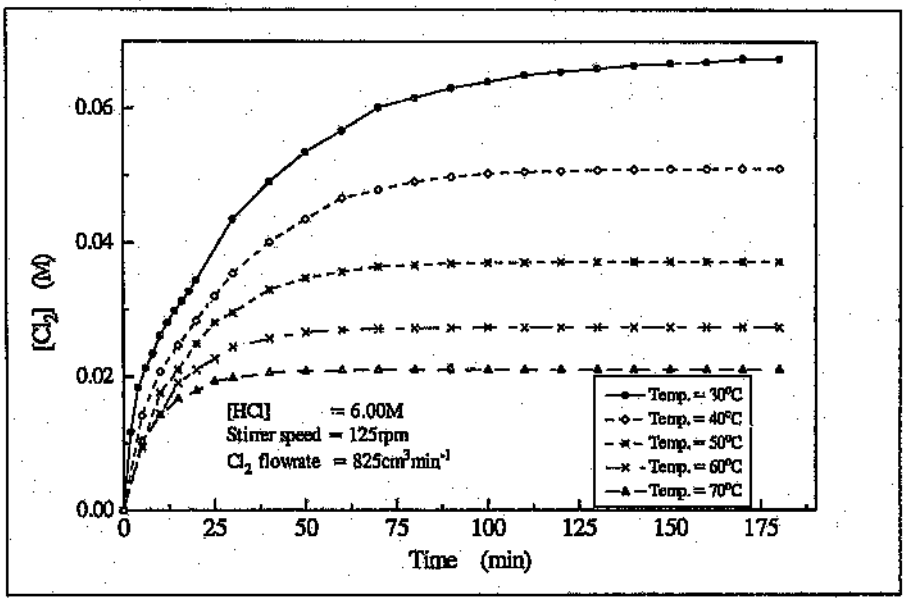


Fig. 4.3 Effect of Temperature on the rate of Chlorine dissolution in 6.00 M HCl.

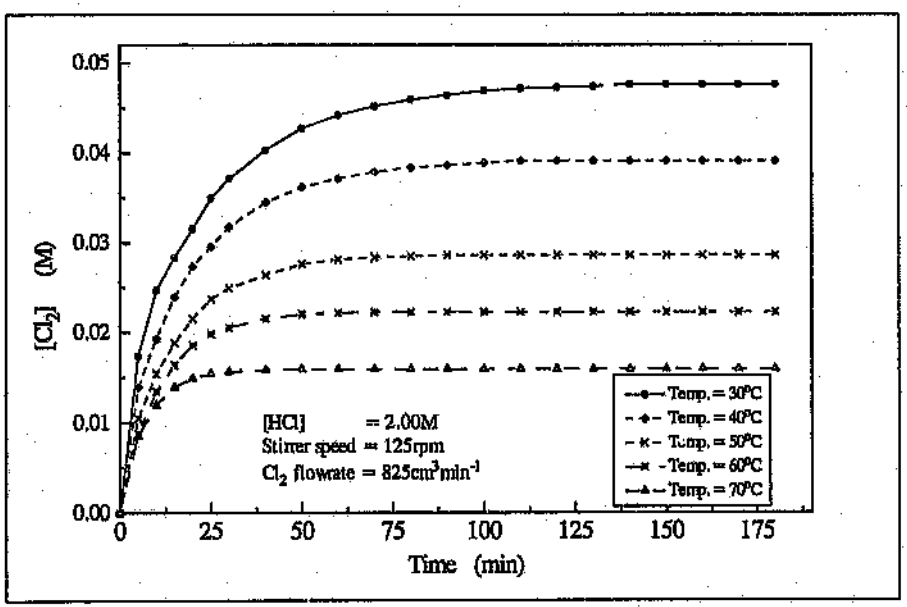


Fig. 4.4 Effect of Temperature on the rate of Chlorine dissolution in 2.00 M HCl.

The dissolution of the chlorine gas into solution is described by the following material balance:

$$\frac{dC}{dt} = -k_m(C - C_s) \qquad 4.1$$

The integration of this differential equation gives the expression:

$$\ln (1 - C/C_s) = - k_m t \qquad 4.2$$

where,

C is the chlorine concentration at time t, C_s is the saturated chlorine concentation and k_m is the mass transfer coefficient for chlorine dissolution.

Thus a plot of $\ln(1-C/C_s)$ versus time t should be linear with slope $-k_m$.

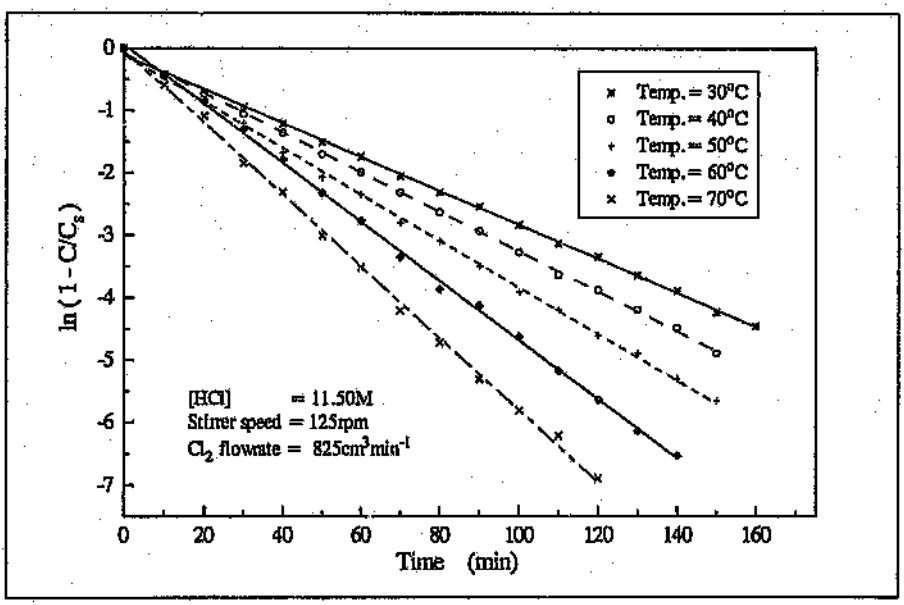


Fig. 4.5 Variation of $\ln(1-C/C_s)$ with time to determine Mass transfer coefficients.
Conditions: *[HCl]= 11.50M, Stir.spd= 125rpm, Cl_2 flow. = 825cm^{3}min^{-1}*

The $\ln(1 - C/C_s)$ versus t graphs were plotted (Fig. 4.5, 4.6 and 4.7) to determine the mass transfer coefficients (k_m) for the chlorine dissolution. The values of the mass transfer coefficients were determined by regression analysis for the acid strengths of 11.50 M, 6.00 M and 2.00 M at different temperatures. These are presented in Table 4.1 below.

Table 4.1: Temperature influence on Mass transfer coefficient of Cl_2 dissolution in HCl

Temperature (°C)	Mass Transfer Coefficient of the Chlorine dissolution		
	[HCl] = 11.50 M k_m (s^{-1})	[HCl] = 6.00 M k_m (s^{-1})	[HCl] = 2.00 M k_m (s^{-1})
30	4.53×10^{-4}	4.83×10^{-4}	6.44×10^{-4}
40	5.30×10^{-4}	6.93×10^{-4}	7.97×10^{-4}
50	6.21×10^{-4}	9.10×10^{-4}	1.11×10^{-3}
60	7.89×10^{-4}	1.15×10^{-3}	1.48×10^{-3}
70	9.59×10^{-4}	1.53×10^{-3}	2.23×10^{-3}

The mass transfer coefficient of the chlorine dissolution is a function of the chemical and physical characteristics of the system such as the temperature, the hydrochloric acid concentration and agitation of the solution. It is shown in Table 4.1 that the mass transfer coefficient of the chlorine dissolution is increased by increasing the temperature and reducing the hydrochloric acid concentration at constant agitation. However, the chlorine dissolution in hydrochloric acid solution decreases with temperature despite the increase in the mass transfer coefficient.

The mass transfer coefficient may be expressed as a function of temperature in the manner of an Arrhenius type relationship:

$$k_m = k_{m,o} \exp\left(-E_a / RT\right) \qquad 4.3$$

From the gradients of $\ln(1-C/C_s)$ against time graphs, an Arrhenius plot was constructed to determine the activation energy and is shown in Figure 4.8.

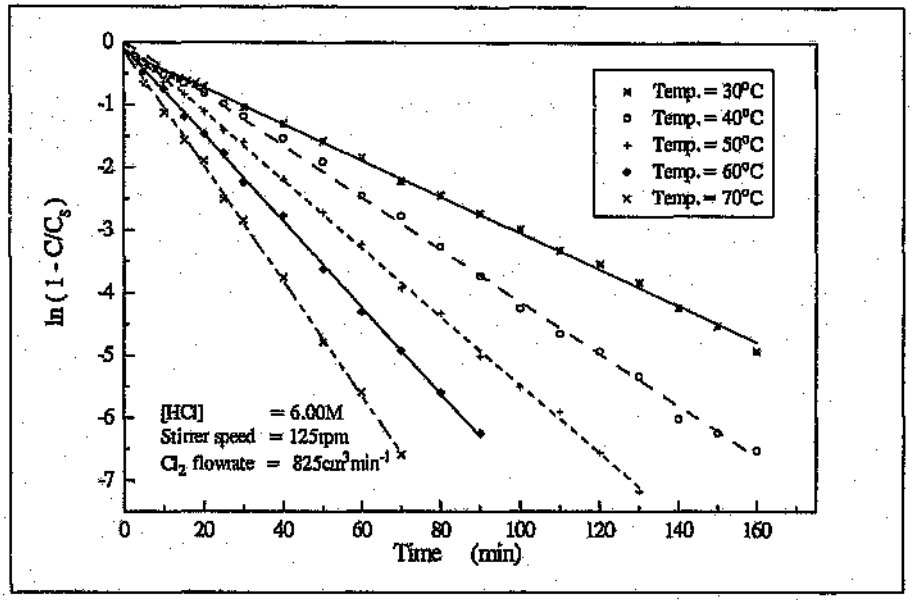


Fig. 4.6 Variation of $\ln(1-C/C_s)$ with time to determine Mass transfer coefficients.

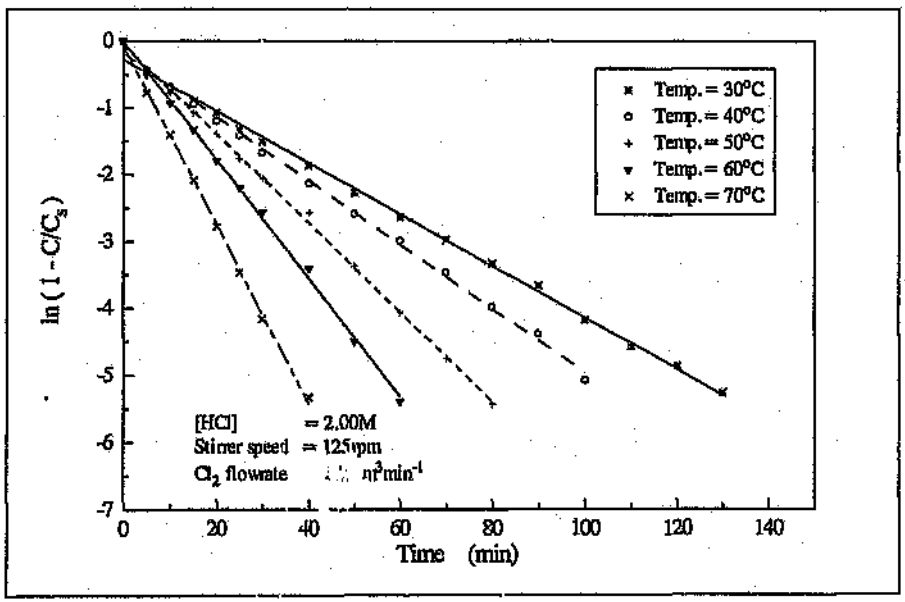


Fig. 4.7 Variation of $\ln(1-C/C_s)$ with time to determine Mass transfer coefficients.

The mass transfer coefficient, k_m results obtained in the three sets of acid concentrations ([HCl]= 11.50 M, 6.00 M and 2.00 M) were used for the Arrhenius plot. The slope is $-E_a/R$ and the intercept is $\ln(k_{m,o})$. From the slope of the Arrhenius graph, the activation energy, E_a, was calculated.

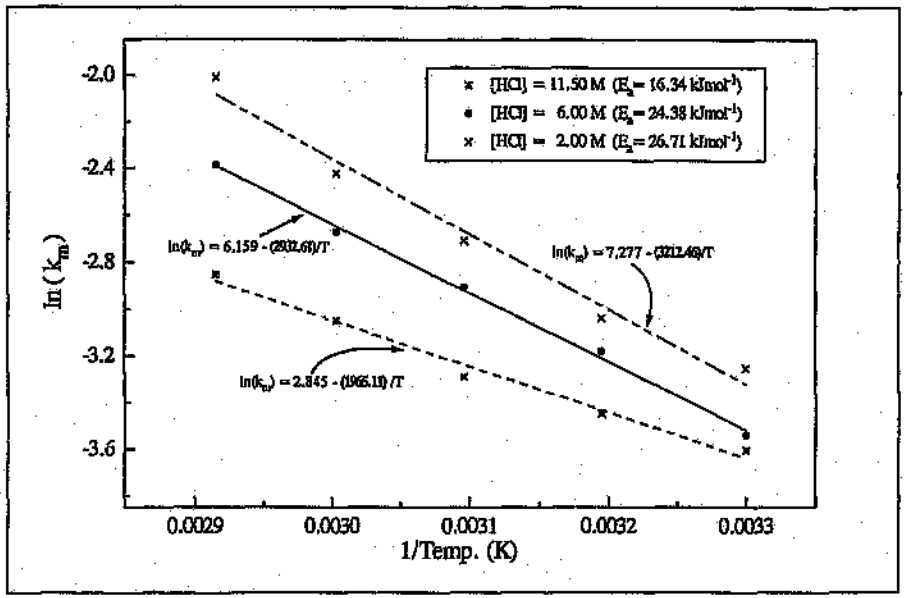


Fig. 4.8 Arrhenius plot for the Chlorine dissolution in HCl solution at diff. Conc.
Conditions: *Stir.spd= 125rpm, Cl_2 flowrate= 825cm^{3}min^{-1}*

From the slope of the graph in Figure 4.8, the activation energy for chlorine dissolution in the hydrochloric acid concentration of 11.50 M was found to be 16.34 kJmol^{-1}. The activation energies for the chlorine dissolution in 6.00 M and 2.00 M HCl solutions are 24.38 kJmol^{-1} and 26.71 kJmol^{-1} respectively. The results show that the lower the concentration of the hydrochloric acid solution the higher the activation energy required to effect the chlorine dissolution. The activation energy values obtained for the dissolution of chlorine in hydrochloric acid solutions indicate a solubility process which is controlled entirely by diffusion of the chlorine gas through the gas-liquid interface into the hydrochloric acid solution.

4.1.3 Effect of HCl concentration on the Saturated Cl_2 concentration.

The tests were performed at constant agitation speed of 125 rpm and chlorine flowrate of 825 cm^3min^{-1} over a period of 180 minutes to make sure that the hydrochloric acid solutions under the experiments were fully saturated with chlorine in order to be compared. The results, plotted in Figure 4.9, indicate that the rate of chlorine dissolution depends on the concentration of the acid solution.

The saturated chlorine gas dissolution was compared with different hydrochloric acid concentrations at different temperatures.

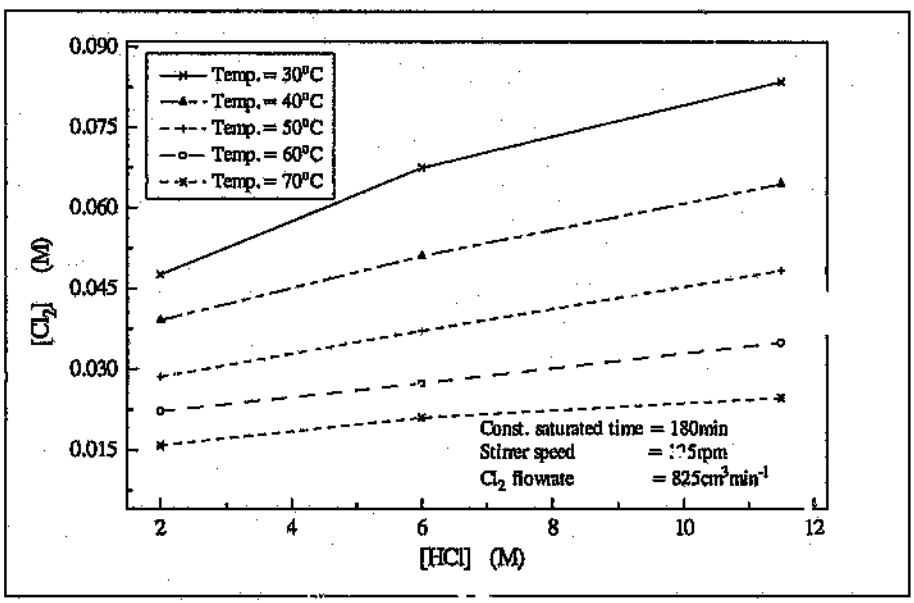


Fig. 4.9 Effect of HCl concentration on the saturated Chlorine concentration.

From Figure 4.9, the results show that the dissolution of the chlorine gas increases as the hydrochloric acid concentration increases. This is probably due to the reduction of the degree of hydrolysis of the chlorine. High concentrations of hydrochloric acid enhance the dissolution of chlorine.

A plot of $\ln(k_m)$ as a function of ln[HCl] is shown in Figure 4.10. The reaction order of the chlorine dissolution with respect to the hydrochloric acid concentration is 0.21 for 30°C and the value increases to 0.47 for the acid solution temperature of 70 °C. From Figure 4.10, it is shown that the reaction order of the chlorine solubility in hydrochloric acid solution increases with an increase in temperature.

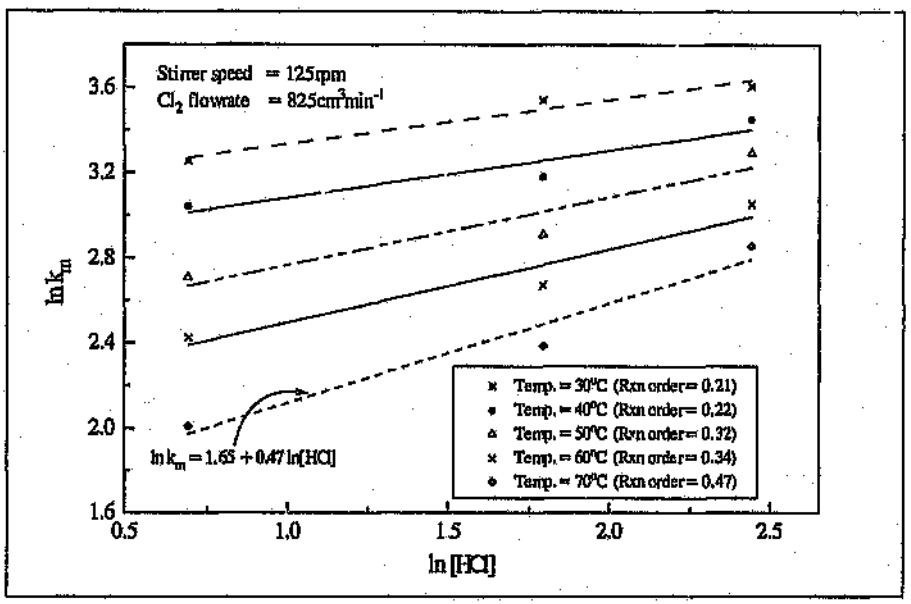


Fig. 4.10 Relationship between the Mass transfer coefficient and HCl concentration at different temperatures and Cl_2 flowrate of 825 cm^3min^{-1}.

Table 4.1 also shows that the mass transfer coefficient increases with a decrease in the hydrochloric acid concentration. This is due to the fact that a dilute hydrochloric acid solution absorbs more chlorine than the concentrated acid therefore increasing the diffusion transfer in the solution. It is therefore certain that the mass transfer coefficient for chlorine dissolution in hydrochloric acid solution depends greatly on the acid concentration and temperature. This observation suggests that the acid strength plays a major role in the rate of chlorine dissolution.

4.1.4 Effect of Chlorine flowrate on the Rate of Chlorine dissolution in HCl.

The effect of chlorine concentration on the rate of dissolution which depends on the gas flowrate was investigated by diluting the chlorine gas with different flowrates of nitrogen into the 6.00 M HCl solution at constant temperature of 50°C. The agitation speed was maintained at 125 rpm and the results are presented in Figure 4.11.

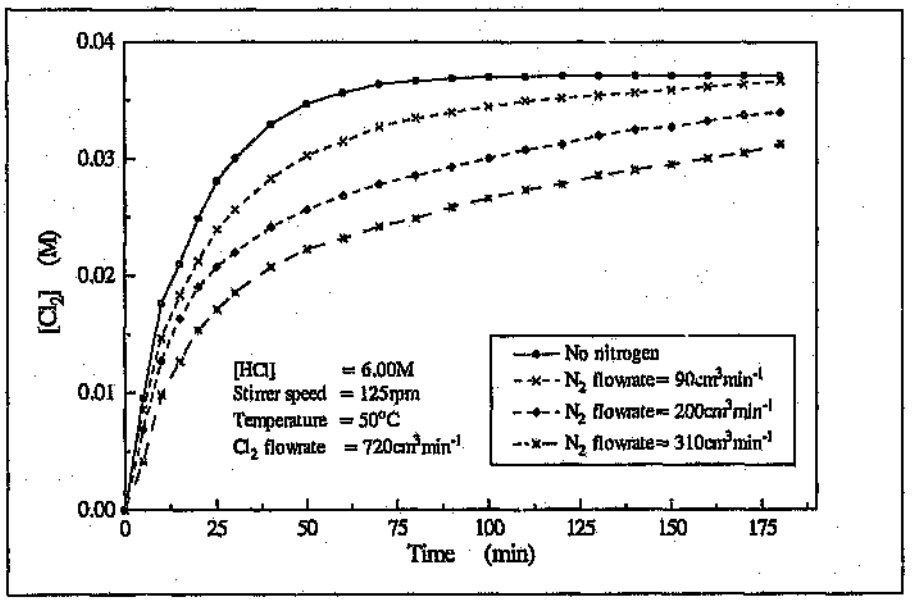


Fig.4.11 Effect of Chlorine concentration on the rate of dissolution in HCl solution.

The results indicate that both the initial rate of chlorine dissolution and the final saturated concentration increase with increased partial pressure of chlorine sparged into the HCl solution. Therefore, the Figure 4.11 also shows that as the concentration of total chlorine in the acid depends on the chlorine massflow, the ultimate concentration of chlorine for all flowrates approaches saturation. This is when the hydrochloric acid solution at that concentration cannot absorb any more chlorine gas. Therefore, at that stage the acid solution is in equilibrium with the chlorine gas flow, that is, the amount of chlorine gas absorbed is equal to the amount of gas released from the acid solution.

4.1.5 Effect of Agitation speed on the Rate of Chlorine dissolution in HCl.

The effect of agitation speed on the rate of dissolution of chlorine gas in HCl solution was also investigated and the results are plotted as Figure 4.12. The results show that an increase in the stirrer speed has a slight influence on the rate of chlorine dissolution in hydrochloric acid. As the agitation speed increases the rate of chlorine dissolution also increases as they converge to a common saturated point of concentration.

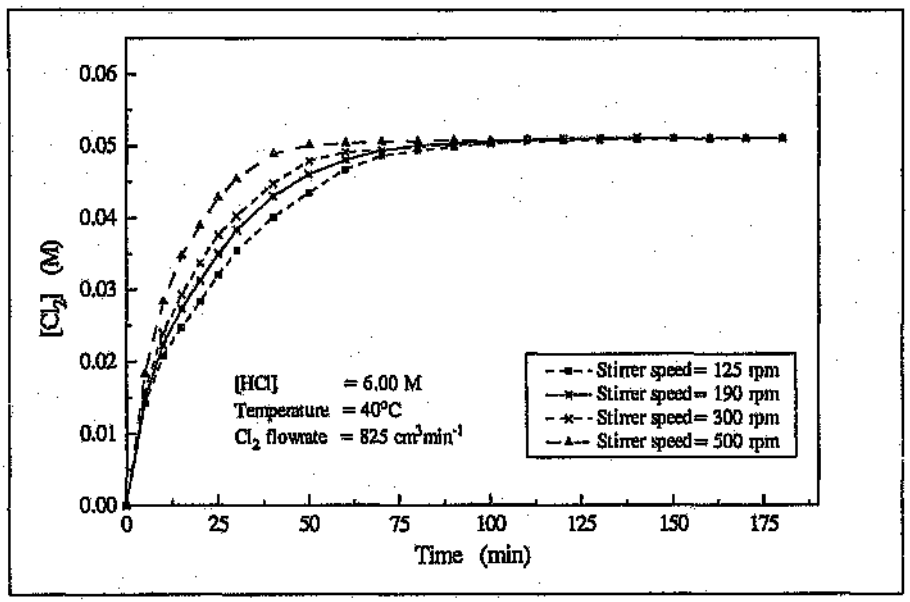


Fig. 4.12 Effect of Agitation on the rate of Chlorine dissolution in HCl solution.
Conditions: *[HCl]= 6.00 M, Temperature= 40°C, Cl_2 flow. = 825 cm^3min^{-1}*

The effect of agitation on the mass transfer coefficient is shown in Figure 4.13. The relationship between the mass transfer coefficient (k_m) and the stirrer speed is shown in Figure 4.14 and the result from the plot indicates an increase in mass transfer coefficient with increase in agitation. The mass transfer coefficient for the chlorine dissolution in hydrochloric acid solution strongly depends on the stirrer speed. The diffusion layer thickness is effectively reduced by increasing the solution agitation.

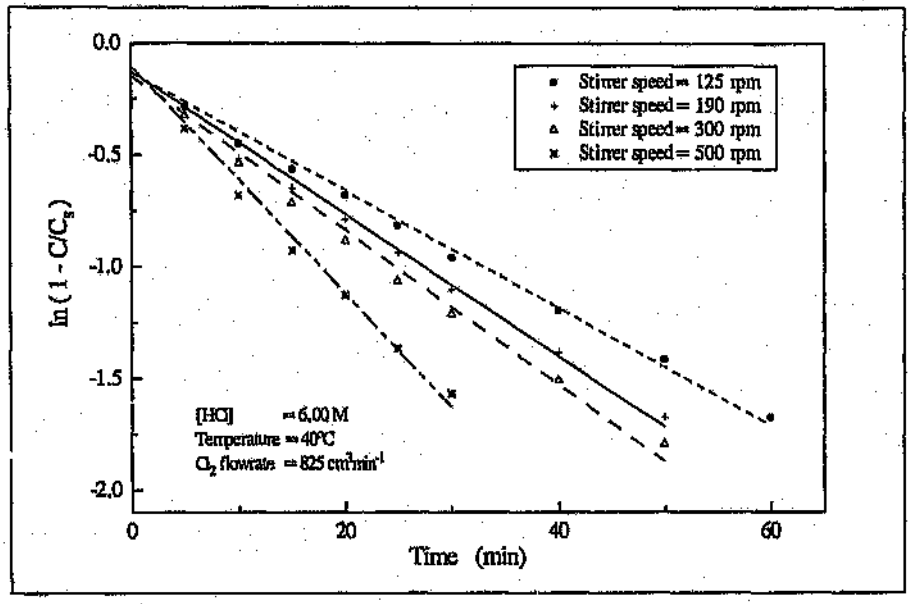


Fig. 4.13 Variation of $\ln(1-C/C_s)$ with time to determine Mass transfer coefficients.

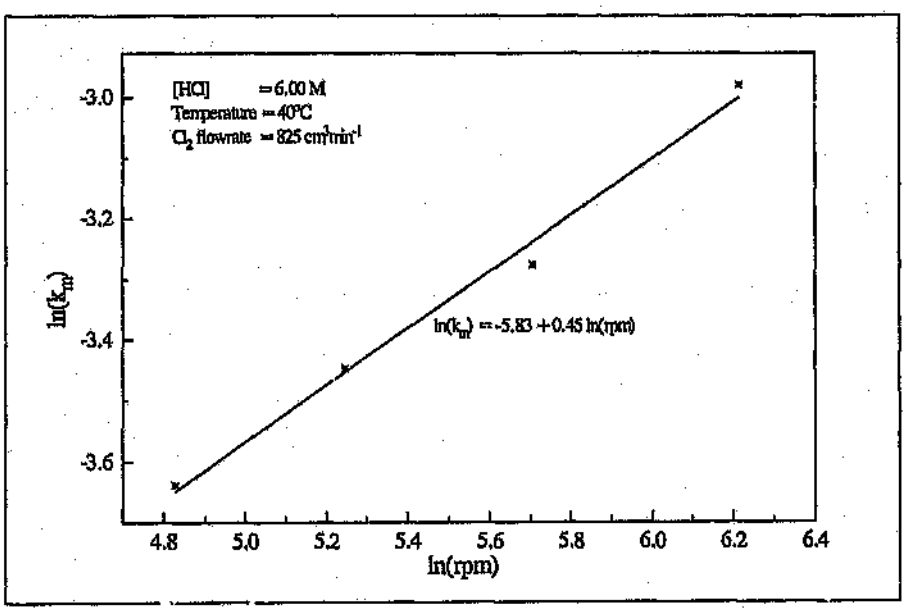


Fig. 4.14 Relationship between the Mass transfer coefficient and Stirrer speeds.

4.2 Experimental results for the Leaching of the Platinum-group metals.

The procedure for the leaching experiments outlined in Section 3.4.2 were followed and the results including the material balances for the leaching tests are presented in Appendix C. All these experiments were conducted using the unscreened concentrate sample except for the particle size leaching. The PGM leaching experiments were conducted under different conditions of temperatures, hydrochloric acid concentrations chlorine concentrations, initial particle size, agitation and reactor pressure.

4.2.1 Reproducibility of the PGMs Leaching

The reproducibility of the leach results was tested on the unscreened sample in 6.00 M hydrochloric acid solution at an agitation speed of 150 rpm and a temperature of 30°C. Figures 4.15 and 4.16 show the results of the first run repeated three times for platinum

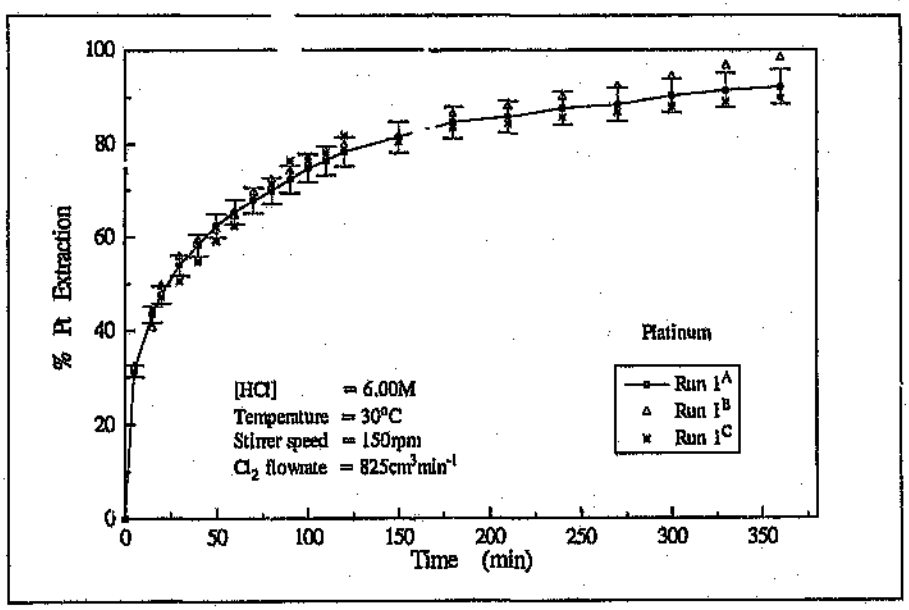


Fig. 4.15 Reproducibility of the Leaching results - *Platinum.*

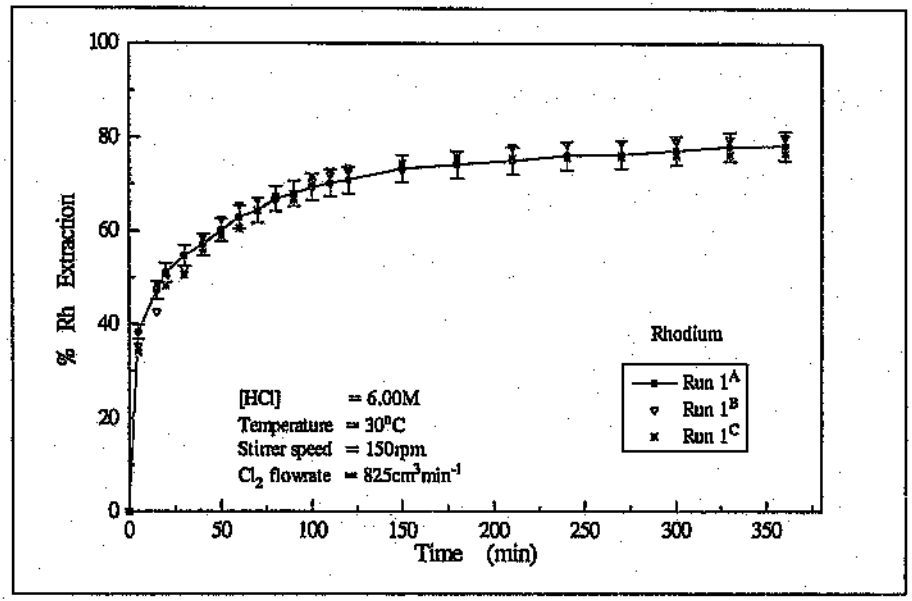


Fig. 4.16 Reproducibility of the Leaching results - *Rhodium.*

and rhodium. These leaching tests used the same experimental conditions and the reproducibility of the measurements were reasonably satisfactory. The maximum difference between the curve points for platinum is 8.69% and 5.99% for rhodium. Similar results were obtained for the rest of the PGMs. The reproducibility results for palladium was the best and ruthenium had the lowest with 12.50% difference between the extraction points of the tests. The iridium and gold results were also reproducible.

4.2.2 Effect of Temperature on the PGMs dissolution rate

Figures 4.17 to 4.22 show the effect of temperature on the dissolution rate of the PGMs and gold. A hydrochloric acid solution strength of 6.00M was maintained for all the different temperatures monitored at a constant stirrer speed of 150 rpm. The increase in temperature from 30°C to 80°C does increase the rate of reaction remarkably despite the fact that chlorine solubility in hydrochloric acid decreases with temperature.

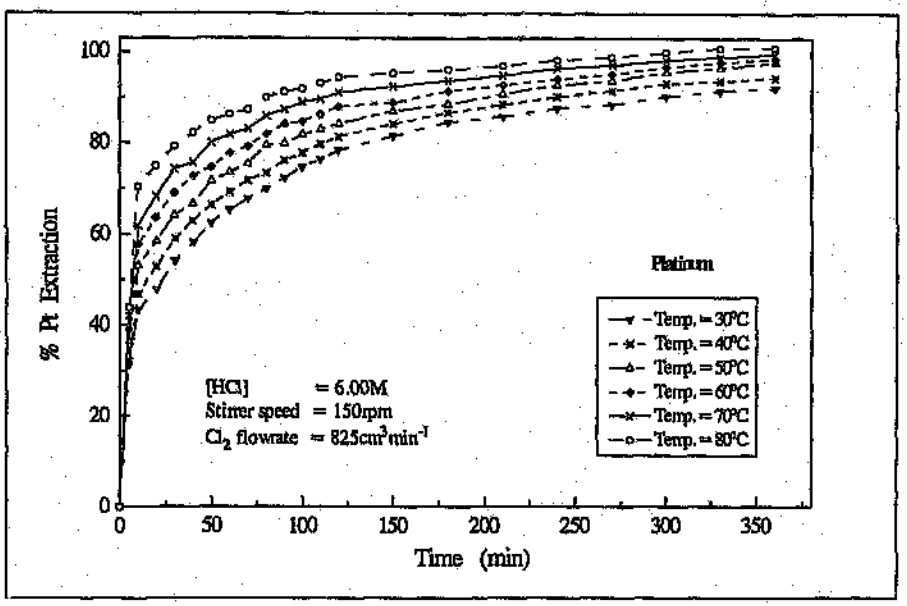


Fig. 4.17 Effect of Temperature on Platinum dissolution rate.

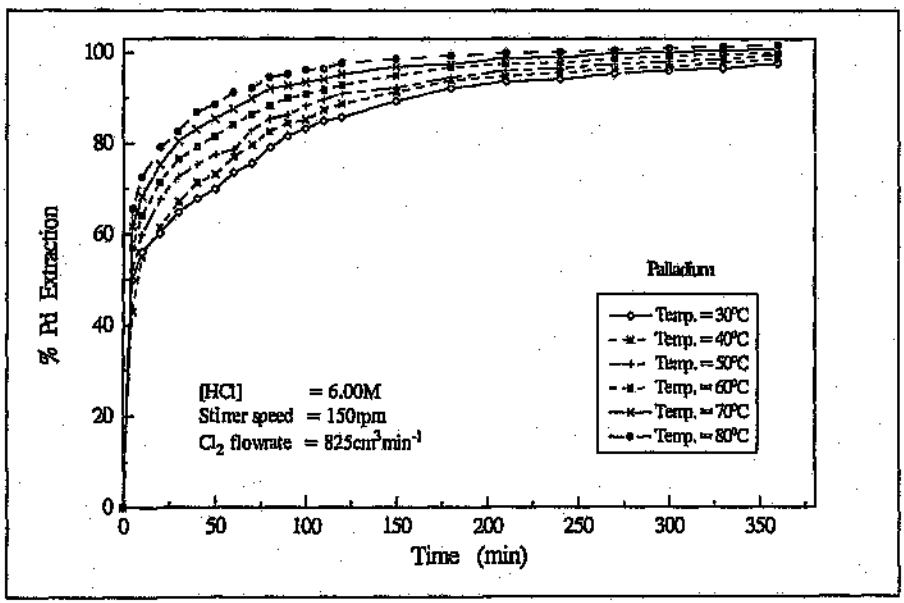


Fig. 4.18 Effect of Temperature on Palladium dissolution rate.

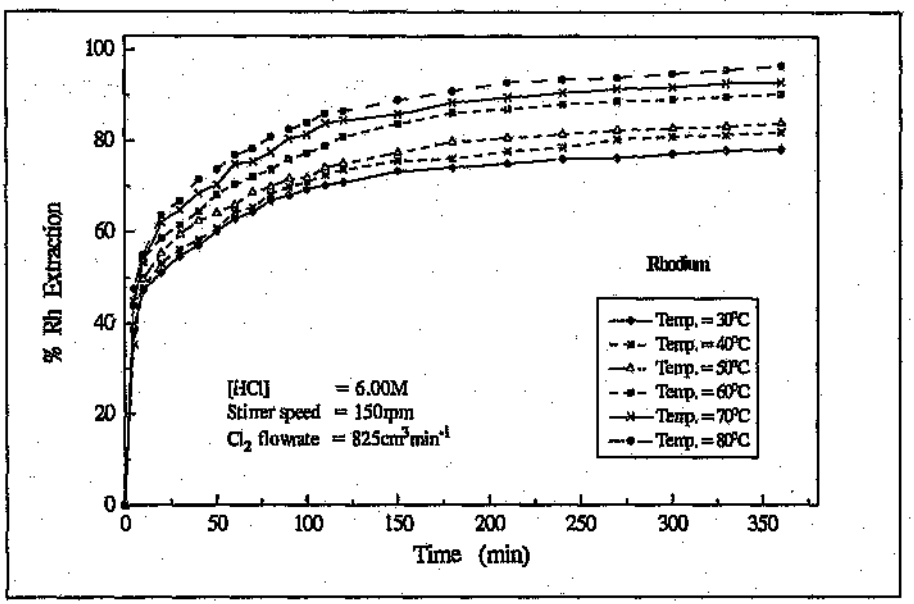


Fig. 4.19 Effect of Temperature on Rhodium dissolution rate.

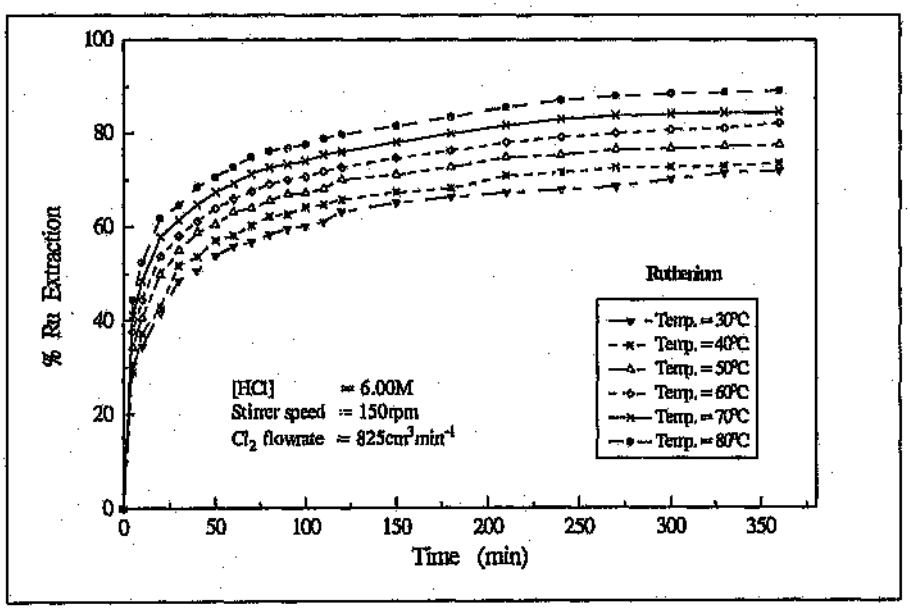


Fig. 4.20 Effect of Temperature on Ruthenium dissolution rate.

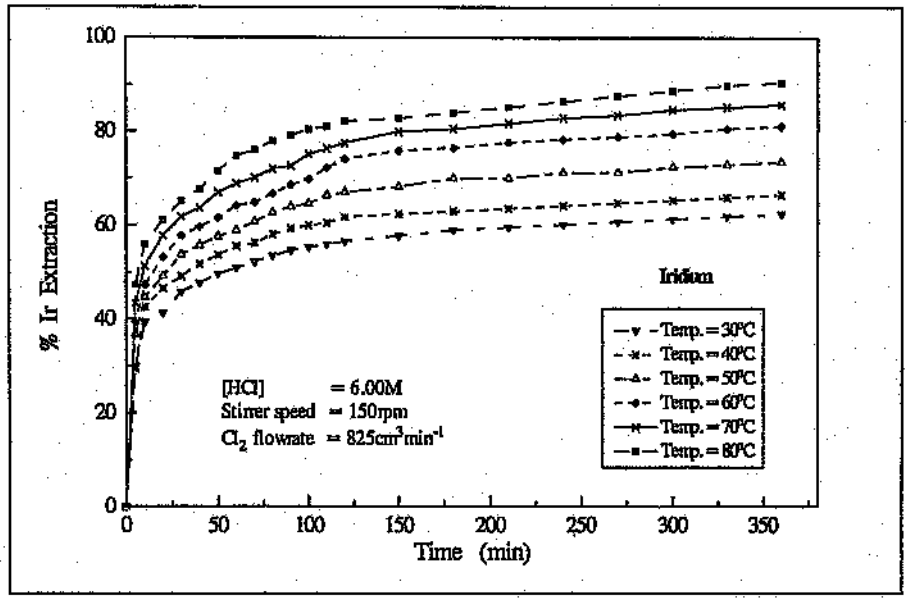


Fig. 4.21 Effect of Temperature on Iridium dissolution rate.

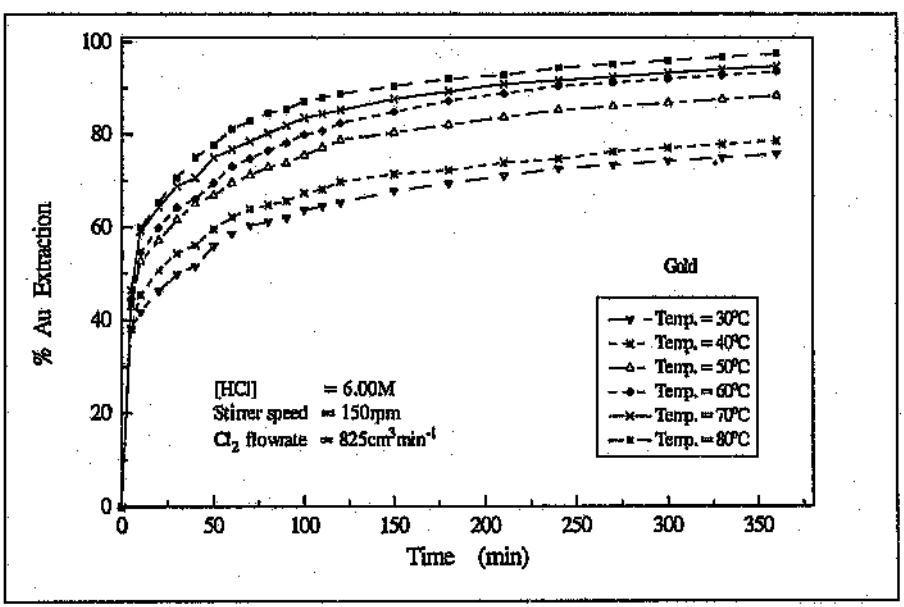


Fig. 4.22 Effect of Temperature on Gold dissolution rate.

This is probably a balance between the increase in the rate of leaching with temperature and a decrease in the chlorine saturation with temperature. It is worth noting that the extraction of platinum and palladium approach completion at higher temperatures, whereas the extraction of the other PGMs is much lower. The rate of dissolution of palladium is almost zero after three hours of leaching at a temperature of 80°C and is expected that the dissolution reaction is almost complete. For most of the other PGMs, a prolonged leaching period together with higher hydrochloric acid concentration would extend their extraction to completion.

4.2.3 Effect of HCl Concentration on the PGMs dissolution rate

The experiments to establish the effect of hydrochloric acid concentration on the rate and extent of PGMs dissolution were performed with acid strengths of 1.0, 2.0, 4.0, 6.0, 8.0 and 10.0 M at a temperature of 60°C and an agitation speed of 150 rpm. A constant chlorine flow of 825 cm^3min^{-1} with initial average concentration of 0.035 M was used for all the experiments. Figures 4.23 to 4.28 illustrate the results for Pt, Pd, Rh, Ru, Ir and Au. The results are modelled and analysed in chapter 5 and the raw data are given in Appendix C.

As expected, these results indicate that increasing the hydrochloric acid concentration increases the rate of dissolution of all the platinum-group metals and gold. High acid concentration has a positive effect on the rate of reaction up to 8.00 M. As seen from all the graphs, the rate of dissolution of the PGMs and gold in the 10.0 M hydrochloric acid is almost zero after about 1 hour of leaching as the reactions slow down.

This implies that the dissolution reactions are complete and the metals recovered are the maximum that can be achieved under this acid concentration. This is considered to be due to the fact that more silver chloride are formed in the 10.0 M hydrochloric acid solution to cover the surface of the PGMs in the sample which passivate them as the reaction proceed.

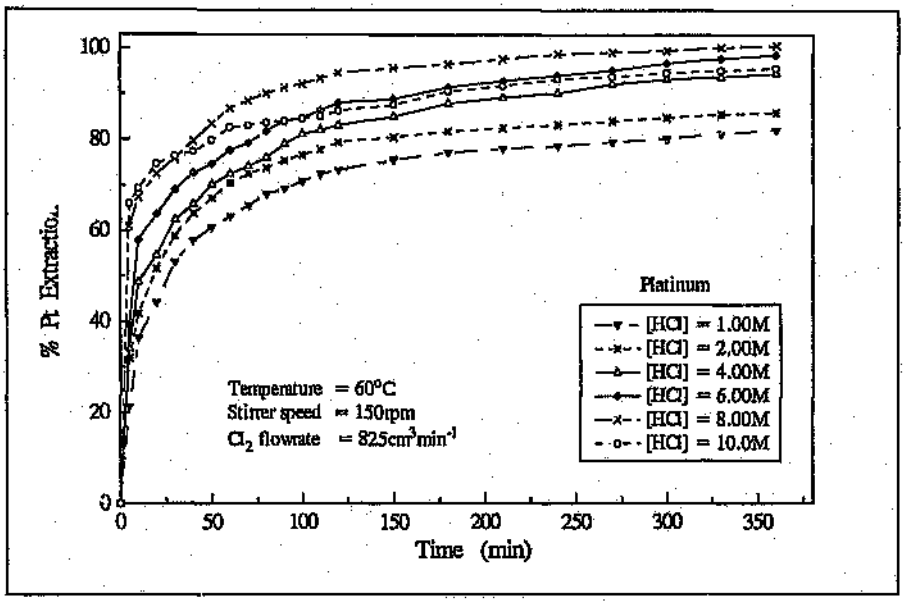


Fig. 4.23 Effect of HCl concentration on Platinum dissolution rate.

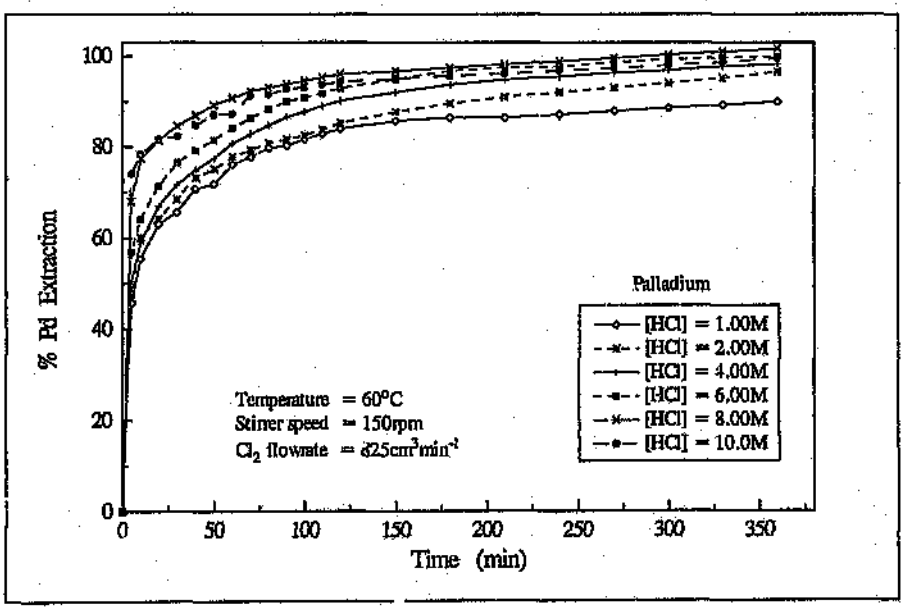


Fig. 4.24 Effect of HCl concentration on Palladium dissolution rate.

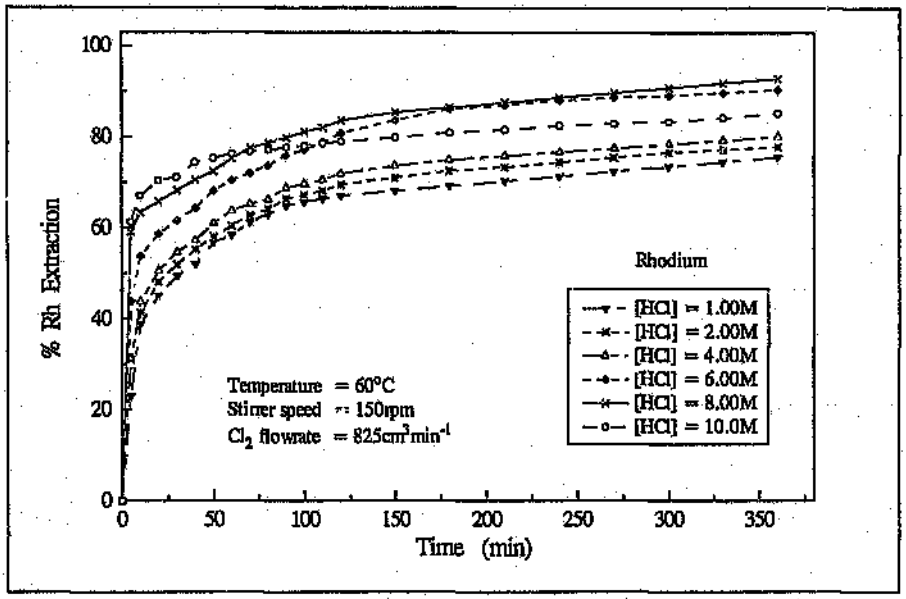


Fig. 4.25 Effect of HCl concentration on Rhodium dissolution rate.

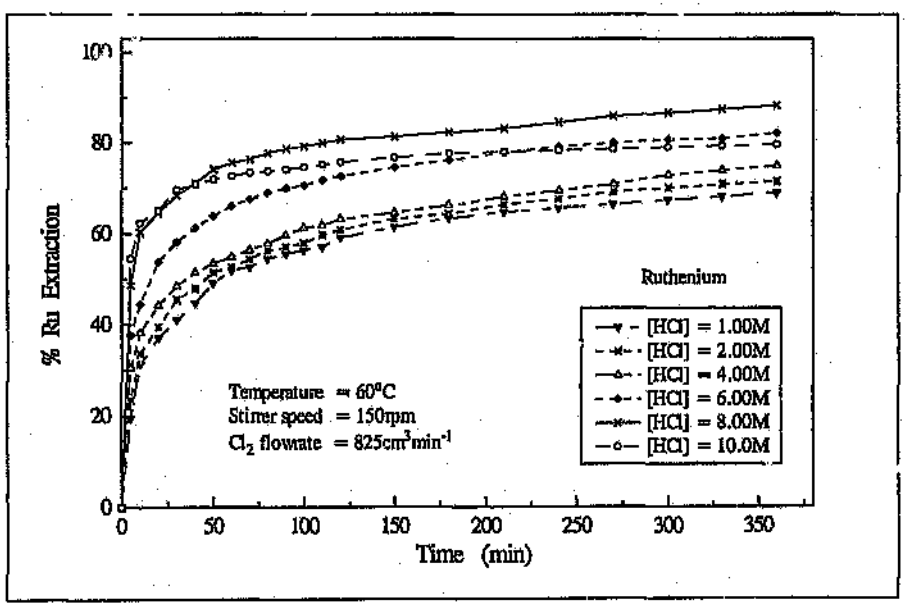


Fig. 4.26 Effect of HCl concentration on Ruthenium dissolution rate.

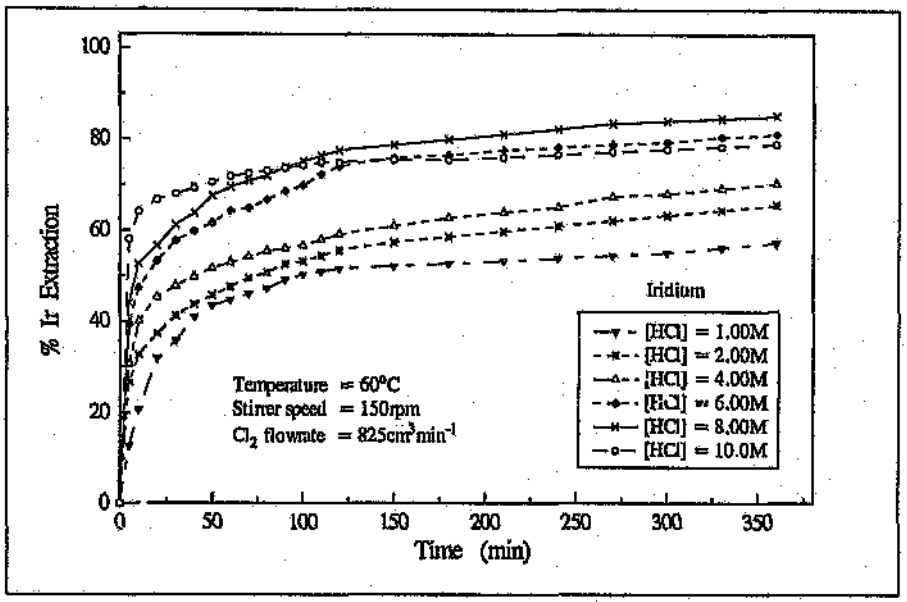


Fig. 4.27 Effect of HCl concentration on Iridium dissolution rate.

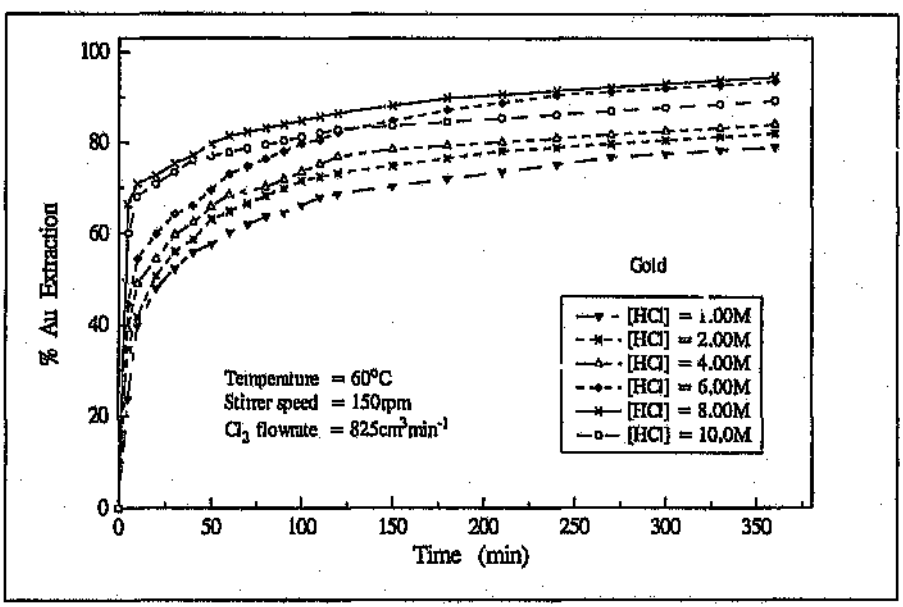


Fig. 4.28 Effect of HCl concentration on Gold dissolution rate.

4.2.4 Effect of Chlorine Flowrate on the PGMs dissolution rate

The PGMs leaching reactions are strongly dependent upon the concentration of the chlorine oxidant. Accordingly, the effect of the chlorine concentration on the platinum-group metals dissolution was investigated at 50°C in hydrochloric acid concentration of 6.00 M. The concentration of the chlorine was varied by diluting it with nitrogen gas at different flowrates and a constant solution agitation of 150 rpm was maintained. The effect of the chlorine concentration on the individual PGMs dissolution is depicted in Figures 4.29 to 4.34. It can be seen clearly that the effect of increasing the chlorine

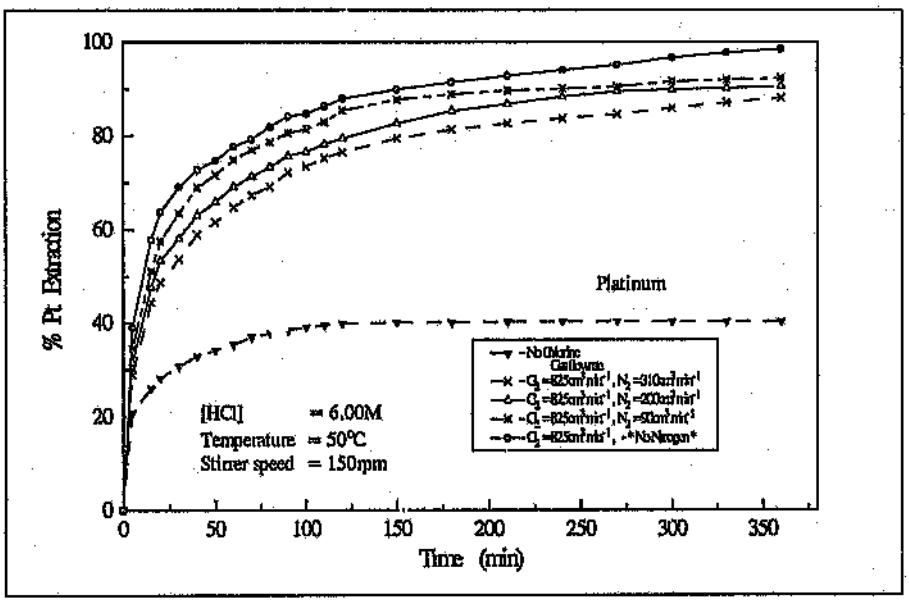


Fig. 4.29 Effect of Chlorine concentration on Platinum dissolution rate.
Conditions: *[HCl]= 6.00M, Temperature= 50°C, Stir. Spd= 150rpm*

concentration has a strong response on the individual PGM dissolution in HCl solution. The higher the chlorine flowrate, the larger was the chlorine concentration to effect the dissolution of the PGMs and therefore the reaction rate increased more rapidly.

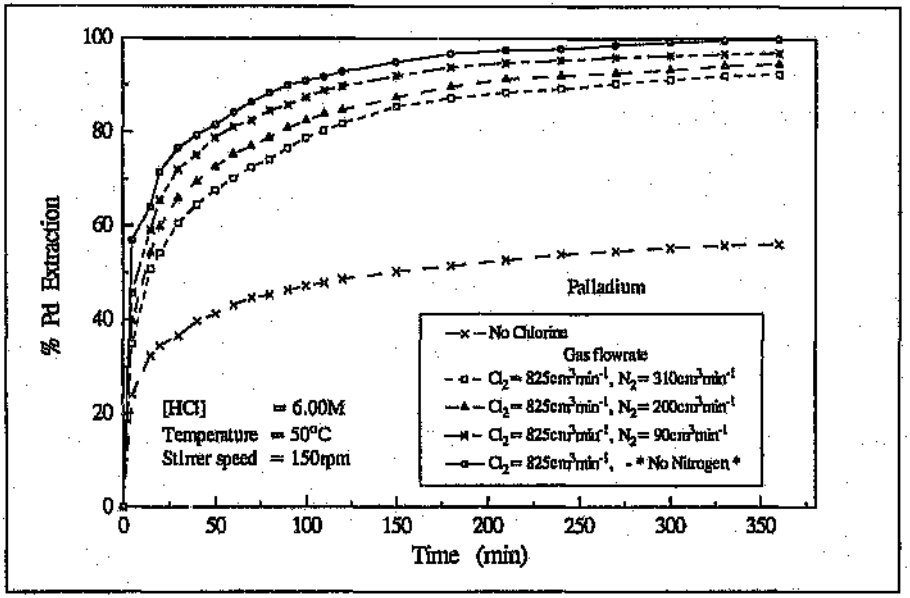


Fig. 4.30 Effect of Chlorine concentration on Palladium dissolution rate.

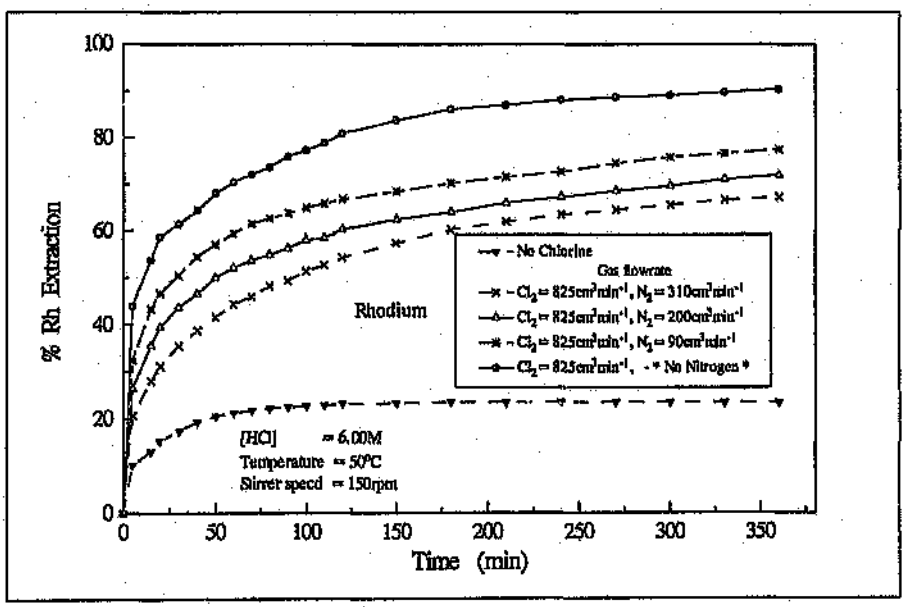


Fig. 4.31 Effect of Chlorine concentration on Rhodium dissolution rate.

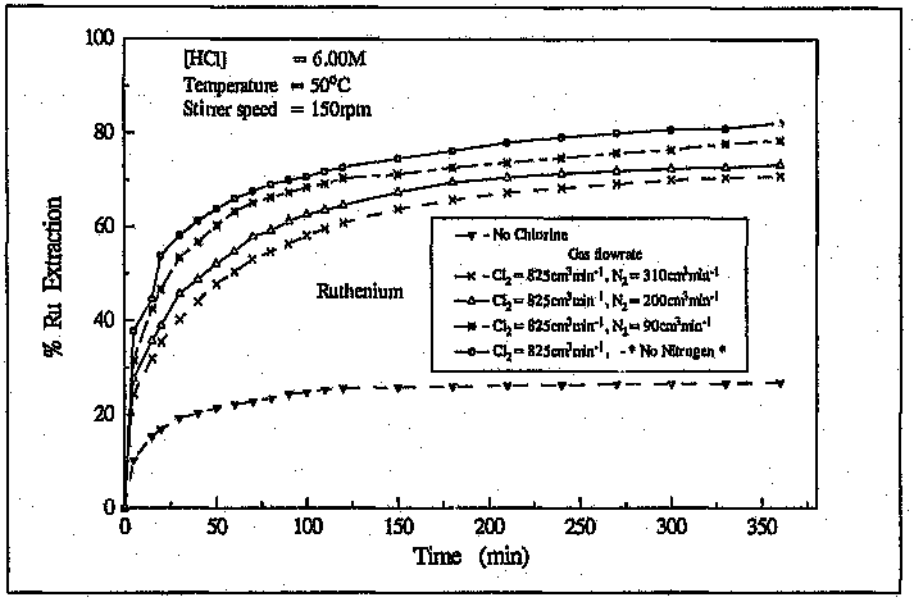


Fig. 4.32 Effect of Chlorine concentration on Ruthenium dissolution rate.

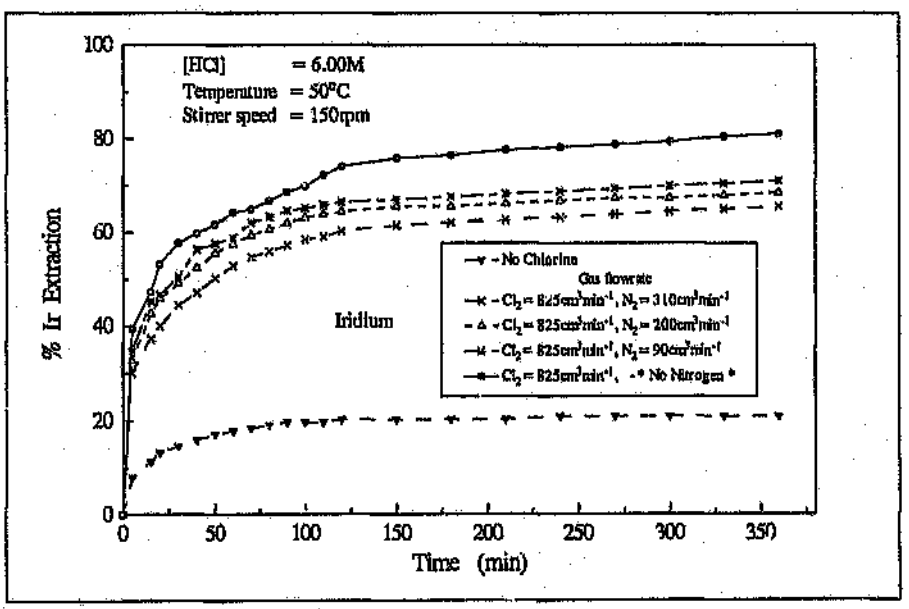


Fig. 4.33 Effect of Chlorine concentration on Iridium dissolution rate.

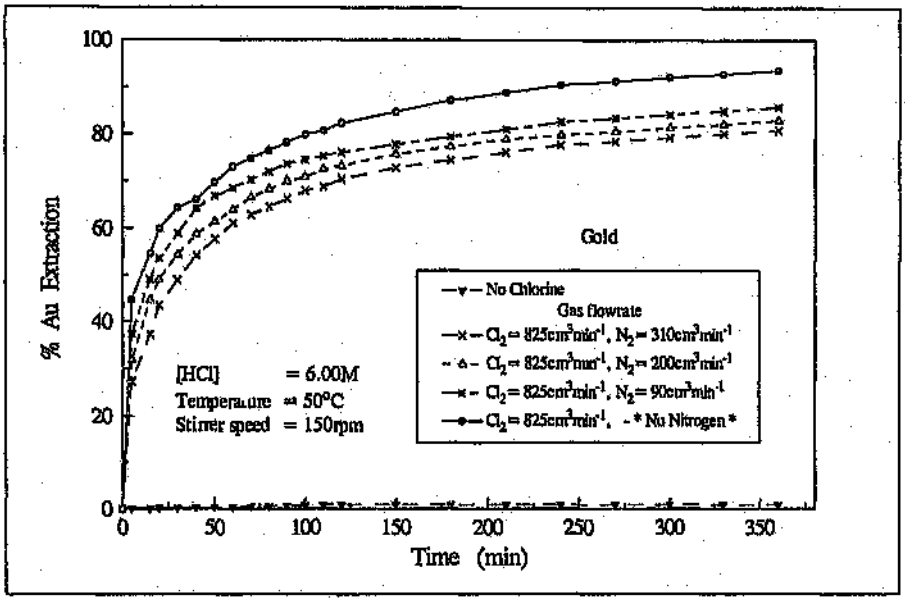


Fig. 4.34 Effect of Chlorine concentration on Gold dissolution rate.

Conditions: *[HCl]= 6.00M, Temperature= 50°C, Stir. Spd= 150rpm*

It is interesting to note that there is significant dissolution in the absence of chlorine, a result that is not expected. This is due to the pretreatment steps in the preparation of the sample used. This concentrate sample used has undergone a sulphuric acid leach with oxygen to remove some of the base metals, followed by a caustic leach to remove selenium and silica. These processes attack some of the PGMs and leave them as oxides in a form of salts in the concentrate which become acid soluble. These acid soluble PGMs do not require chlorine or any form of oxidant to dissolve them.

This was investigated and proved by leaching different materials generated from this concentrate. These are the 4th and 5th stage materials from the Base Metal Refinery process line and a material produced from a dry chlorination of the concentrate followed by hydrogen reduction. The results for their dissolutions are presented in section 5.1 of chapter 5.

4.2.5 Effect of Initial Particle Size on the Rate of PGMs dissolution

The effect of initial particle size on the rate of PGMs extraction was also examined by measuring the reaction rate for the size fractions -38 μm, +90 -150 μm, 300 μm, +420+500 μm, and 600 +850 μm under 6.00 M hydrochloric acid solution with the initial total chlorine concentration of 0.036 M at 60°C and a stirrer speed of 150 rpm. The results are presented in Figures 4.35 to 4.40 for all the PGMs and gold.

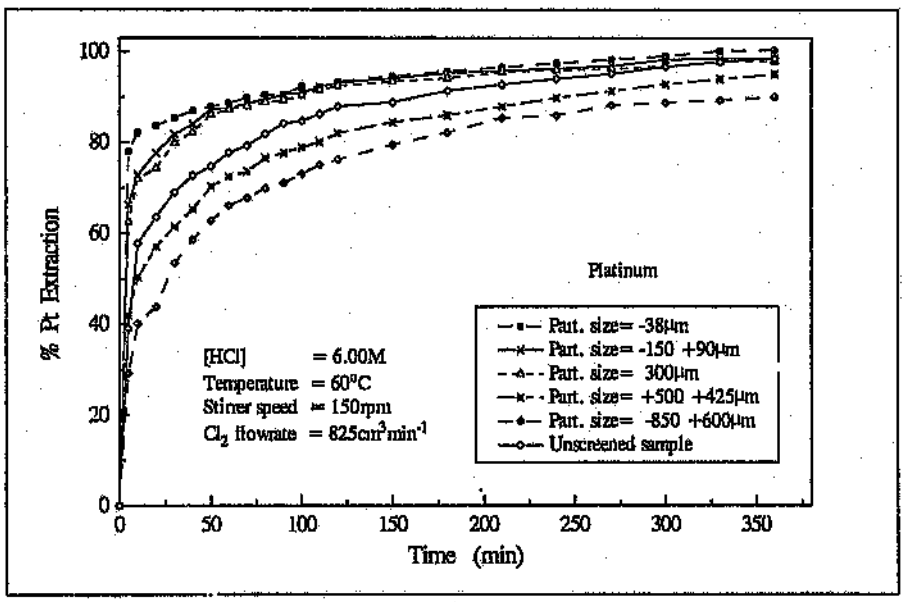


Fig. 4.35 Effect of the initial Particle size on Platinum dissolution rate.
Conditions: *[HCl]= 6.00M, Temperature= 60°C, Stir. Spd= 150rpm*

From these figures it is observed that as the particle size decreases, the rate of dissolution of the platinum group metals increases remarkably. The rate of dissolution of the PGMs is dependent on the surface area of the particles to be leached by the chlorine in the 6.00 M hydrochloric acid solution. An inverse relationship exists between the particle size and the rate of dissolution. Therefore, the smaller particle size results in a faster dissolution rate because of the increasing surface area.

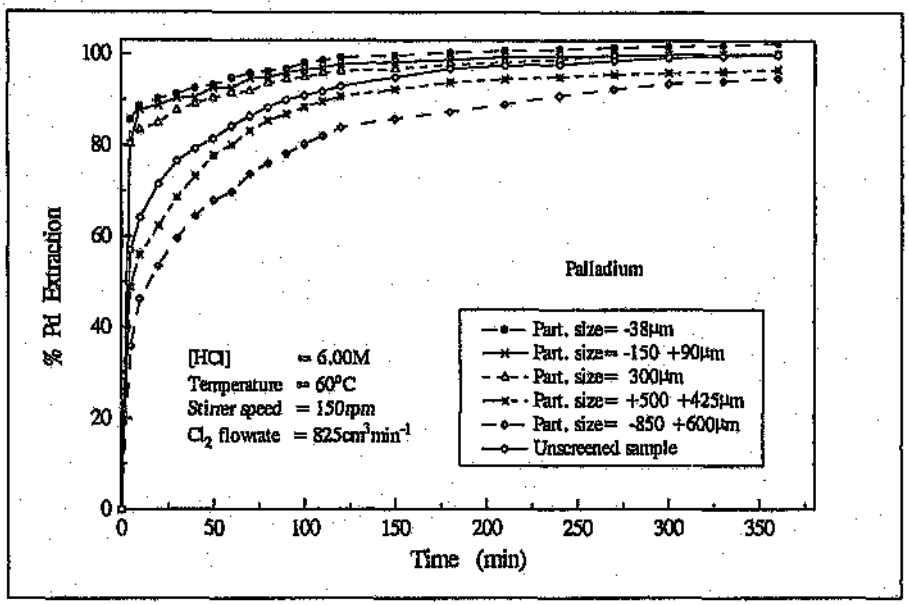


Fig. 4.36 Effect of the initial Particle size on Palladium dissolution rate.

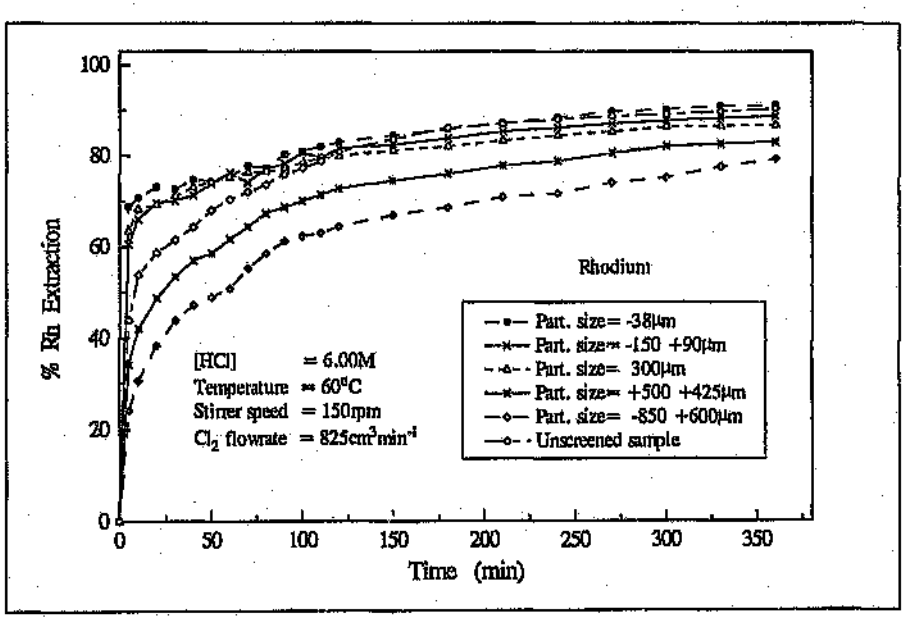


Fig. 4.37 Effect of the initial Particle size on Rhodium dissolution rate.

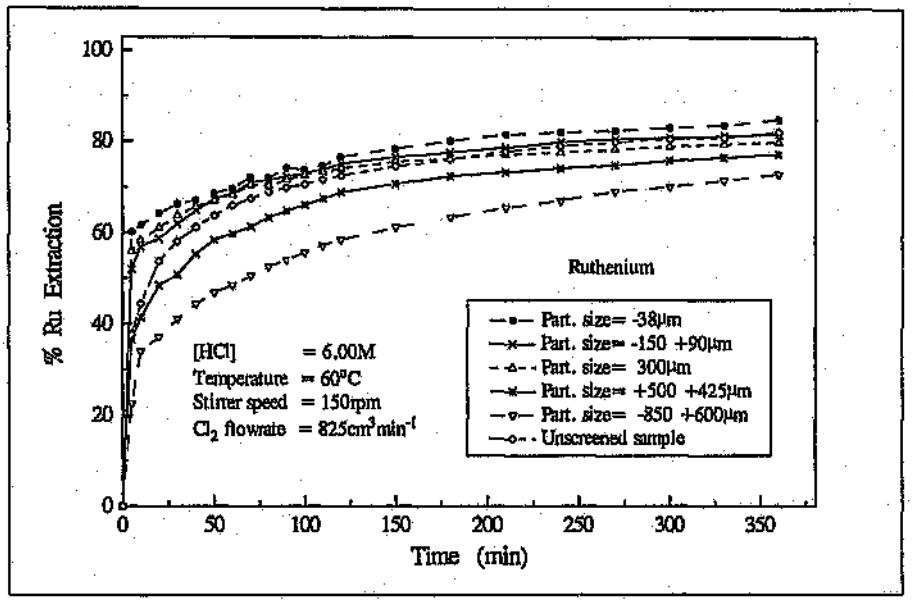


Fig. 4.38 Effect of the initial Particle size on Ruthenium dissolution rate.

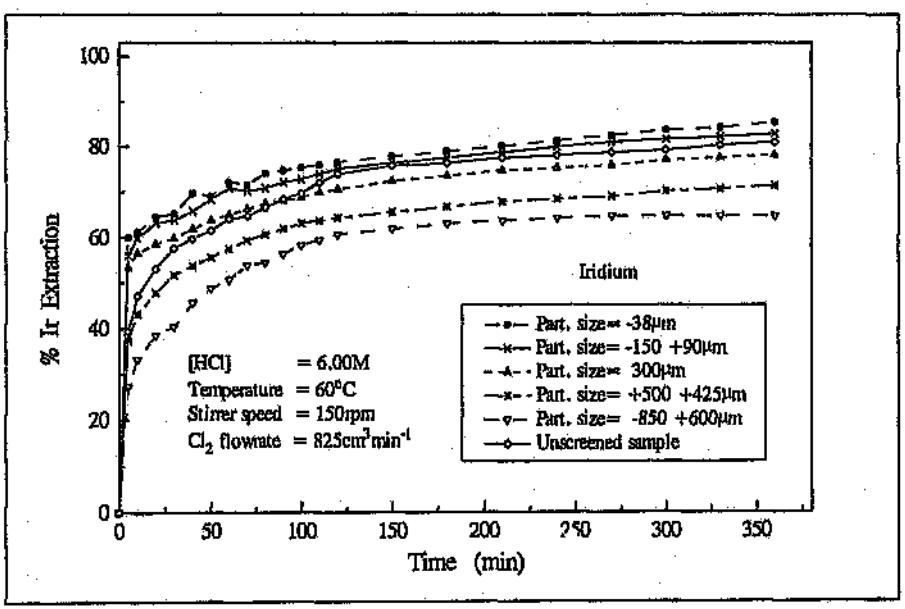


Fig. 4.39 Effect of the initial Particle size on Iridium dissolution rate.

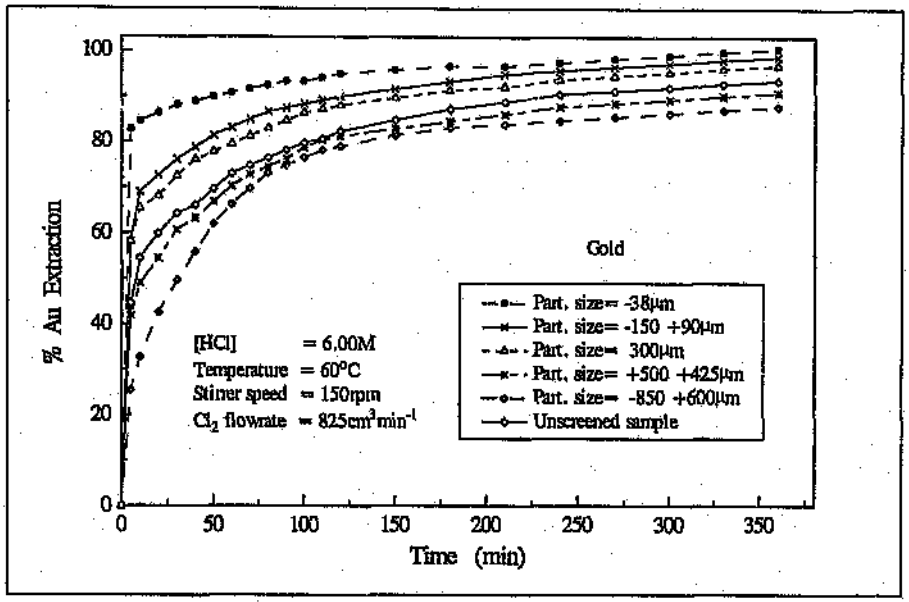


Fig. 4.40 Effect of the initial Particle size on Gold dissolution rate.

Conditions: *[HCl]= 6.00M, Temperature= 60°C, Stir. Spd= 150rpm*

4.2.6 Effect of Agitation speed on the Rate of PGMs dissolution

The effect of stirring speed on the extraction of PGMs was tested on the unscreened sample at the same initial conditions of hydrochloric acid concentration of 6.00 M, with an initial chlorine concentration of 0.036 M and a temperature of 60°C. The difference between the runs show clearly that the agitation speed has a marked effect on the rate of dissolution of platinum-group metals to some extent. The results are shown in Figures 4.41 to 4.46. These results show an increase in the rate of dissolution for an increase in stirring speed for the five runs at 80, 150, 210, 320 and 450 rpm.

The results of the agitation effect for all the PGMs indicate a very close extraction rate after about 300 rpm. This may suggest that the rate of dissolution is independent of agitation at higher speeds when all the particles are in suspension. The optimum speed

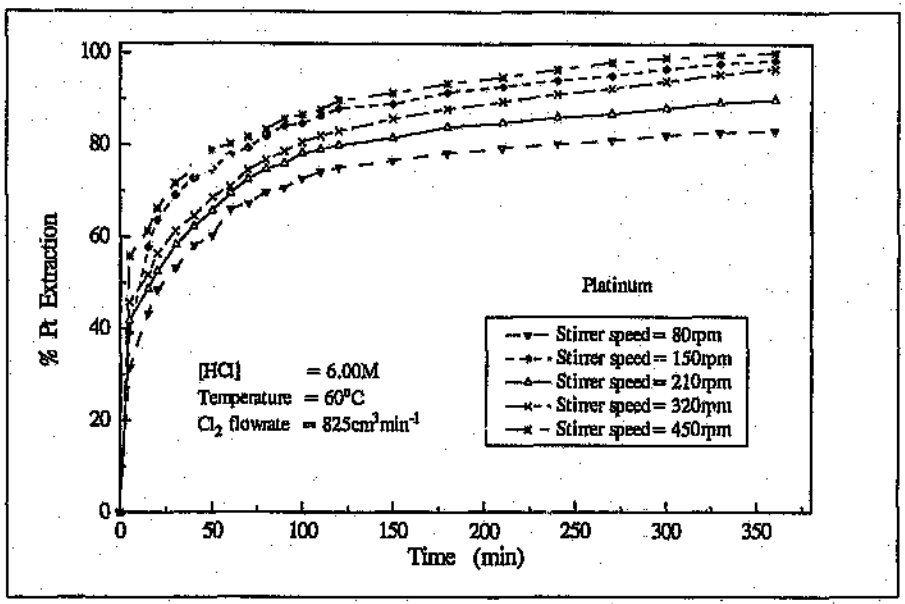


Fig. 4.41 Effect of Agitation speed on Platinum dissolution rate.

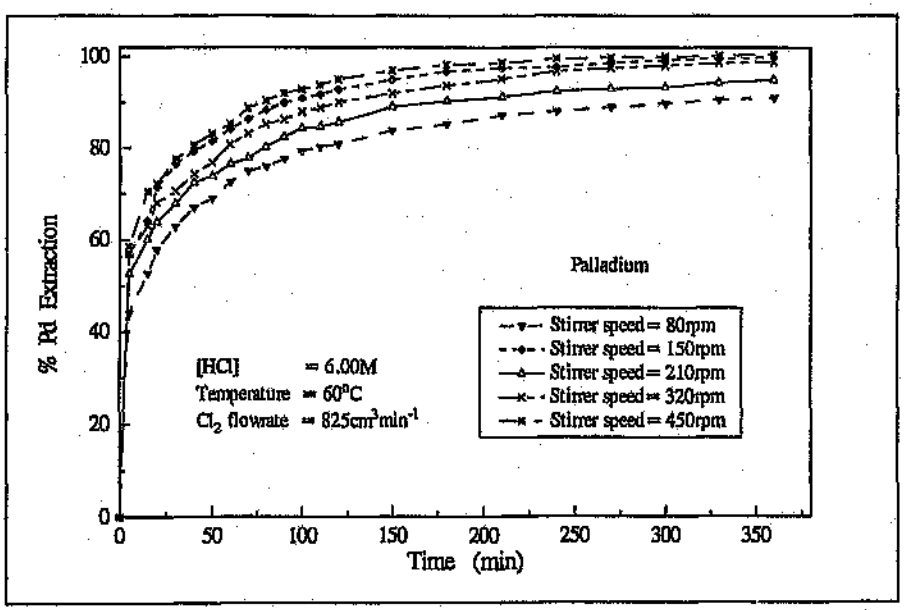


Fig. 4.42 Effect of Agitation speed on Palladium dissolution rate.

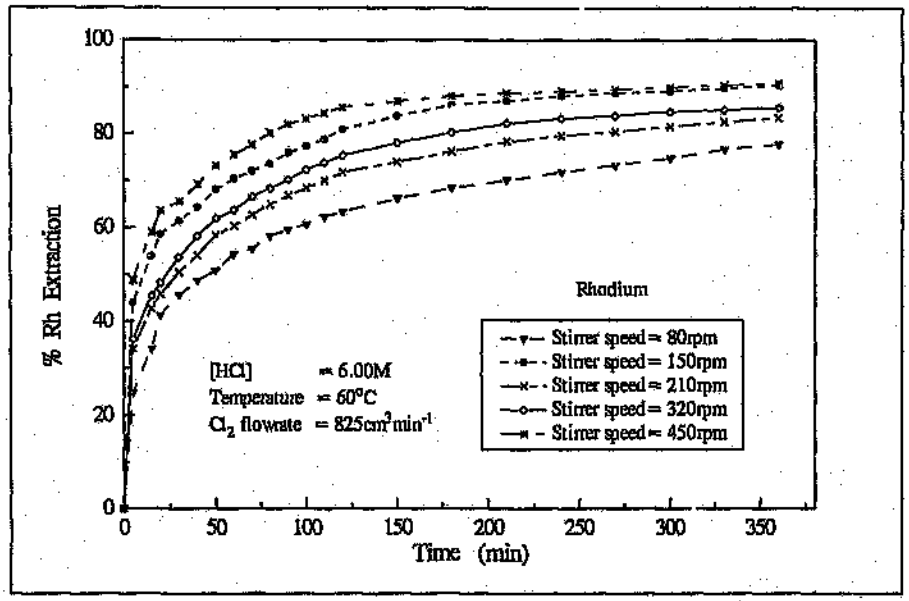


Fig. 4.43 Effect of Agitation speed on Rhodium dissolution rate.

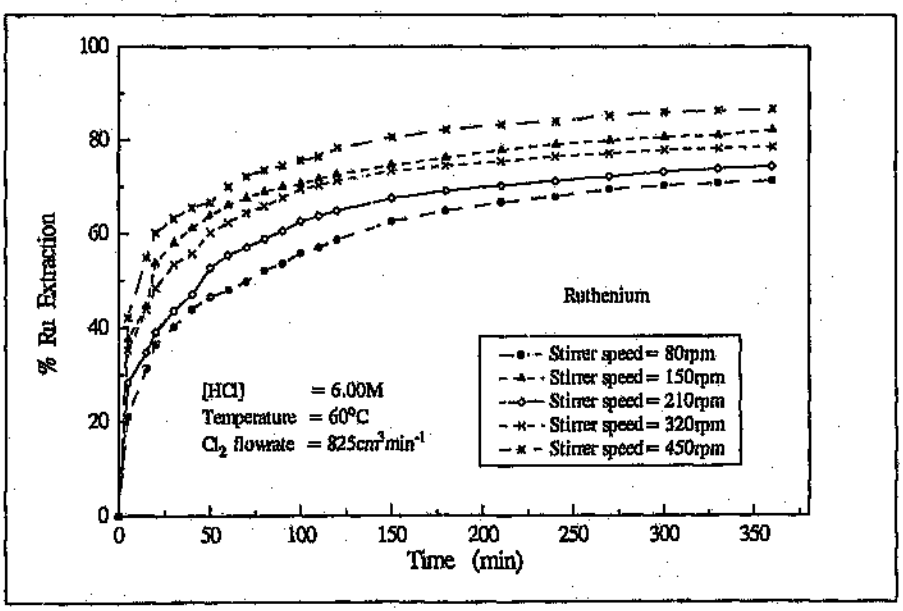


Fig. 4.44 Effect of Agitation speed on Ruthenium dissolution rate.

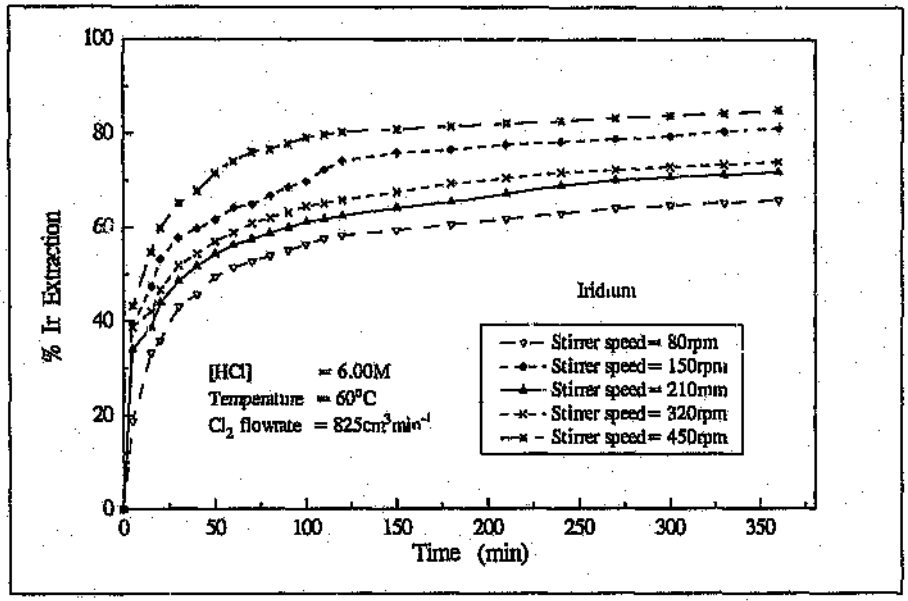


Fig. 4.45 Effect of Agitation speed on Iridium dissolution rate.

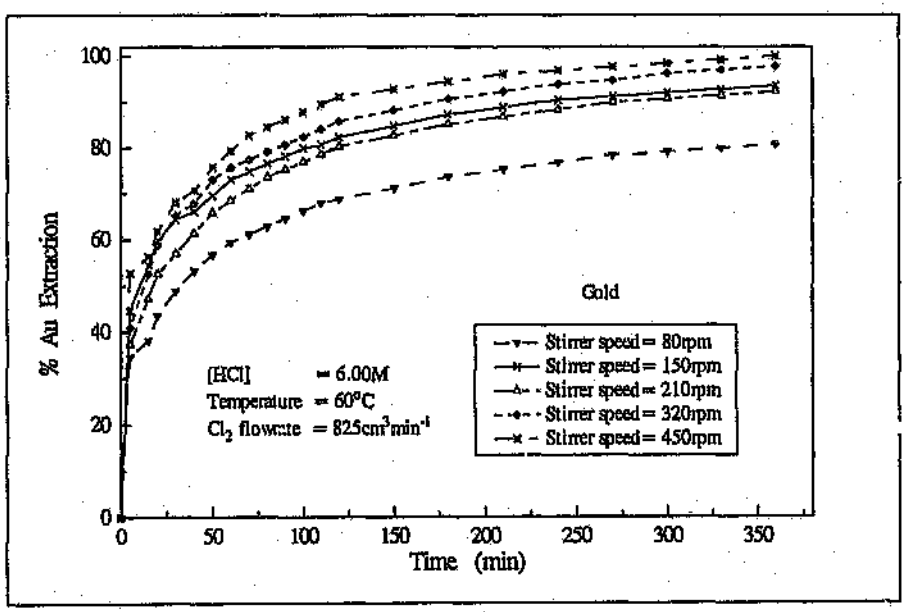


Fig. 4.46 Effect of Agitation speed on Gold dissolution rate.

for fu'l suspension of the sample particles are around 300 rpm. Therefore the influence of agitation predicts that at lower agitation below 300 rpm the rate of PGM dissolution is controlled by transport whereas at higher agitation speed it is independent.

4.2.7 Effect of Reactor Pressure on the Rate of PGMs dissolution

The effect of the reactor pressure on the rate of PGMs dissolution was investigated. The experiments were performed in an autoclave with 6.00 M hydrochloric acid solution at a constant temperature of 50°C. The agitation speed was maintained at 150 rpm and chlorine flow of 825 cm^3min^{-1} was used throughout the tests. The autoclave pressure was varied from 345 kPa to 1034 kPa. The results obtained are shown in Figures 4.47 to 4.52 which indicates an increase in the dissolution rate of PGMs with increasing pressure.

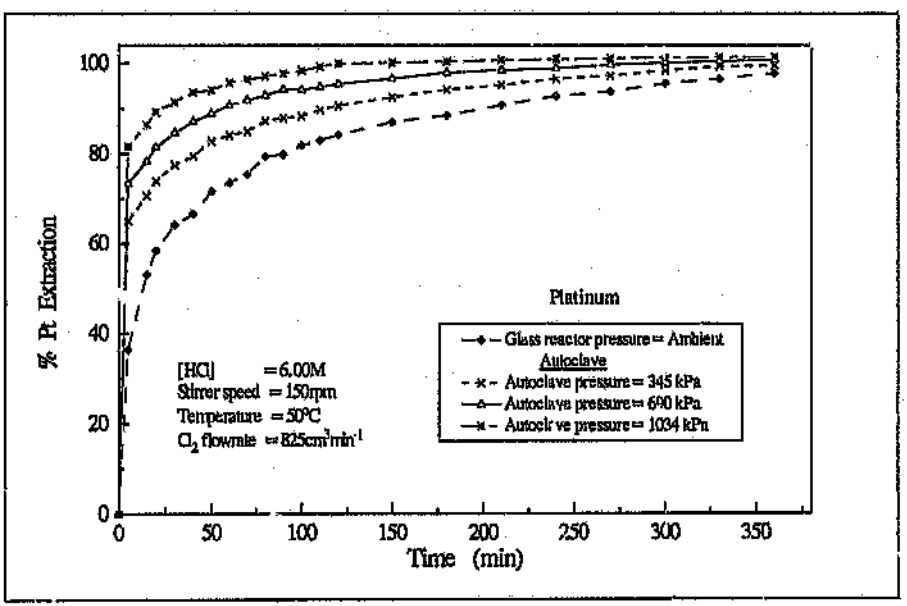


Fig. 4.47 Effect of Reactor pressure on Platinum dissolution rate.
Conditions: *[HCl]= 6.00M, Temperature= 50°C, Stir. Spd= 150rpm*

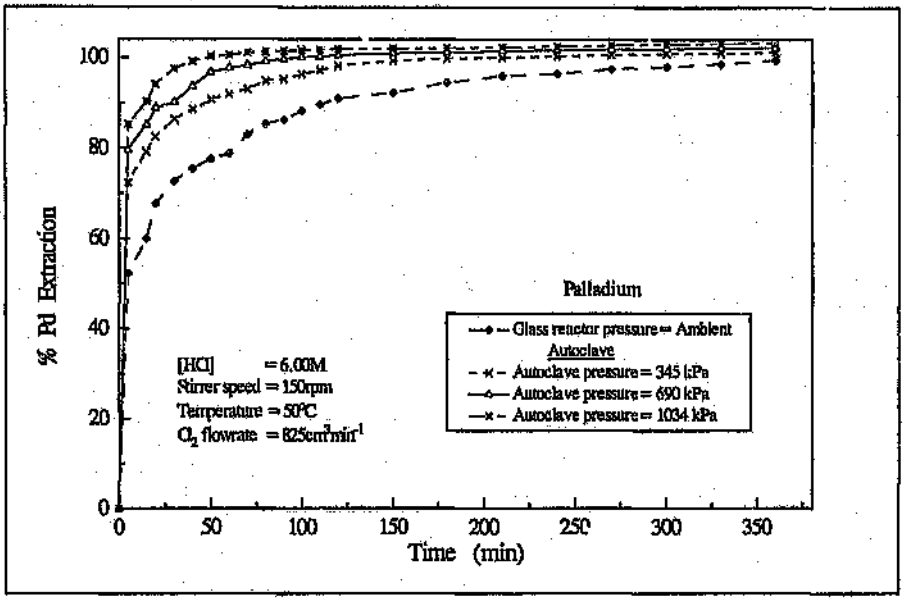


Fig. 4.48 Effect of Reactor pressure on Palladium dissolution rate.

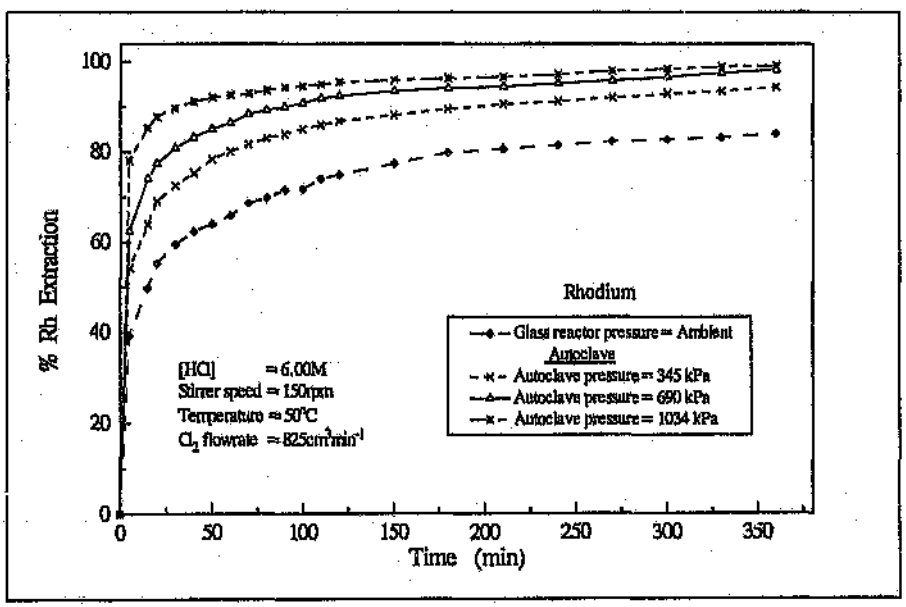


Fig. 4.49 Effect of Reactor pressure on Rhodium dissolution rate.

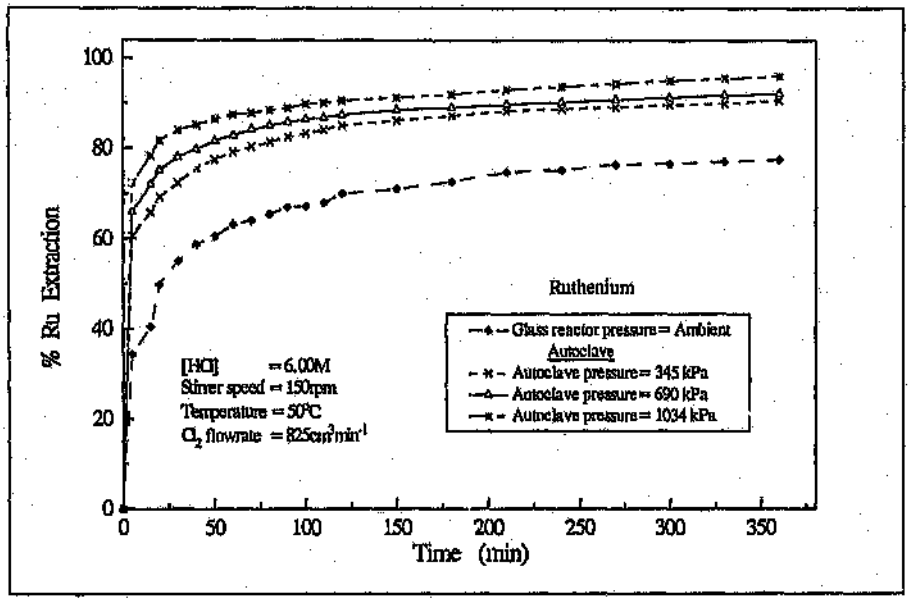


Fig. 4.50 Effect of Reactor pressure on Ruthenium dissolution rate.

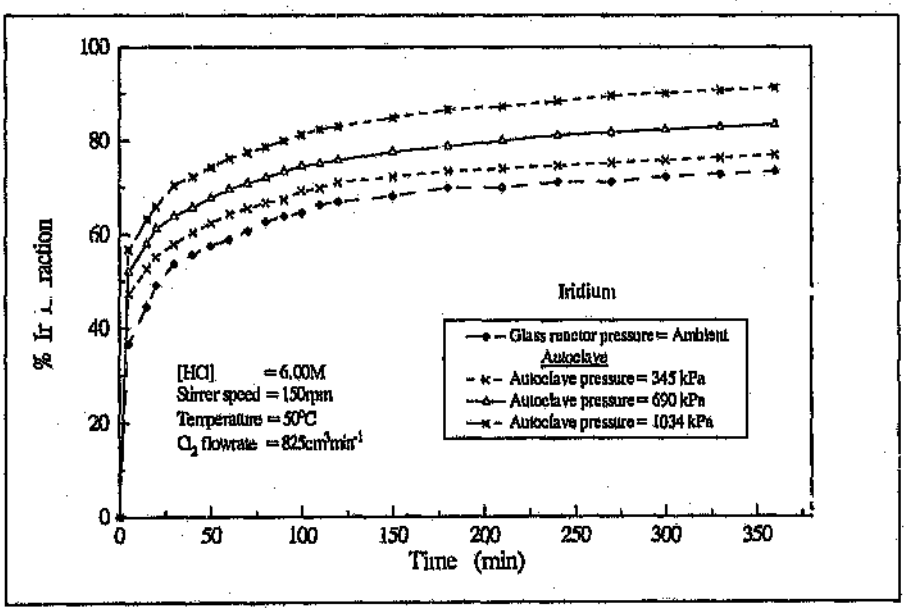


Fig. 4.51 Effect of Reactor pressure on Iridium dissolution rate.

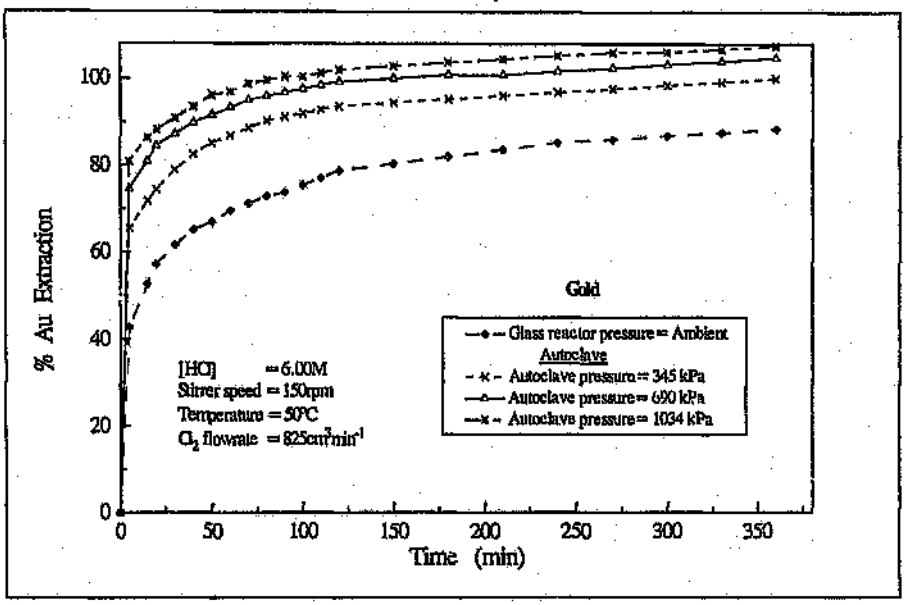


Fig. 4.52 Effect of Reactor pressure on Gold dissolution rate.

Conditions: *[HCl]= 6.00M, Temperature= 50°C, Stir. Spd= 150rpm*

4.2.8 Redox potentials measurement during the Leach test

The redox and corrosion potentials of the leach solutions were monitored during the PGM dissolutions. The raw data for the redox potentials measured with each of the laboratory leach test is presented with the PGM extractions in Appendix C The redox potentials results for the leach to monitor temperature effect on the PGM dissolutions are shown in Figure 4.53. The redox and corrosion potentials measurements made during the dissolution of PGMs without chlorine is presented as Figure 4.54.

From the Figure 4.53, it is observed that the redox potential of the leach solution decreases initially before it increases and stabilises as the PGMs dissolve. This observation is seen clearly in the leach without chlorine which shows that there is a link between chlorine concentration and redox potential as shown in Figures 5.25 to 5.27.

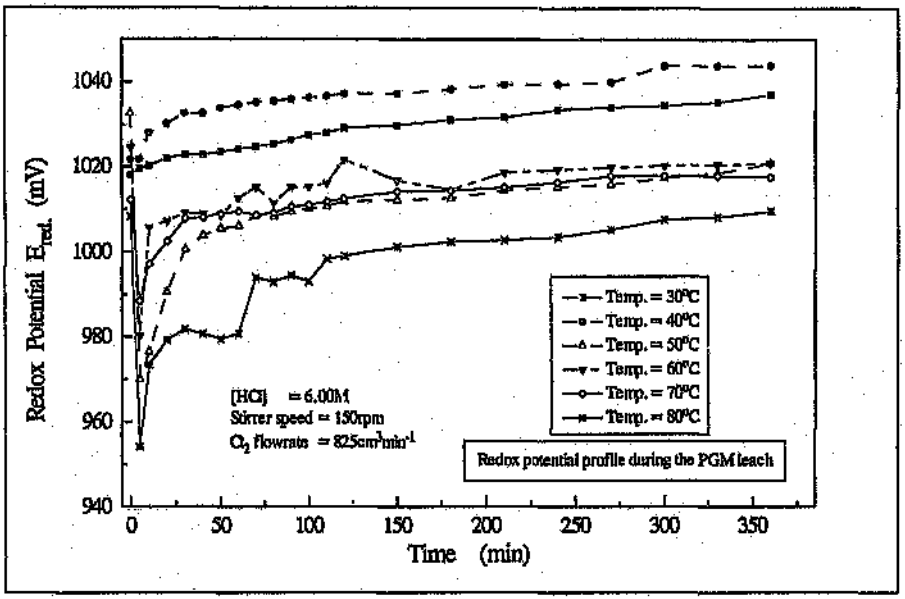


Fig. 4.53 Redox potential measurement during the leach test with temperature effect.

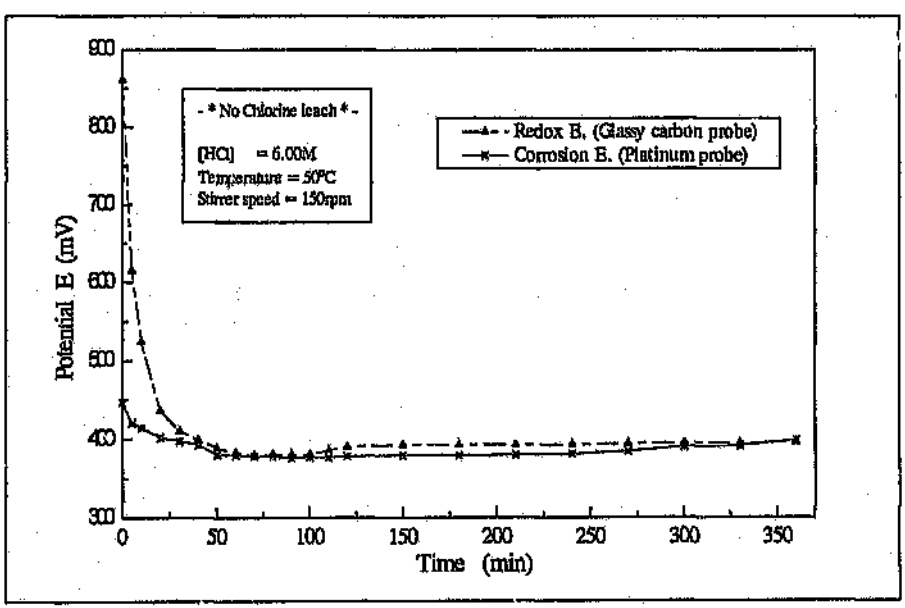


Fig. 4.54 Comparison of Redox and Corrosion potentials during No Cl_2 leach test.

4.3 Results for the Impala plant Reactor Test

The procedure for the plant tests outlined in section 3.7 to determine the mass transfer coefficient, the heat transfer coefficient and the percentage ex :raction of PGMs were followed. All the tests were conducted in the same Impala plant reactor 2101. The test results are presented below. This industrial test results are used to scale up the laboratory test results and to derive a computer program for the plant leaching process.

4.3.1 Heat Transfer Coefficient of the Impala Plant Reactor

The heating and the cooling curves for the Impala PMR reactor 2101 were measured in order to obtain values for the overall heat transfer coefficients for the heating and the cooling operations. The measured temperature curves are shown below in Figure 4.55.

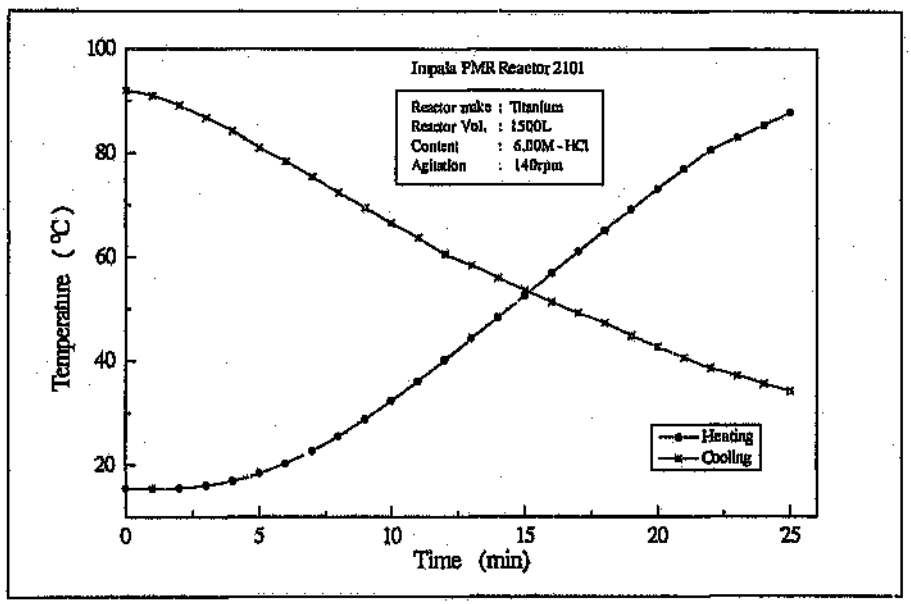


Fig. 4.55 Heating and Cooling curves for the Impala PMR reactor 2101.

The heating and cooling curves may be described by the energy balance which is

derived and solved in Appendix E1. The solution of the energy balance is given by:

$$\ln\left(\frac{T_j - T}{T_j - T_o}\right) = -\frac{U_H A}{\sum_i N_i C_{p_i}} t \qquad 4.4$$

where

T_j = Temperature of the fluid in the reactor jacket

T_o = Initial temperature of the vessel fluid

U_{ht}= Overall heat transfer coefficient

A = Heat transfer area

N_i = Number of moles of component i in the reactor

C_{pi}= Specific heat capacity of the compo . i

The plot of the left hand side of this equation 4.4 against time t is a straight line, and the heat transfer coefficient can be evaluated from the slope of this line. Figure 4.56 shows the plot of the data for this equation.

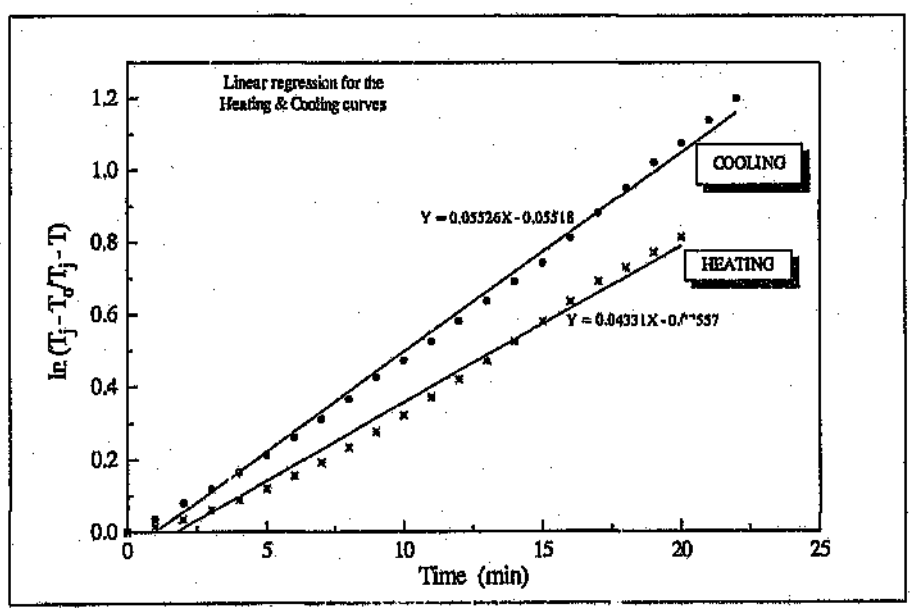


Fig. 4.56 Overall Heat transfer coefficient for the Impe'a PMR reactor 2101.

From the slopes of the graph, the heat transfer coefficients for the Impala PMR reactor 2101 during the test are calculated in Appendix B1 and are given as:

For the cooling,

$$U_{ht} = 647.60\ Wm^{-2}K^{-1} \qquad 4.5$$

For the heating,

$$U_{ht} = 507.55\ Wm^{-2}K^{-1} \qquad 4.6$$

Therefore, the rate of heat generation in the reactor as a result of heating is given by the equation of the heat transfer in an agitated reactor having an external jacket :

$$\begin{aligned} q_{heating} &= U_{ht} A(T_w - T) \\ &= 507.55 \times 6.3(116.8 - 11.8) \\ &= 335.74 kJs^{-1} \end{aligned} \qquad 4.7$$

This is the rate at which energy is generated in the PMR reactor 2101 in the course of the leaching reaction when the reactor is at an initial temperature of 11.8°C in winter.

4.3.2 Mass Transfer Coefficient of the Impala Plant Reactor.

The procedure for the determination of the mass transfer coefficient for the plant reactor 2101 outlined at section 3.7 (i) was followed and the chlorine concentration in the 6.00 M hydrochloric acid solution in the reactor was measured at selected time intervals. The results for the chlorine dissolution in the acid is plotted as Figure 4.57.

From the equation 4.1, the value of $\ln(1 - C/C_s)$ was plotted against time in order to determine the mass transfer coefficient for the plant reactor. The result is shown in the Figure 4.58 below. The mass transfer coefficient for the Impala PMR glass-lined reactor 2101 was found to be 0.0312 min^{-1}. The mass transfer coefficient for the laboratory glass reactor used for the experiments under similar conditions as the plant gave a value of 0.0546 min^{-1}. This shows that the mass transfer in the laboratory reactor is better than that of the plant and therefore gives a better chlorine transport to the hydrochloric acid solution to effect the dissolution.

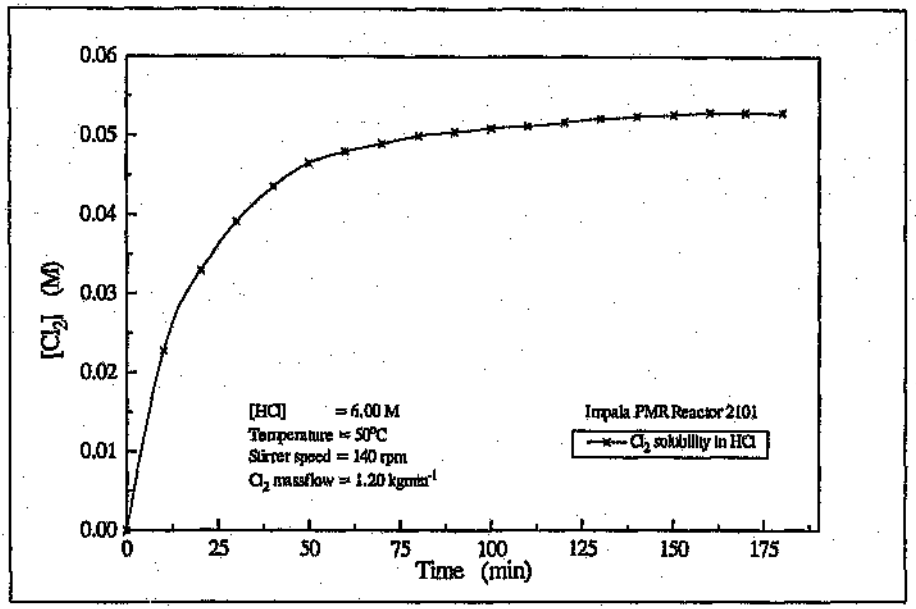


Fig.4.57 Chlorine dissolution in 6.00M HCl solution in the Impala PMR reactor 2101

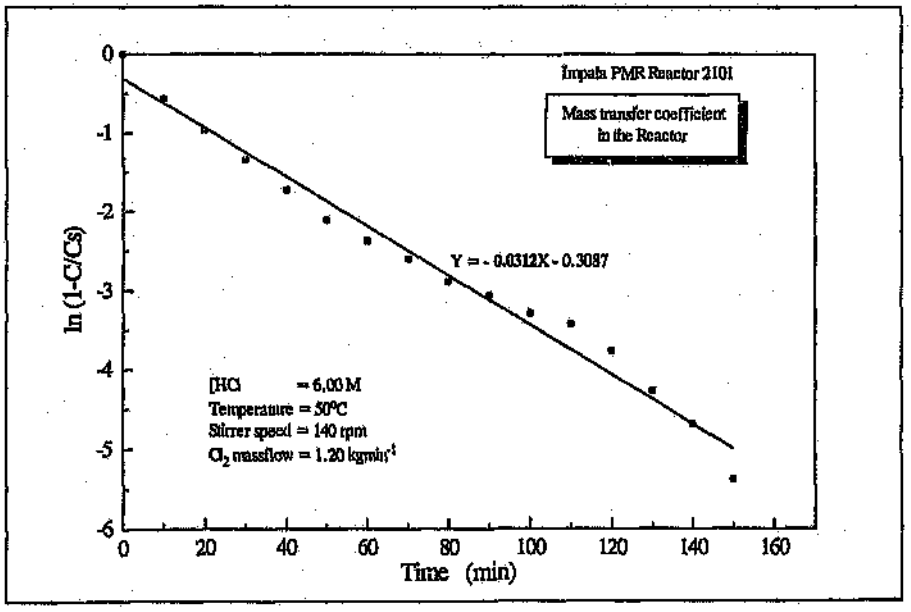


Fig. 4.58 Determination of the Mass Transfer Coefficient of the Impala Plant reactor.

4.3.3 The Impala plant Leach Test Results

The procedure for the full-scale plant reactor leach test outlined at section 3.7 (iii) was followed systematically. The results for the 6 hour plant leach test of the same platinum group metal concentrate material is presented as Figure 4.59.

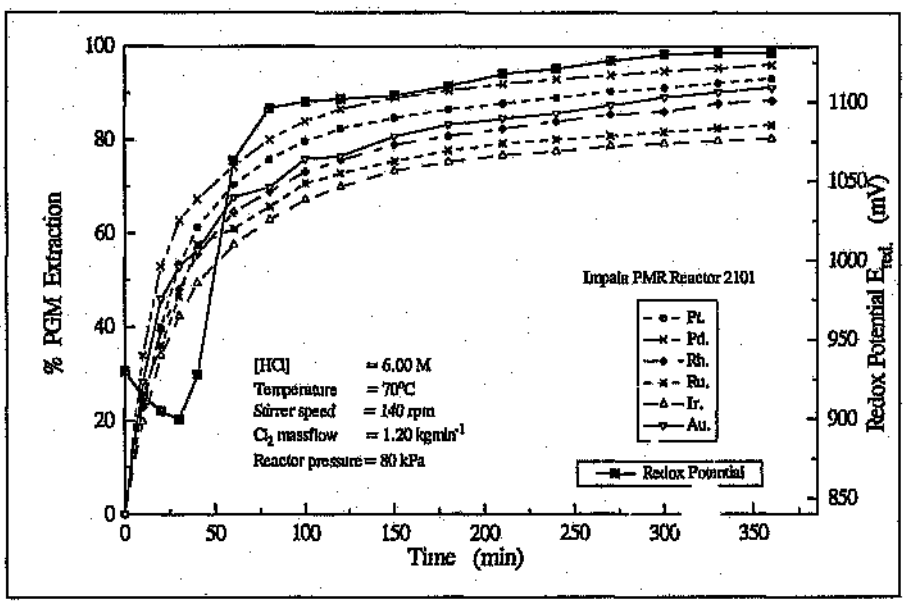


Fig. 4.59 Dissolution of PGMs with Redox potentials in the Impala PMR reactor.

The results from the PGM dissolution indicated that 93.22% of the platinum is extracted at the plant scale. The palladium extraction is 96.14%, rhodium is 88.49%, ruthenium is 83.24% and that of iridium is 80.35%. The gold extraction is 91.28%.

The redox potential of the PGM dissolution in the plant reactor was monitored alongside of the leach at 70°C and the result is incorporated in the Figure 4.59. It is observed during the leach that the redox potential decreases at the start of the leach as the PGMs quickly consume the dissolved chlorine in the solution. It then increases dramatically after 30 minutes as the chlorine concentration increases.

CHAPTER 5

5.0 ANALYSIS OF THE EXPERIMENTAL RESULTS

In this chapter all the experimental results for the dissolution of the PGMs are analysed to determine the kinetics of the leaching. The leaching models to simulate the leaching kinetics are also considered here.

5.1 Applications of the Model to the Experimental Results

The results obtained indicated that the rate of PGMs dissolution in hydrochloric acid solution with chlorine is strongly dependent on the temperature of the leaching solution, the concentrations of the acid and that of the chlorine. The particle sizes also have a positive effect on the rate of dissolution.

A typical graph of the chemical reaction control of the shrinking-particle model for platinum in the concentrate sample is shown in Figure 5.1 with a low activation energy of 12.53 $kJmol^{-1}$. The shrinking-particle model did not adequately fit the data obtained from the direct dissolution of the PGMs since the concentrate sample used for this work was realised to contain two classes of PGM particles. The first type of PGM particles present in the concentrate sample is acid-soluble which did not require chlorine to dissolve them and the second type is the chlorine soluble particles.

The nature of the concentrate sample used for the experiments is due to the processing stages that the material had gone through. At the Impala Platinum Refineries, the residue from the 4^{th} and 5^{th} stages of the Base Metal Refinery operation line is the concentrate feed for the Precious Metal Refinery from which the platinum-group metals and gold are recovered. The 5^{th} stage material, which has undergone a sulphuric acid and caustic leaches, is the concentrate material used for all the experiment reported in this thesis. In view of this, the two different components of PGM particles present in

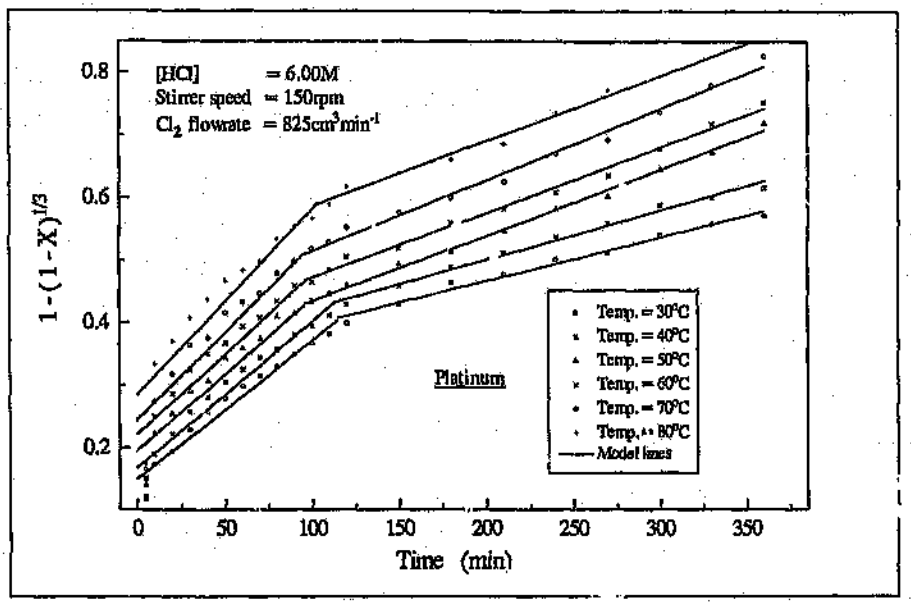


Fig. 5.1 Plot of $1-(1-X)^{1/3}$ vs Time for Platinum on total HCl/Cl_2 leach.

the concentrate sample which was used for all the testwork were investigated. This was done by leaching the 4th stage concentrate material (before caustic leach), the 5th stage material (after caustic leach) and a concentrate sample after dry chlorination of the same concentrate with hydrogen reduction. These three materials were subjected to the same leaching conditions for 6 hours in 6.00 M hydrochloric acid solution without chlorine or an oxidant at a temperature of 60°C and agitation of 150 rpm.

The results from this investigation are presented as Figures 5.2 to 5.4. These results indicate that 40.79% of the platinum is recovered from the 5th stage material whereas 24.26% is recovered from the 4th stage material and only 0.623% is obtained from the leaching of the dry chlorinated material with hydrogen reduction. These results also explain the fact that the hydrogen reduced material contains pure platinum-group metals, which requires chlorine or an oxidant to be able to dissolved them in a hydrochloric acid solution. The dissolution results are tabulated below (Table 5.1).

Table 5.1 Percentage PGM Extraction of different Stages material without Chlorine.

Conditions: *[HCl]= 6.00 M, Agitation speed= 150 rpm, Temp. = 60°C*

Platinum-Group Metals	% PGM Extraction without Chlorine		
	5th Stage Material *(after caustic leach)*	4th Stage Material *(after H_2SO_4 leach)*	Dry Chlorinated Mat. *(after H_2 reduction)*
Pt.	40.79	24.26	0.623
Pd.	56.63	37.16	3.108
Rh.	24.14	20.50	0.725
Ru.	26.88	17.60	0.513
Ir.	20.84	16.65	0.540
Au.	0.790	0.647	0.641

The acid soluble PGMs in the residue after the 4th and 5th stages may be an oxide in a form of a salt which dissolves easily in acid solution. This does not give the true picture of the rate of dissolution of the PGMs in hydrochloric acid solution with chlorine.

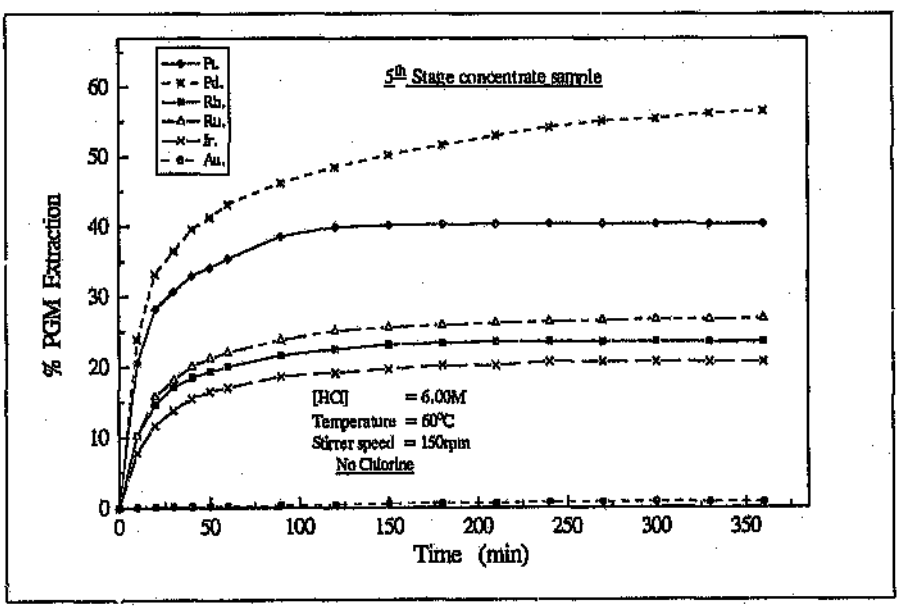


Fig. 5.2 Dissolution of the 5th stage PGM concentrate material without Chlorine.

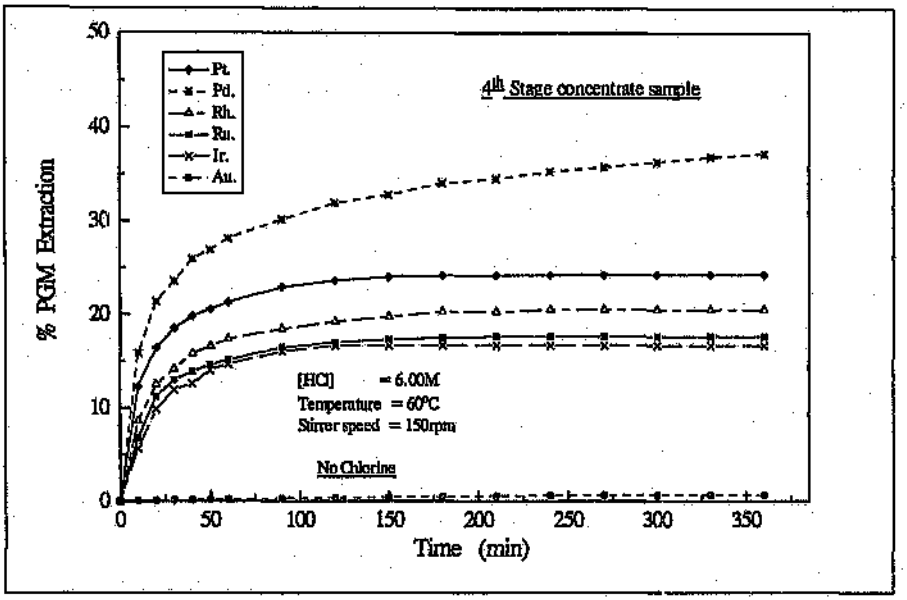


Fig. 5.3 Dissolution of the 4th stage PGM concentrate material without Chlorine.

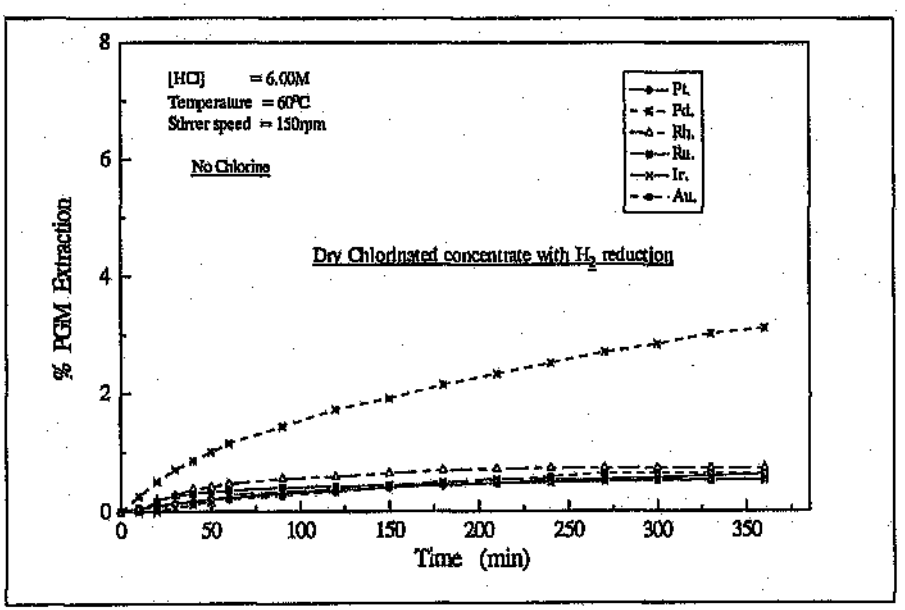


Fig. 5.4 Dissolution of the Dry chlorinated PGM concentrate without Chlorine.

The mineralogical analysis of the concentrate sample revealed some oxides of PGMs which might not need an oxidant like chlorine to dissolve them in hydrochloric acid solution. The oxide formation may be due to either the sulphuric acid leach, the caustic leach or some other processes at the Base Metal refinery operational line.

It is therefore believed that the sulphuric acid with oxygen leach at a high temperature and pressure to remove nickel, copper, cobalt and iron together with the caustic leach to remove selenium and tellurium in the concentrate produce the acid-soluble PGM fraction. In view of this, it was then decided to subtract the acid-soluble PGMs extraction part from the total chlorine leach results before applying the shrinking particle model on the resulting data to look at the dissolution reaction involving chlorine. There was a good agreement between the resulting data and the surface chemical reaction control of the shrinking particle model expression for all the parameters controlling the reaction.

The equation used to calculate the conversion for the chlorine soluble PGM fractions from the total dissolution of the platinum-group metal is derived as illustrated below. If the acid soluble PGMs are denoted by A and the chlorine soluble ones are represented by C then X_A and X_C are the conversions of the acid soluble and chlorine soluble PGM fractions respectively. Therefore, X represent the overall conversion of the platinum-group metals.

$$X = \frac{\text{Mass of PGM dissolved}}{\text{Total mass of PGM}}$$

$$= \frac{\text{Mass of A dissolved}}{\text{Total mass of A}} \times \frac{\text{Total mass of A}}{\text{Total mass of PGM}} + \frac{\text{Mass of C dissolved}}{\text{Total mass of C}} \times \frac{\text{Total mass of C}}{\text{Total mass of PGM}} \qquad 5.1$$

Therefore,

$$X = X_A f_A + X_C f_C \qquad 5.2$$

where,

f_A = the fraction of the concentrate material that is acid soluble, and

f_C = the fraction of the concentrate material that is chlorine soluble.

But,

$$f_A + f_C = 1 \qquad 5.3$$

Therefore

$$X = X_A f_A + X_C(1 - f_A) \qquad 5.4$$

From the leaching of the platinum-group metals in only acid without chlorine, $f_A = X_A$ at the end of the acid soluble leach was determined. However, at every point in time,

$$X_C = \frac{X - X_A f_A}{1 - f_A} \qquad 5.5$$

Therefore, equation 5.5 is substituted in all the shrinking particle model equations expressed in chapter 2. The equation of the chemical reaction control of the shrinking particle model finally becomes

$$1 - (1 - X_C)^{1/3} = k_s t \qquad 5.6$$

for the chlorine soluble PGM fractions in the concentrate material. A similar rate equation is obtained for the acid soluble PGM fractions and is expressed as

$$1 - (1 - X_A)^{1/3} = k_s t \qquad 5.7$$

The results for the rate of conversions of the acid soluble PGMs fractions, chlorine soluble PGMs and the total dissolution of the platinum-group metals with chlorine in hydrochloric acid solution for the same set of data is shown for platinum in Figure 5.5. The graph indicated that even at the initial leaching period, the rate of dissolution of the chlorine soluble PGM fraction is much more faster than the dissolution of the acid soluble PGMs in only hydrochloric acid solution. This observation explains the fact that the rate of conversion of pure PGMs into their soluble chloro-complexes require chloride ions to quickly drive the dissolution reactions. This also supports the argument that the acid soluble PGMs may be in the form of oxides which were produced during

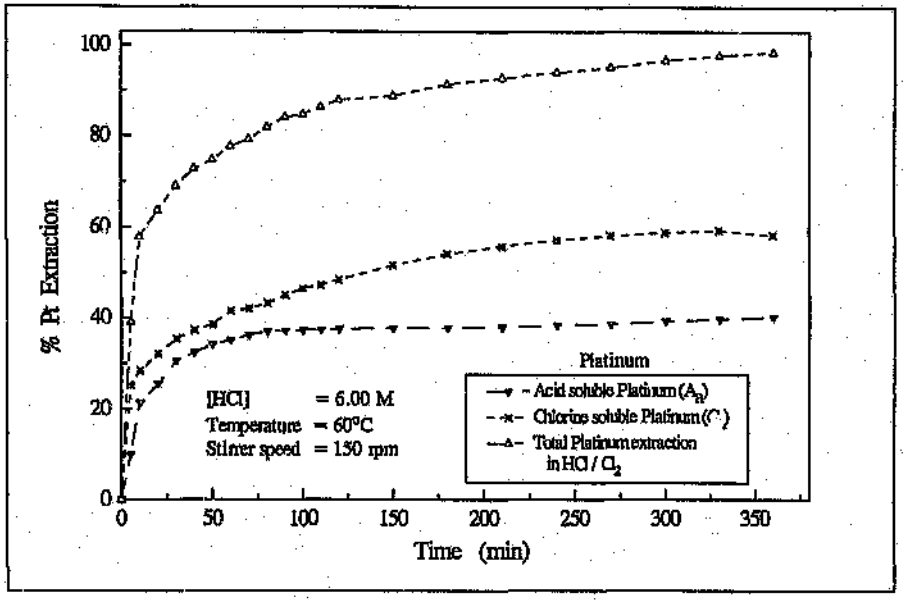


Fig. 5.5 Comparison of Acid soluble, Chlorine soluble and Total Platinum extraction.

the nickel, copper and cobalt removal from the concentrate by sulphuric acid with oxygen pressure leach. The sum of the acid soluble and the chlorine soluble PGM extractions is equal to the total extraction of the platinum-group metals with chlorine as illustrated by equation 5.2. Therefore, the ratio of the conversion of the acid soluble platinum to the conversion of the total platinum dissolution in the material is the amount of the leachable acid soluble platinum in the concentrate. This also applies to all the other platinum-group metals. It is shown from Figure 5.5 that almost all the acid soluble platinum dissolves within two hours of leaching with good agitation.

Similar graphs to compare the acid soluble PGMs, the chlorine soluble PGMs and the total extraction of the platinum group metals as explained above were obtained for palladium and the other platinum-group metals. They all show the same characteristic behaviour as plotted for platinum. The amount of acid soluble gold in the concentrate material was very negligible.

5.2 The Leaching Rate Model

The rate models presented in Chapter 2 were considered and tested on the dissolution of the chlorine soluble PGMs. This is shown for platinum in Figures 5.6 to 5.9 below. The results depicted that the diffusion models either through a reaction product or film layer do not fit the data obtained. This agrees with the fact that the platinum group metals dissolution process leaves no product layer to affect the leaching rate. The reactants and products transfer through a film layer into the main solution also do not control the process.

Since the rate of dissolution of the platinum-group metals was observed to increase remarkably with increasing temperature, the chemical reaction control was then considered to be the rate driving step. The chlorine soluble PGMs extraction data generated according to equation 5.5 from the experimental results for the dissolution

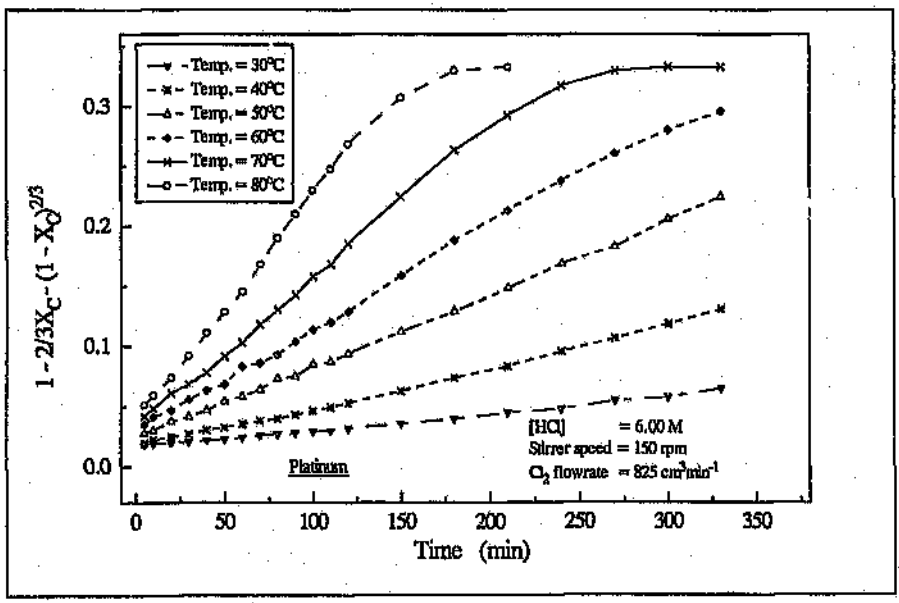


Fig. 5.6 Product layer diffusion $[1-2/3X_C-(1-X_C)^{2/3}]$ control model plot for the Chlorine soluble Platinum dissolution.

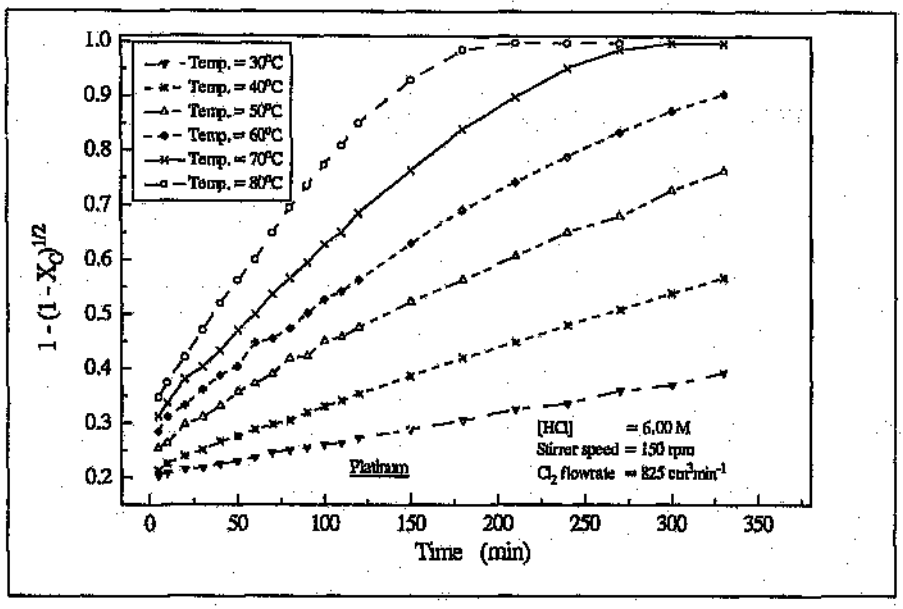


Fig. 5.7 A plot of Film layer diffusion control model for large particles - Platinum.

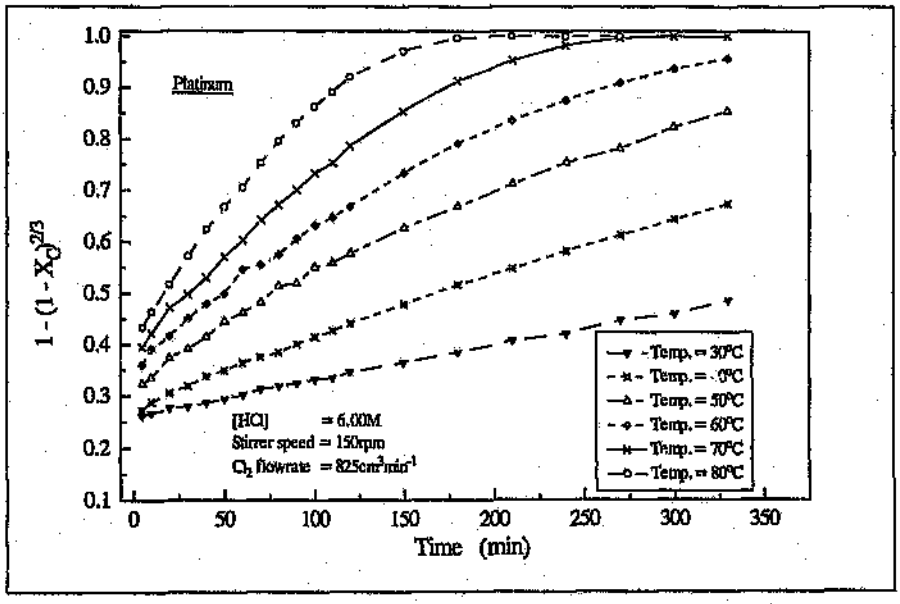


Fig. 5.8 A plot of Film-layer diffusion control model for small particles - Platinum.

of the platinum-group metals which were presented in Chapter 4 are analysed in terms of the chemical reaction control of the shrinking-particle model. The chemical reaction control of the shrinking-particle model at the mineral surface was found to control the leaching reaction adequately for all the chlorine soluble platinum-group metals. The apparent dissolution rate constants, k_s were obtained from the slope of the lines of the representative plots of $1-(1-X_C)^{1/3}$ against time. These rate constants are used to determine the activation energy, the order of reaction with respect to the hydrochloric acid concentration, the order of reaction with respect to the concentration of chlorine and the effect of the particle size.

The chlorine soluble PGMs results at different dissolution temperatures for the chemical reaction control of the shrinking particle model (equation 5.6) were plotted for platinum and is presented as Figure 5.9. The same graphs were plotted for the other PGMs and

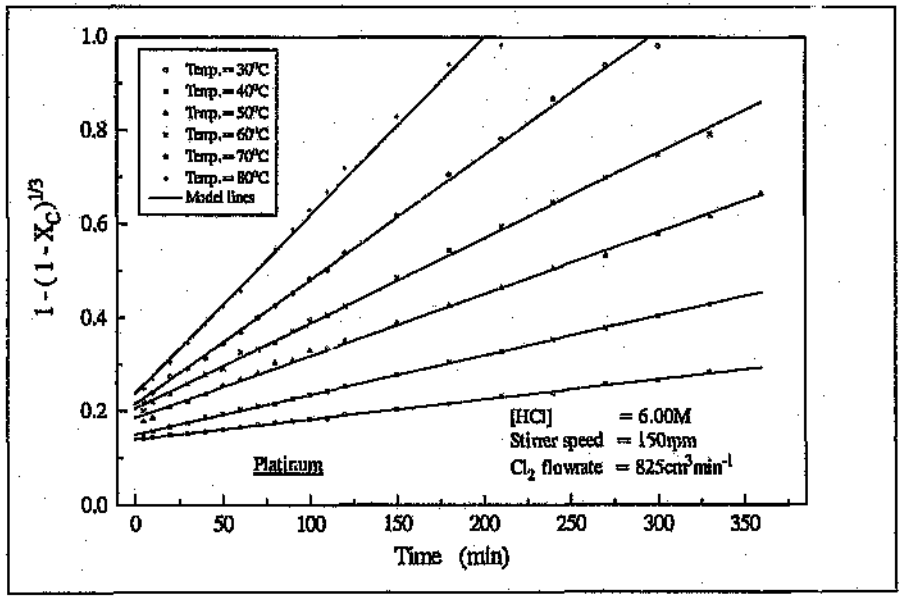


Fig. 5.9 Chemical reaction $[1-(1-X_C)^{1/3}]$ control model plot for the Chlorine soluble Platinum dissolution.

are shown in section 5.3. The rate model $[1-(1-X_C)^{1/3}]$ versus t graphs for the dissolution of the chlorine soluble PGMs have non-zero intercepts as shown in Figure 5.9. This identification clearly confirms the complexity of the dissolution of platinum group metals in this concentrate used. The reason for this phenomena is thought to be that during the leaching process, both the chlorine soluble and acid soluble PGMs dissolve together under the influence of the chlorine oxidant. Their rate of dissolutions in hydrochloric acid solution with chlorine, however are not the same since the acid soluble PGMs are believed to be oxides. Obviously, the initial rate of dissolution of the acid soluble PGMs in the presence of the chlorine oxidant would be much more faster than that of the chlorine soluble PGMs which are pure metals.

Now, when the dissolution of the acid soluble PGMs in only hydrochloric acid is subtracted from the total PGM dissolution in hydrochloric acid solution with chlorine, it raises the initial rate of dissolution of the chlorine soluble PGMs by a factor equal to the value of their intercepts on the rate equation graphs. This means that the values of the $[\ 1-(1-X_C)^{1/3}\ ]$ intercept on the chlorine soluble PGM rate model graph is the final rate of the acid soluble PGM dissolution. This is confirmed by the rate model graphs for the acid soluble PGMs which start from the origin of the graph. This condition prevails during the total dissolution of the PGMs for just the initial period of about less than one hour, when the chlorine soluble PGMs pick up their true dissolution behaviour as the amount of the acid soluble PGMs in the concentrate gets depleted. In view of this, the values of the intercept on the rate model graph for the chlorine soluble PGMs depend on the compositions of the platinum group metal fractions in the concentrate together with the change in conditions of the leach.

The chemical reaction control of the shrinking particle model (equation 5.7) was also applied to the acid soluble platinum group metals data and the results for platinum are shown in Figure 5.10 for different temperatures. The graph shows that the model fits the data obtained for the acid soluble PGMs perfectly well from the origin. This model was applied to all the data obtained for the effect of the parameters that affected the dissolution of the acid soluble PGMs to determine the order of reaction with respect to

the hydrochloric acid concentration and the activation energy for the individual metals.

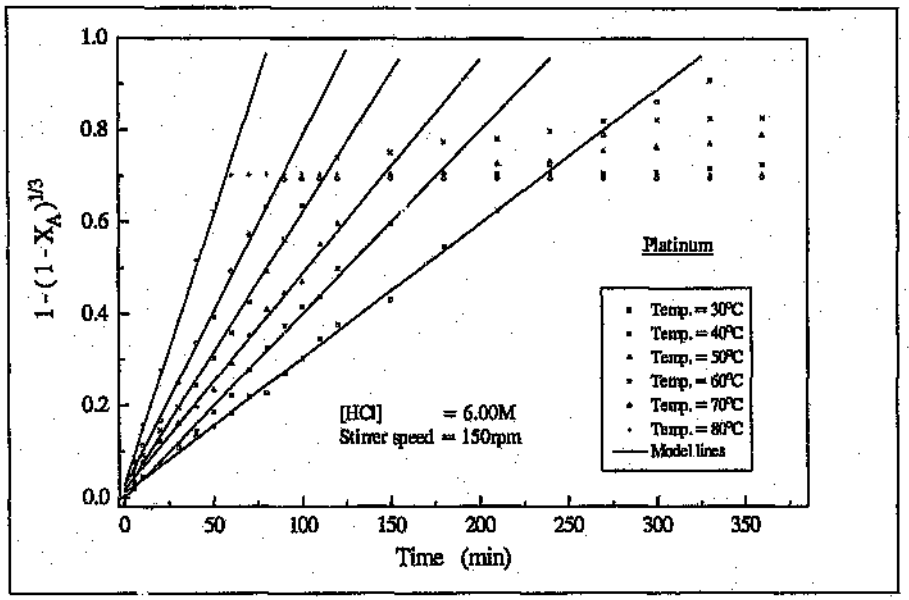


Fig. 5.10 Chemical reaction $[1-(1-X_A)^{1/3}]$ control model plot for the Acid soluble Platinum dissolution.

Both graphs for the chlorine soluble and acid soluble platinum, for instance, show a fit for the surface chemical reaction control but the combine effect is different as seen in Figure 5.1. This graph (Figure 5.1) shows a break in the model fit. The initial fit is the rate effect on the acid soluble platinum which basically takes about two hours to completely dissolve, thereafter the effect on the chlorine soluble platinum is shown clearly. The initial jump from the graph origin on the $[1-(1-X)^{1/3}]$ intercepts of the model rate plot for the total platinum group metals dissolution is the combined effect of the initial dissolution of the chlorine soluble PGMs and that of the acid soluble PGMs dissolution. This trend is seen in all the analysis for the dissolution of the platinum group metals in the concentrate used for this work.

5.3 Analysis of the Rate of Cl_2 soluble PGM dissolution with Temperature.

The chemical reaction control of the shrinking particle model was applied on the dissolution data obtained for the chlorine soluble fraction of the PGMs in the concentrate sample for different temperatures. Therefore, from equation 2.1, a plot of $1-(1-X_C)^{1/3}$ against time t gives a linear relationship. The slope given by k_s, is related to the activation energy by the Arrhenius equation:

$$k_s = A_o \exp\left(-E_a/RT\right) \qquad 5.8$$

where,

A_o = Arrhenius pre-exponential factor,

E_a = Activation energy, ($kJmol^{-1}$)

R = gas constant, ($8.314\ Jmol^{-1}K^{-1}$),

T = absolute temperature (K).

By taking logarithms of the equation 5.8, we get:

$$\ln k_s = -\frac{E_a}{RT} + \ln A_o \qquad 5.9$$

Therefore, a plot of $\ln(k_s)$ against 1/T for the chlorine soluble PGMs is a straight line with a slope of $-E_a/R$ and an intercept of $\ln(A_o)$.

The effect of temperature on the rate of reaction is illustrated for the chlorine soluble Pt, Pd, Rh, Ru, Ir and total Au as Figures 5.11 to 5.16. An Arrhenius plot of the reaction rate constants k_s from equation 5.9 is modified to $\ln(k_s/[Cl_2]^b)$ to correct the temperature dependence on the chlorine solubility in hydrochloric acid solution which also has an influence on the rate of dissolution of PGMs. This graph is presented in Figure 5.17. It is well to note that this Arrhenius plot exhibited excellent linearity over the entire temperature range for all the PGMs and gold. The linearity of all the plots with correlation coefficients greater than 0.98 are illustrative of good linear fits.

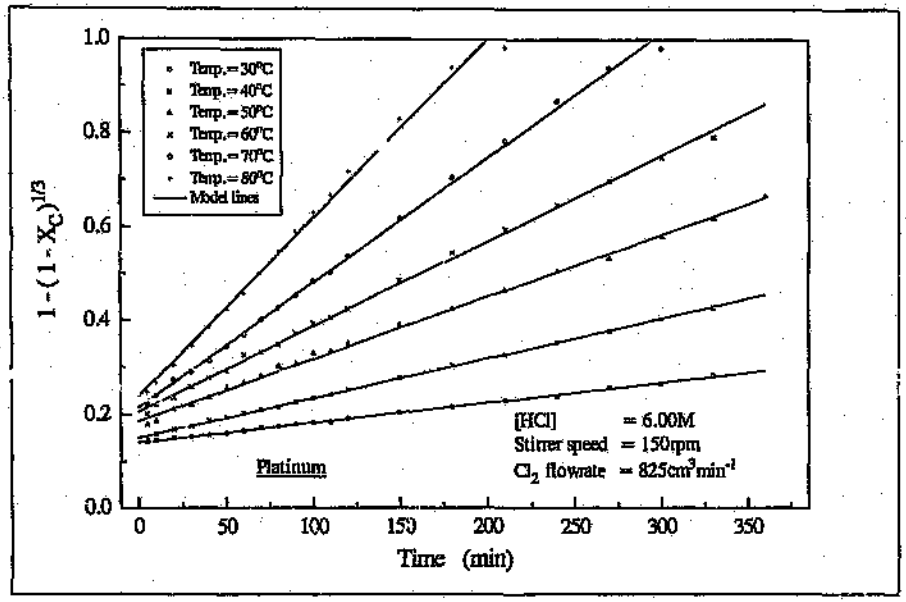


Fig. 5.11 Dependence of Temperature on the rate of Chlorine soluble Pt. dissolution.

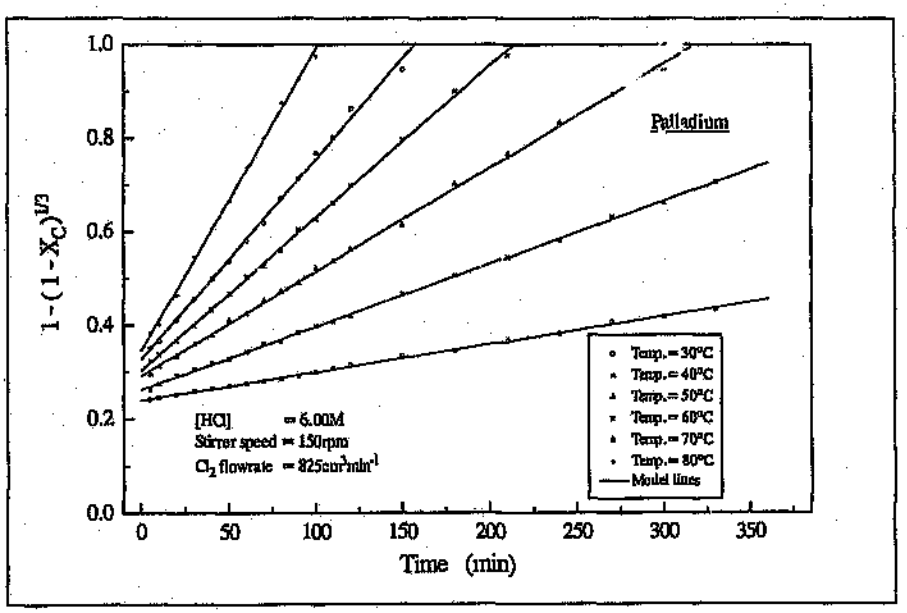


Fig. 5.12 Dependence of Temperature on the rate of Chlorine soluble Pd. dissolution.

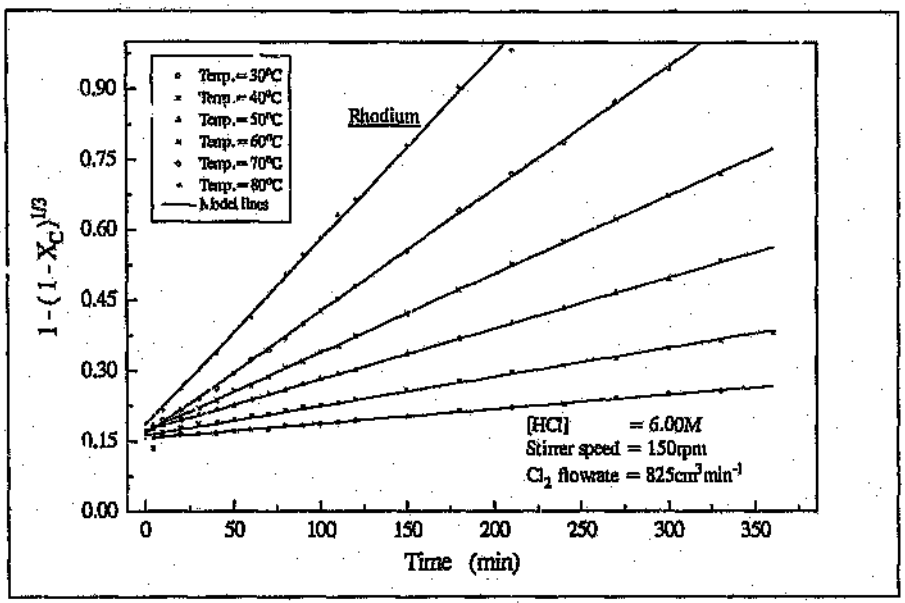


Fig. 5.13 Dependence of Temperature on the rate of Chlorine soluble Rh. dissolution.

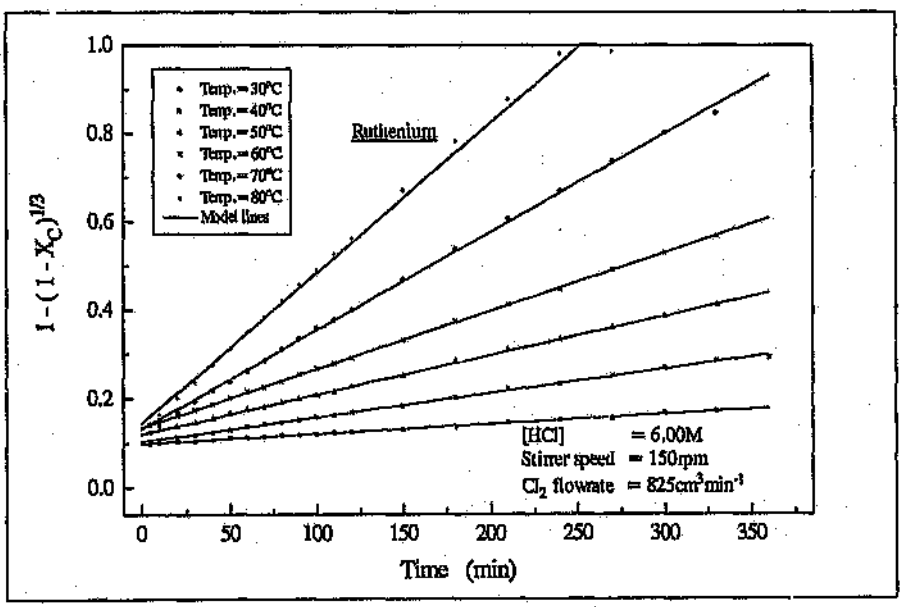


Fig. 5.14 Dependence of Temperature on the rate of Chlorine soluble Ru. dissolution.

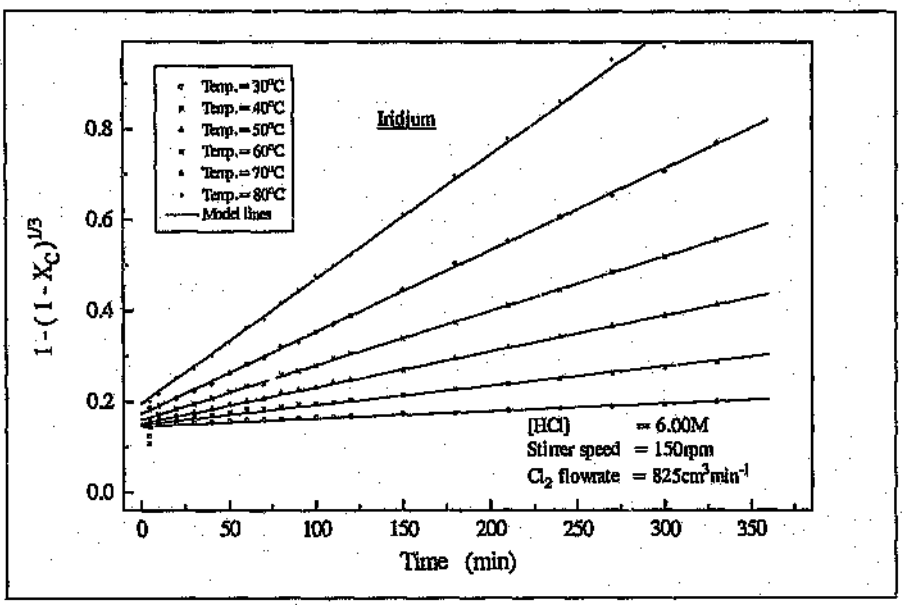


Fig. 5.15 Dependence of Temperature on the rate of Chlorine soluble Ir. dissolution.

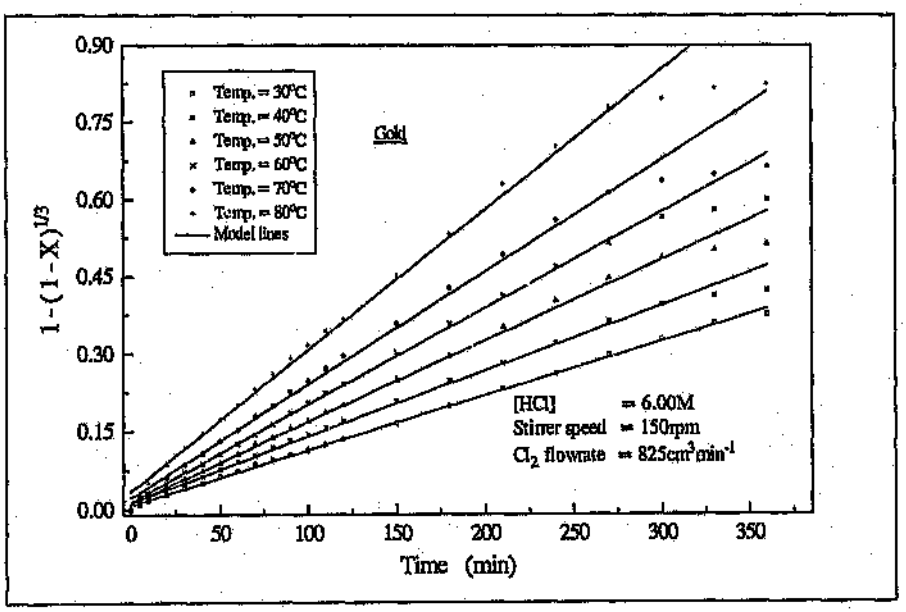


Fig. 5.16 Dependence of Temperature on the rate of reaction of Au. dissolution.

The figures above show good agreement between the experimental data and the model equation for all the chlorine soluble PGMs fractions in the concentrate sample. Therefore, it is concluded that the dissolution rate is described by the chemical reaction control of the shrinking particle model.

A plot of $\ln(k_s/[Cl_2]^b)$ versus 1/T is shown in Figure 5.17 below. From the Arrhenius graph, the activation energy for the chlorine soluble platinum was calculated to be 42.36 kJmol^{-1}, the palladium was 40.19 kJmol^{-1}; rhodium was 44.56 kJmol^{-1}; ruthenium was 46.62 kJmol^{-1}, iridium was 47.60 kJmol^{-1} and gold was 40.44 kJmol^{-1}

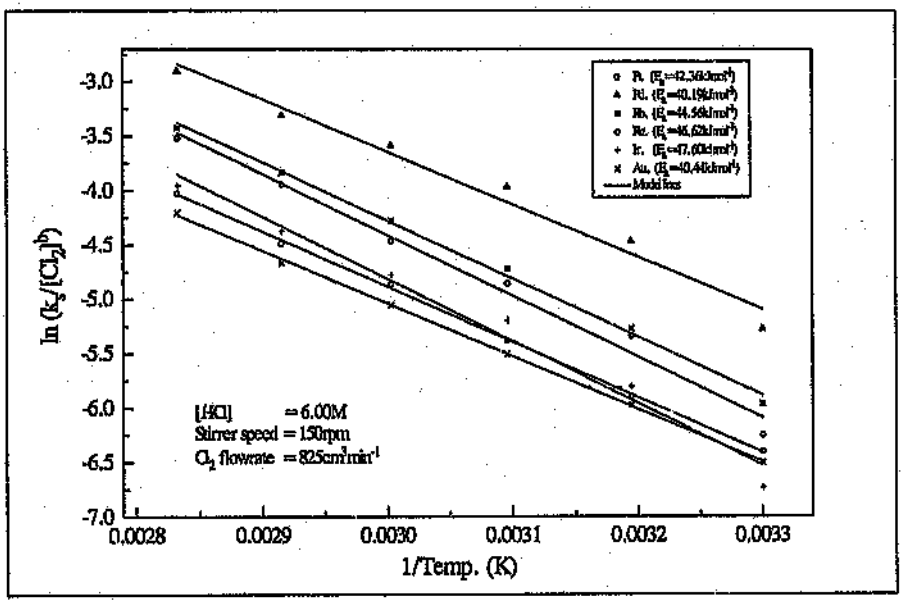


Fig. 5.17 Arrhenius plot for dissolution of Cl_2 soluble PGMs and Au in HCl/Cl_2 media.

These values of activation energy for the chlorine soluble PGMs and gold lie within the range for surface chemical reaction control that is, they are above 40 kJmol^{-1}. Therefore, it is concluded that the rate-controlling step is a chemical reaction occurring at the surface of the PGMs particles.

5.4 Analysis of the Rate of Cl_2 soluble PGM dissolution with HCl conc.

The results for the leaching of PGMs under different HCl concentrations in Chapter 4 have established that increasing the acid strength increases the rate of dissolution. The relationship between the acid concentration and the rate of reaction for a spherical particle reacting according to the surface chemical reaction control of the shrinking particle model is given by:

$$1-(1-X)^{1/3} = k_s'[HCl]^a t \qquad 5.10$$

where k_s' is the apparent rate constant for the surface reaction control at different HCl concentrations. Therefore, the graphs of $1-(1-X_C)^{1/3}$ against time, t, for the various

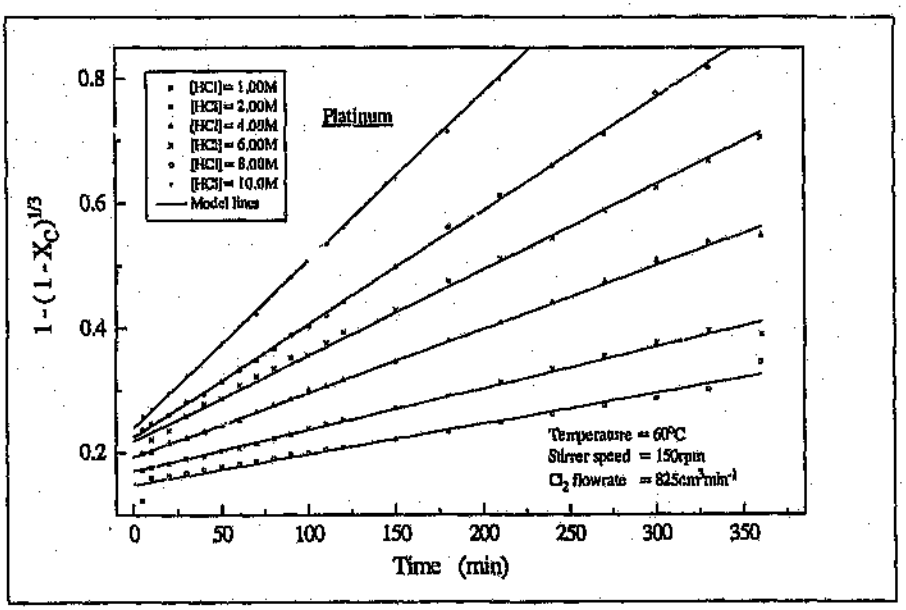


Fig. 5.18 Effect of HCl concentration on the Rate of Cl_2 soluble Pt. dissolution.

hydrochloric acid concentrations which produced a linear relationships were plotted for all the chlorine soluble fractions of the PGMs in the concentrate and are presented as Figures 5.18 to 5.23. The values of the rate constants k_s' were determined by regression

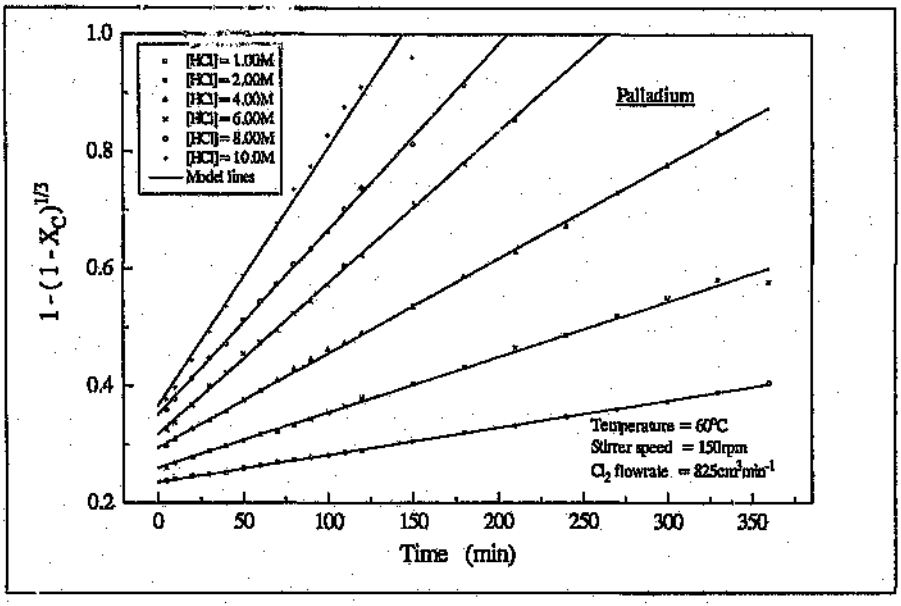


Fig. 5.19 Effect of HCl concentration on the Rate of Cl_2 soluble Pd. dissolution.

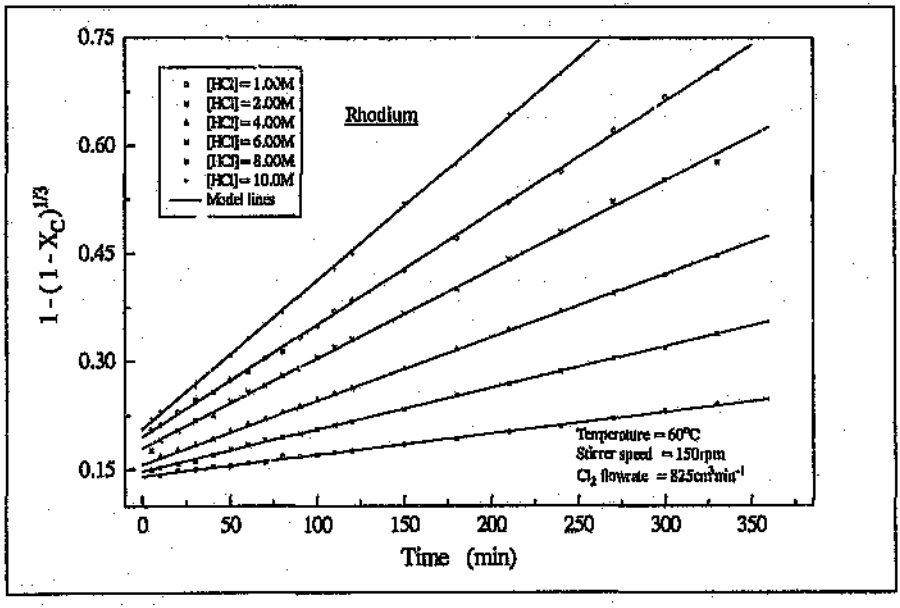


Fig. 5.20 Effect of HCl concentration on the Rate of Cl_2 soluble Rh. dissolution.

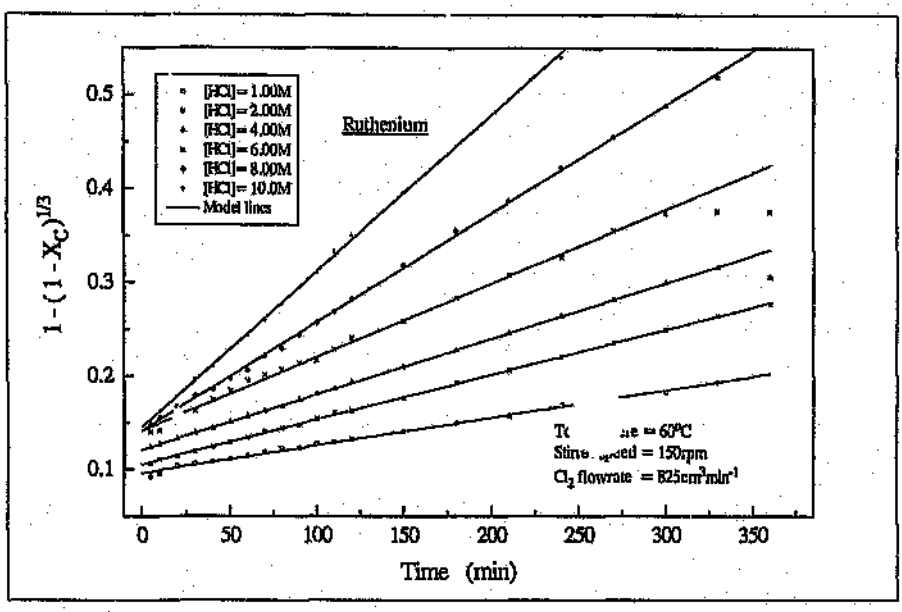


Fig. 5.21 Effect of HCl concentration on the Rate of Cl_2 soluble Ru. dissolution.

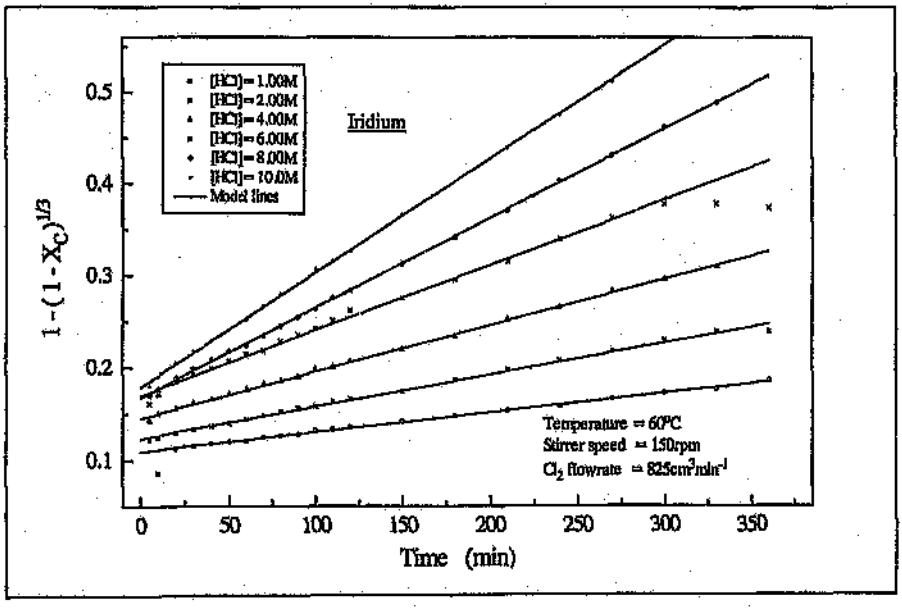


Fig. 5.22 Effect of HCl concentration on the Rate of Cl_2 soluble Ir. dissolution.

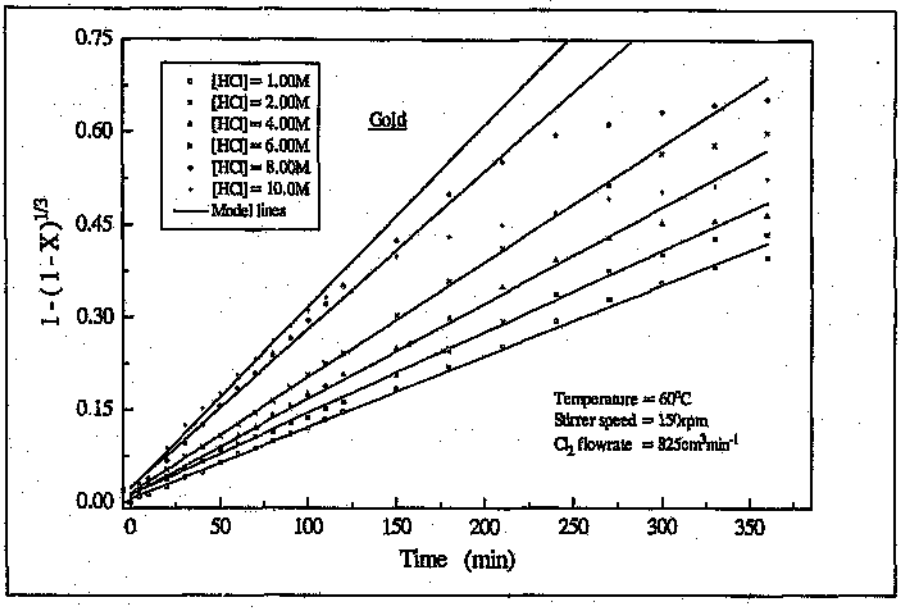


Fig. 5.23 Effect of HCl concentration on the Rate of total Gold dissolution.

analysis of the model plots for the different acid concentrations. A plot of $\ln(k'_s)$ against ln[HCl] yields a straight line whose slope is equal to the reaction order, α, with respect to hydrochloric acid concentration. For the vast majority of the experimental graphs shown, it was found that the correlation coefficient is greater than 0.90 with most of them in excess of 0.98. Such values are of good linear fits. In view of the high correlation coefficient values obtained for all the chlorine soluble platinum group metals and gold, it is reasonable to conclude that the chemical reaction control which was applied as the rate-driving step gives a good representation of the experimental data.

The reaction order of the chlorine soluble platinum with respect to hydrochloric acid concentration is 0.70 and 0.94 was obtained for palladium. The order of reaction for the rest of the chlorine soluble PGMs are 0.81 for rhodium, 0.68 for ruthenium and iridium was 0.75. The order of reaction for gold was 0.76. These reaction orders are within the range of values which are normally surface chemical reaction control.

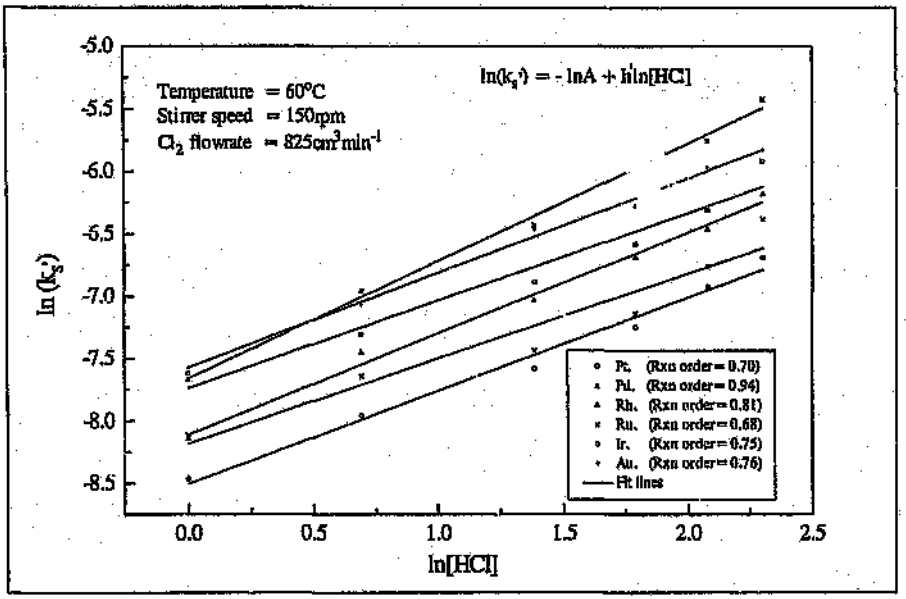


Fig. 5.24 Reaction order with respect to HCl conc. for chlorine soluble PGMs and Au.

5.5 Analysis of the Rate of PGM dissolution with Chlorine concentration.

(i) Determination of the Chlorine concentration in the PGM leach solution

The various amounts of chlorine gas that were passed into the 6.00 M hydrochloric acid solution dissolved to produce different chlorine concentrations. It was very difficult to calculate the actual chlorine concentration in the PGM leach solution by the iodometric titration due to the dark colour of the solution which makes it difficult to determine the end point accurately. In view of this, the concentration of chlorine added into the hydrochloric acid solution at different flowrates during the leaching of the platinum group metals were determined from the relationship between the chlorine concentration and the redox potentials. The two fundamental parameters that were used to control the behaviour of the metals in aqueous solution are the pH and the oxidation potential of the solution.

The redox potential of the leach solution was measured for each test. All these redox potential measurements of the solutions in the reactor during the experiments were done using the glassy carbon electrode so as not to contaminate the leach solutions with the platinum electrode which was used to check the corrosion potential of the solutions. The measured redox potentials were used to estimate the chlorine concentrations in the solution during the leaching process.

From the half reaction of the chlorine dissolution;

$$Cl_2 + 2e^- \rightleftharpoons 2Cl^- \qquad 5.11$$

the redox potential is related to the chlorine concentration by an equation similar to the Nernst equation:

$$E = E^o + \frac{RT}{nF}\ln\left\{\frac{[Cl_2]}{[Cl^-]^2}\right\} \qquad 5.12$$

where,

E = the solution redox potential,

E^o= the standard redox potential,

R = the gas constant (= 8.314 $JK^{-1}mol^{-1}$)

F = the Faraday's constant (= 96500 $Cmol^{-1}$)

n = the number of moles of chlorine (= 2)

The equation 5.12 therefore becomes

$$E = E^o + \frac{RT}{2F}\ln[Cl_2] - \frac{RT}{2F}\ln[Cl^-]^2 \qquad 5.13$$

which reduces to

$$E = E^{o'} + \frac{RT}{nF}\ln[Cl_2] \qquad 5.14$$

where the constant,

$$E^{o'} = E^{o} - \frac{RT}{2F}\ln\left[Cl^{-}\right]^{2} \qquad 5.15$$

The redox potentials E of the chlorine in hydrochloric acid solutions were measured and the results are plotted as Figures 5.25 to 5.27 for temperatures of 30, 50 and 60 °C. These data were fitted into equation 5.14 and a plot of the redox potential E_{red} of the solution against $\ln[Cl_2]$ gives a linear relationship with (RT/2F) being the gradient. This is shown in Figure 5.28.

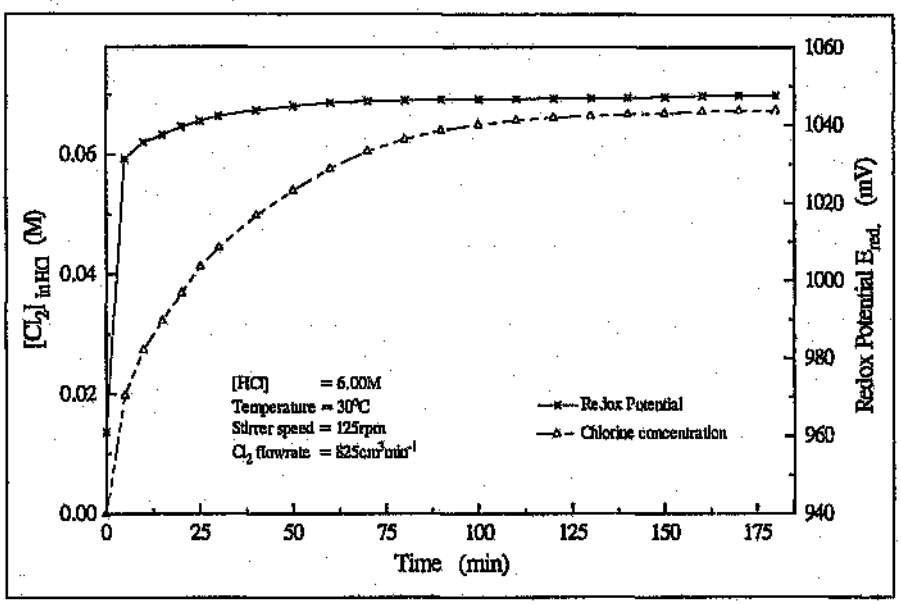


Fig 5.25 Relationship between Chlorine concentration and Redox potential with time for [HCl] = 6.00 M and Temperature = 30°C

Now, the values of the redox potentials of the leach solution which were monitored during the platinum-group metals dissolution process were used to calculate the chlorine concentration of the leach solution from the 60°C line of Figure 5.28. This is because the effect of chlorine concentration on the dissolution of platinum-group metals were

conducted with 6 00 M hydrochloric acid at a temperature of 60°C. The equation of the line describing the condition is;

$$E_{red} = 1085.48 + 14.48 \ln[Cl_2] \qquad 5.16$$

from which the chlorine concentrations were calculated with the measured redox potentials of the leach solution. The calculated chlorine concentrations are presented in Table 5.2 below.

Table 5.2 Chlorine concentrations from Redox potentials during PGM dissolution.
Condition: *[HCl]= 6.00M, Temperature= 60°C, Agitation speed= 150rpm*

Average condition	Gas flowrates (cm^3min^{-1})			
	Cl_2=825 N_2 =0	Cl_2=825 N_2 =90	Cl_2=825 N_2 =200	Cl_2=825 N_2 =310
$E_{red.}$ (mV)	1051.00	1037.90	1029.80	1020.10
$[Cl_2]$ (M)	0.0924	0.0374	0.0214	0.0109

Now, by substituting equation 5.16 into equation 5.15, the standard redox potential E^o for the PGM dissolution in 6.00 M hydrochloric acid solution at 60°C is calculated to be 36.90 mV.

The redox potential also plays a vital role in the PGM dissolution. The kinetic limitations generally require significant overpotential to drive the reactions. This is always the case when using potentials in predicting redox behaviour. For instance, the platinum dissolution reaction;

$$Pt + 6Cl^-_{(aq)} \rightleftharpoons PtCl_6^{2-}{}_{(aq)} + 4e^- \qquad 5.17$$

is related to the equilibrium redox potential of the solution with an equation similar to

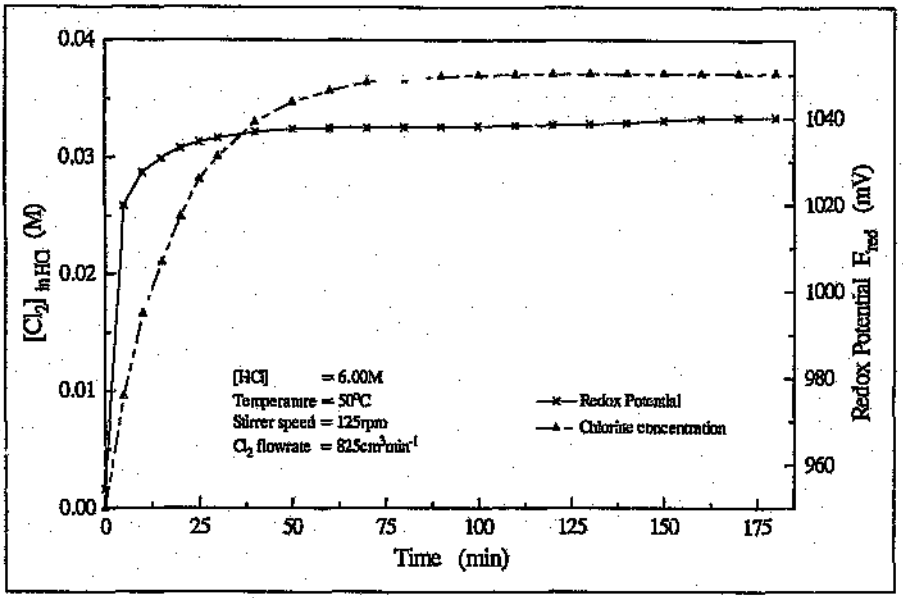


Fig 5.26 Relationship between Chlorine conc. and Redox potential with time at 50°C.

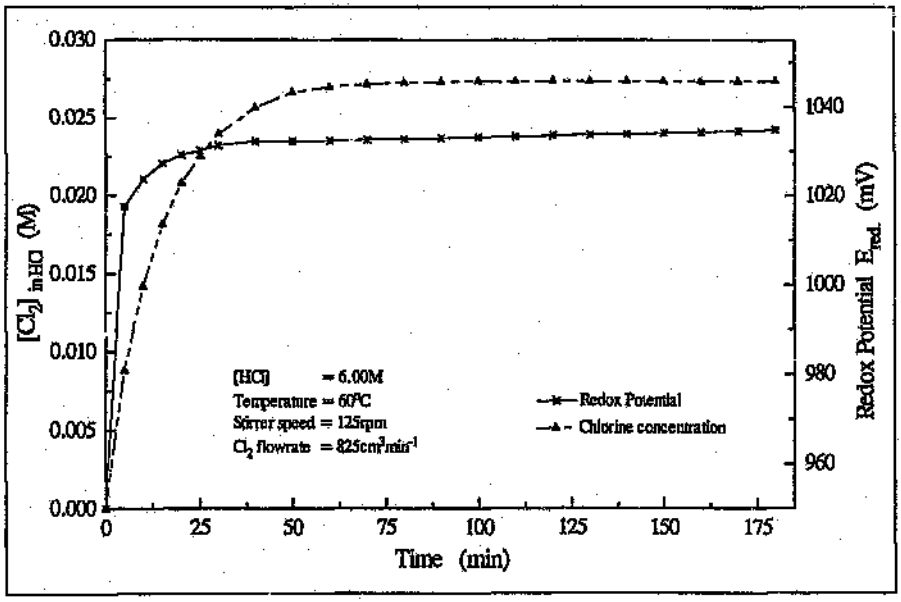


Fig 5.27 Relationship between Chlorine conc. and Redox potential with time at 60°C.

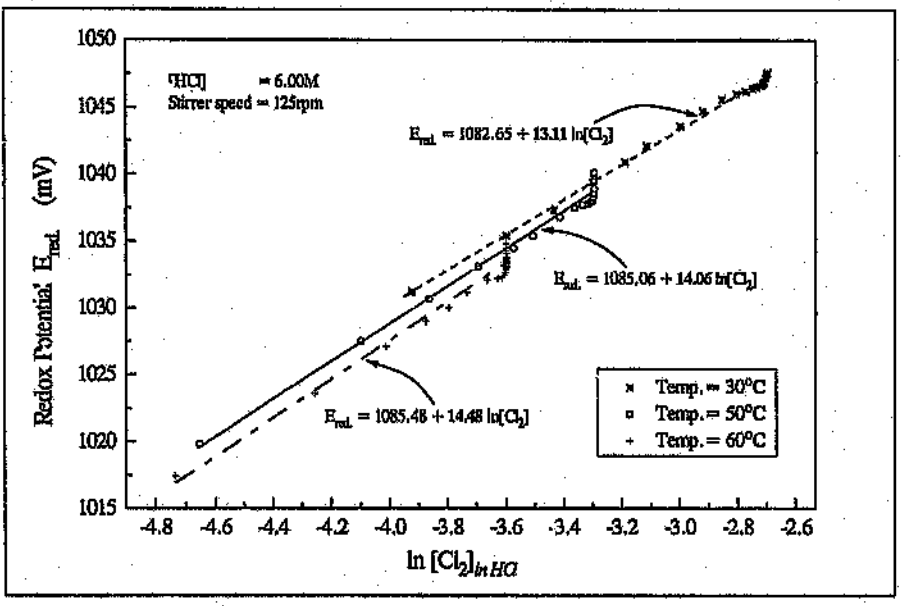


Fig. 5.28 Relationship between the Redox potential and the Chlorine concentration.

the Nernst equation (equation 5.18)

$$E = 0.76 + \frac{RT}{4F}\ln\left\{\frac{[PtCl_6^{2-}]}{[Pt][Cl^-]^2}\right\} \qquad 5.18$$

From a thermodynamic point of view, in an HCl solution of unit activity Pt(IV), Pt and Cl^-, the Pt(IV) is reduced to Pt metal at potentials below 0.76 V and the Pt metal is oxidised at potentials above 0.76 V. The Pt(IV) is the most stable state of platinum so a redox potential of more than 0.76 V must be ensured during the dissolution (equation 5.17). A similar expression can be written for the other platinum-group metals to establish the potentials at which the chloro-complexes of the platinum-group metals are stable in solution. In practice, the potentials are measured using a reference electrode such as the saturated calomel electrode (SCE) which has a potential of 0.245 V versus the normal hydrogen electrode (NHE). Therefore, the conversion of the potentials versus NHE involves adding 0.245 V to the observed value.

(ii) Rate of Chlorine soluble PGMs dissolution with Chlorine concentration

The results of the variation of chlorine flowrate as shown in chapter 4 indicated that leaching at higher flow rates of chlorine resulted in greater rates of dissolution of the platinum group metals. The chlorine concentrations were determined from the chlorine flowrates. The various amounts of chlorine added into the 6.00 M hydrochloric acid solution during the leaching experiments were calculated from the relationship between the chlorine dissolution rate and the redox potential of the solution as explained in section 5.5(i).

The relationship between the chlorine concentration and the rate of reaction according to the chemical reaction control of the shrinking particle model is expressed as:

$$1-(1-X_c)^{1/3} = k_s^*[Cl_2]^b t \qquad 5.19$$

for the chlorine soluble PGMs in the concentrate. The constant k_s^* is the intrinsic rate constant which depends on temperature and the hydrochloric acid concentration. The plots of $1-(1-X_C)^{1/3}$ versus time presented as Figures 5.29 to 5.34 for all the platinum-group metals and gold show that the experimental results adequately fit the shrinking-particle model for the chlorine soluble fractions. The gold in the concentrate material had no acid soluble fraction. The apparent rate constants obtained from the slopes of these plots were used to determine the order of reaction, b, with respect to the chlorine concentration.

The graphs of $\ln(k_s^*)$ against $\ln[Cl_2]$ were also plotted and the gradients obtained from the linear relationships are the order of reaction for the individual chlorine soluble PGMs with respect to chlorine concentration. According to Figure 5.35, the order of reaction of the chlorine soluble platinum with respect to chlorine concentration is found to be 0.49, palladium is 0.78 and rhodium is 0.77. The chlorine soluble ruthenium had 0.79 order of reaction with respect to chlorine concentration whereas iridium is 0.71 and the gold is in the order of 0.50.

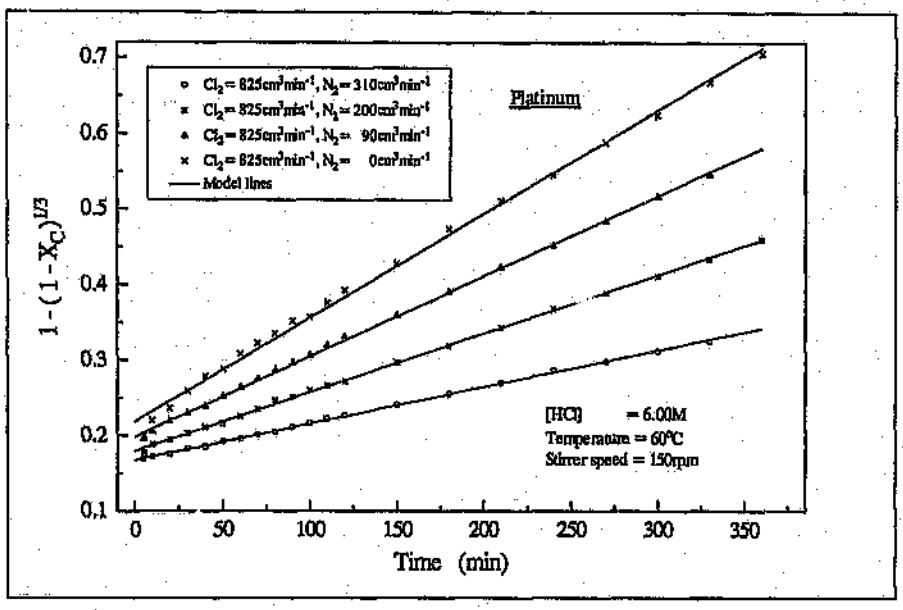


Fig. 5.29 Variation of the leaching rate with Cl_2 conc. for the Cl_2 soluble Platinum.

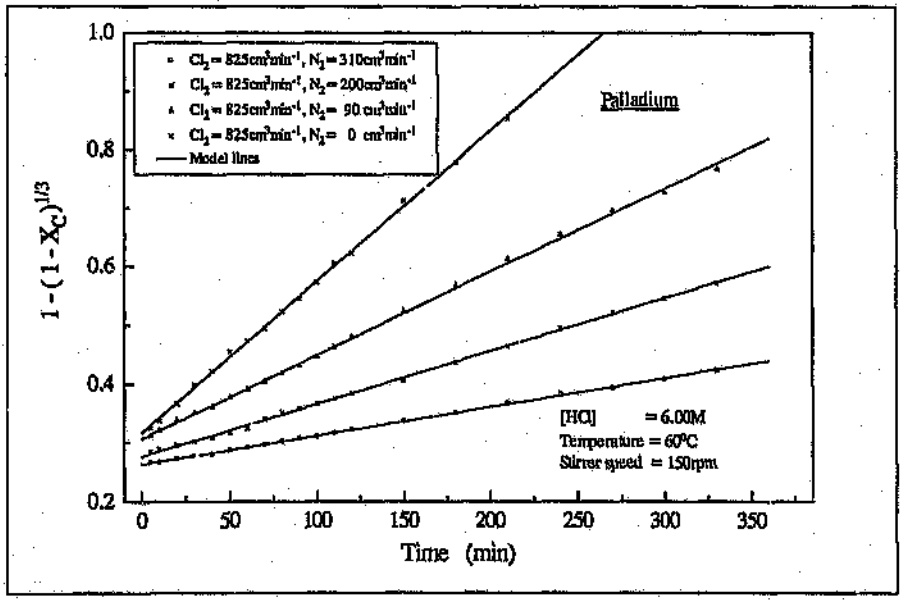


Fig. 5.30 Variation of the leaching rate with Cl_2 conc. for Cl_2 soluble Palladium.

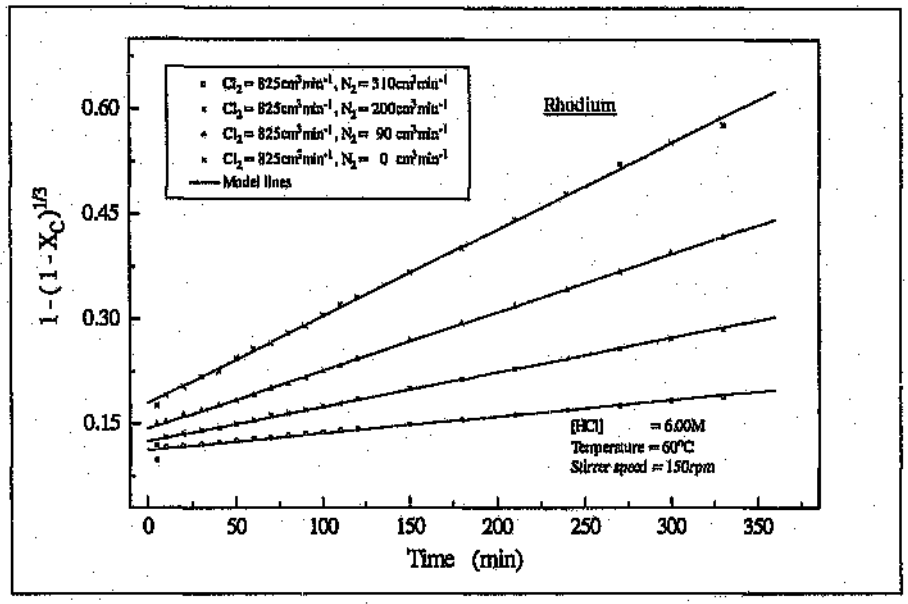


Fig.5.31 Variation of the leaching rate with Cl_2 conc. for the Cl_2 soluble Rhodium.

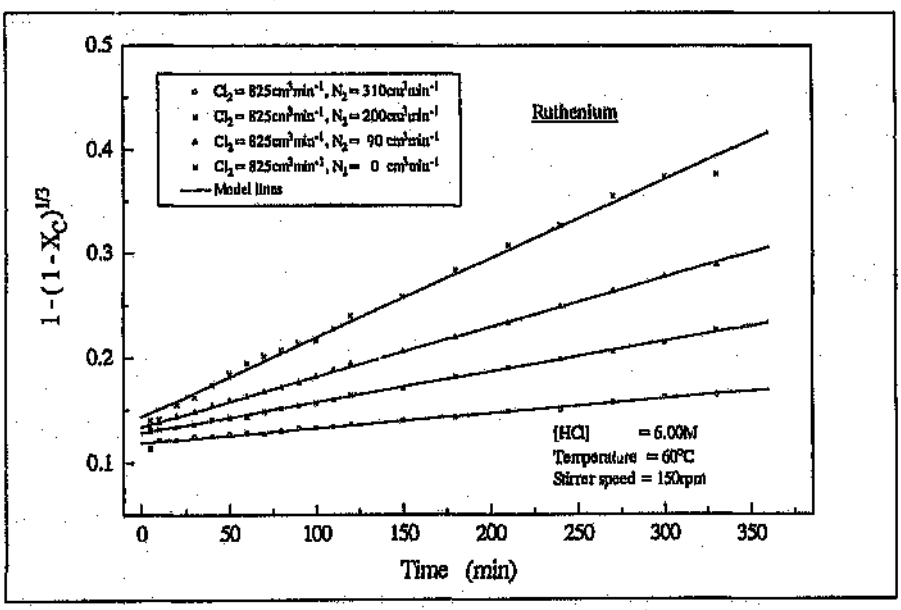


Fig. 5.32 Variation of the leaching rate with Cl_2 conc. for the Cl_2 soluble Ruthenium.

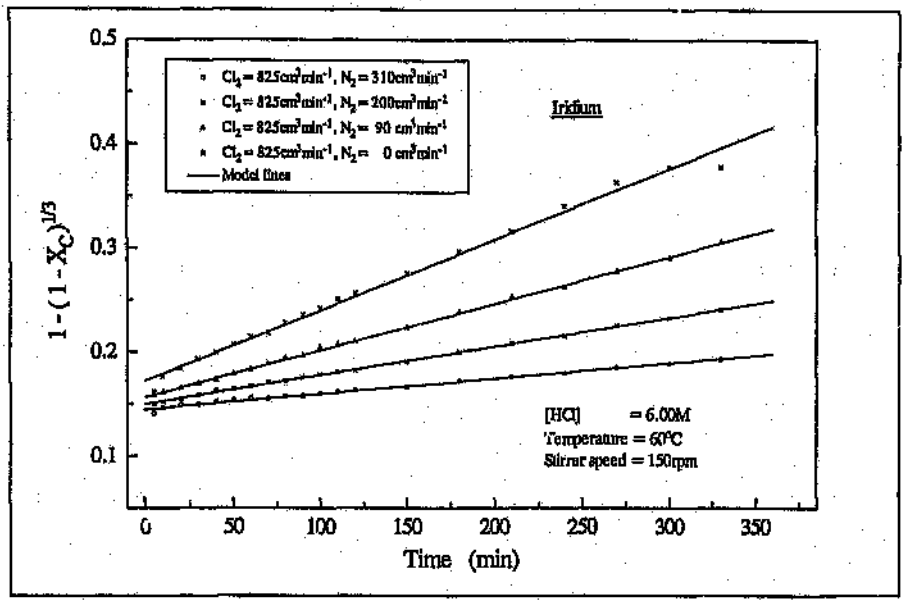


Fig. 5.33 Variation of the leaching rate with Cl_2 conc. for the Cl_2 soluble Iridium.

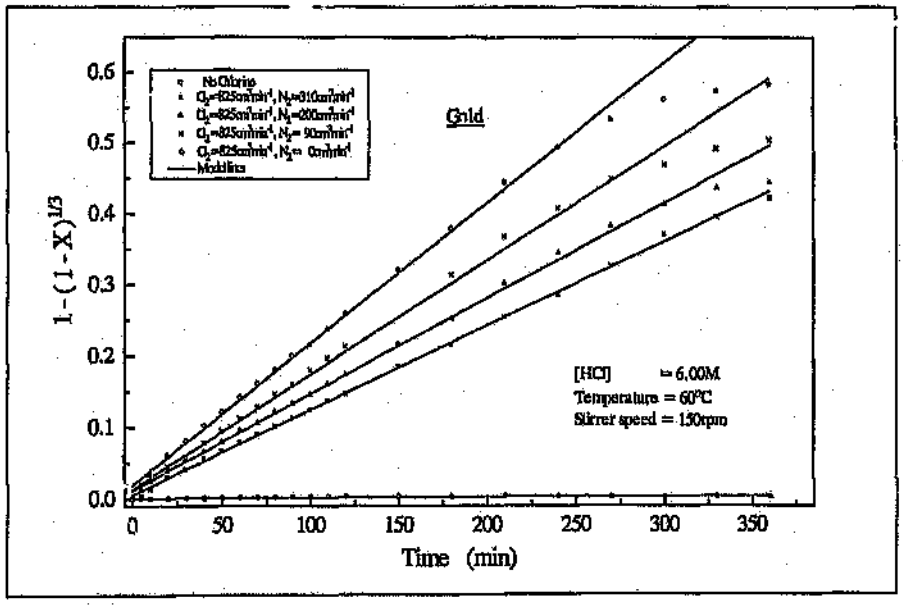


Fig. 5.34 Variation of the leaching rate with Chlorine concentration for the Gold.

The high value of activation energy together with these reaction orders of the PGMs dependency on the chlorine concentration also support that the dissolution process is controlled entirely by the rate of a surface chemical reaction.

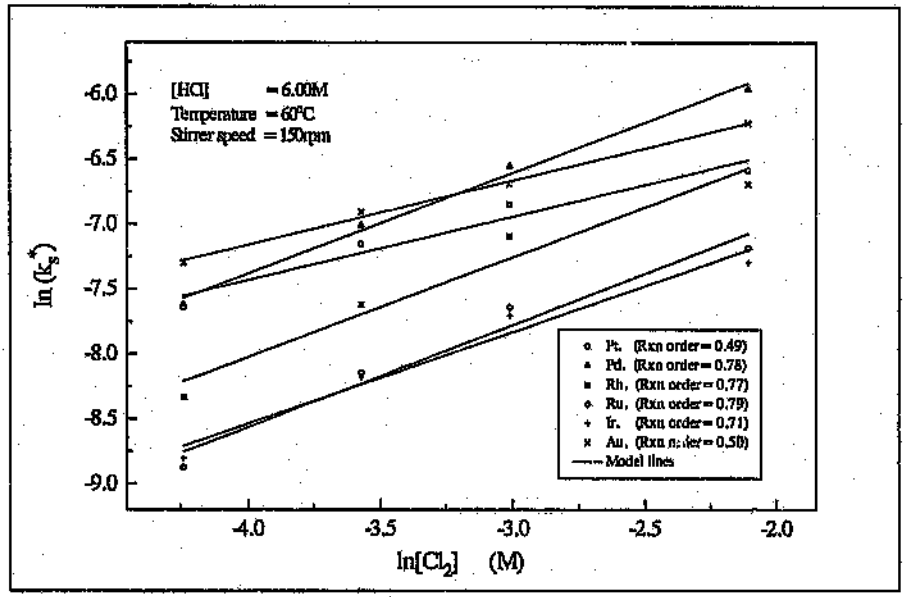


Fig. 5.35 Reaction order with respect to Cl_2 conc. for the Cl_2 soluble PGMs and Au.

5.6 Effect of Initial particle size on the rate of Cl_2 soluble PGM dissolution

The effect of the initial particle size on the rate of PGM dissolution was studied by applying the shrinking particle model on the chlorine soluble PGMs which were analysed according to the surface reaction control. The rate model relationship with the initial particle diameter can be expressed by the following function:

$$1-\left(1-X_C\right)^{1/3}=\frac{k_s^+}{d_o}t \qquad 5.20$$

where k_s^+ is the apparent rate constant and d_o is the initial particle diameter. The results obtained from plots of $1-(1-X_C)^{1/3}$ against time for the different initial particle diameters

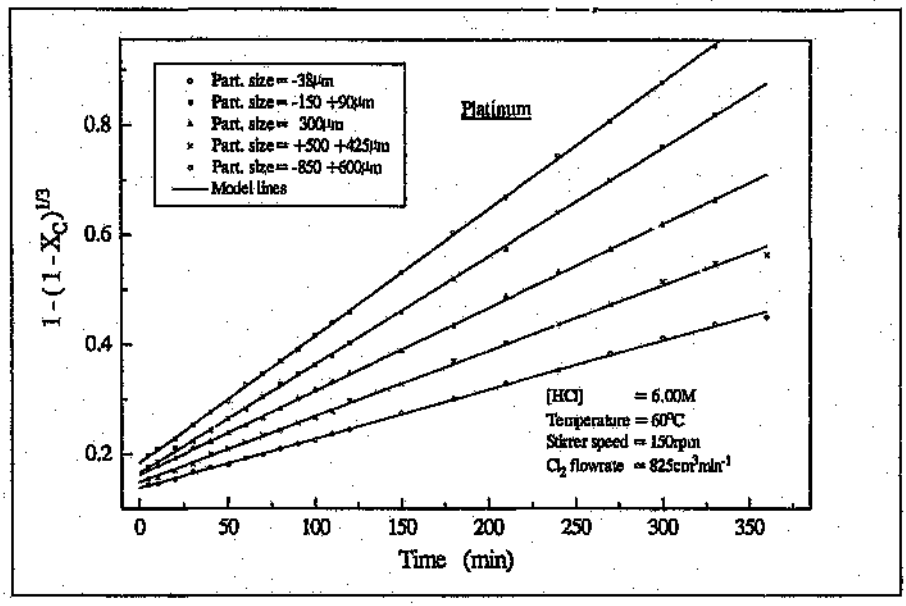


Fig. 5.36 Variation of the leaching rate with the initial particle size for Cl_2 soluble Pt.

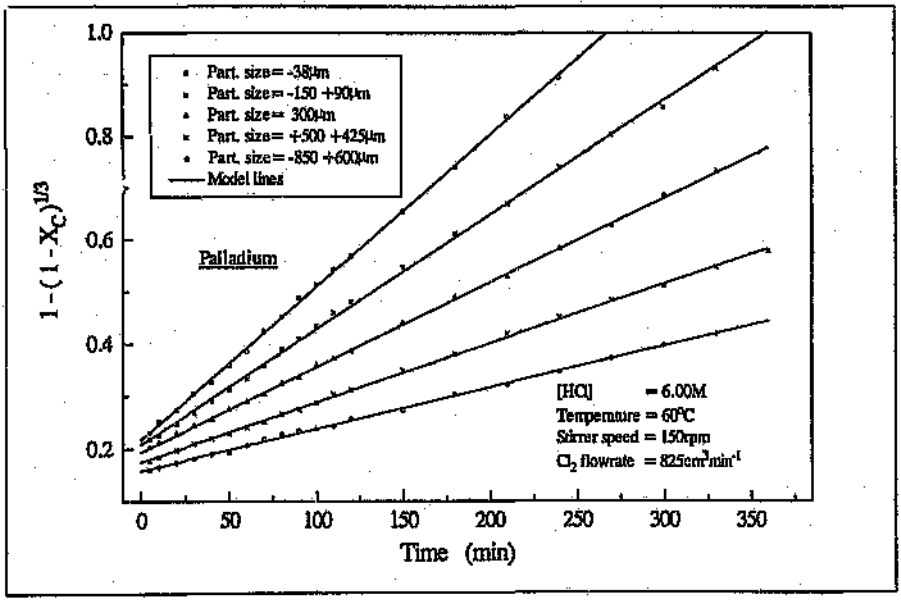


Fig. 5.37 Variation of the leaching rate with the initial particle size for Cl_2 soluble Pd.

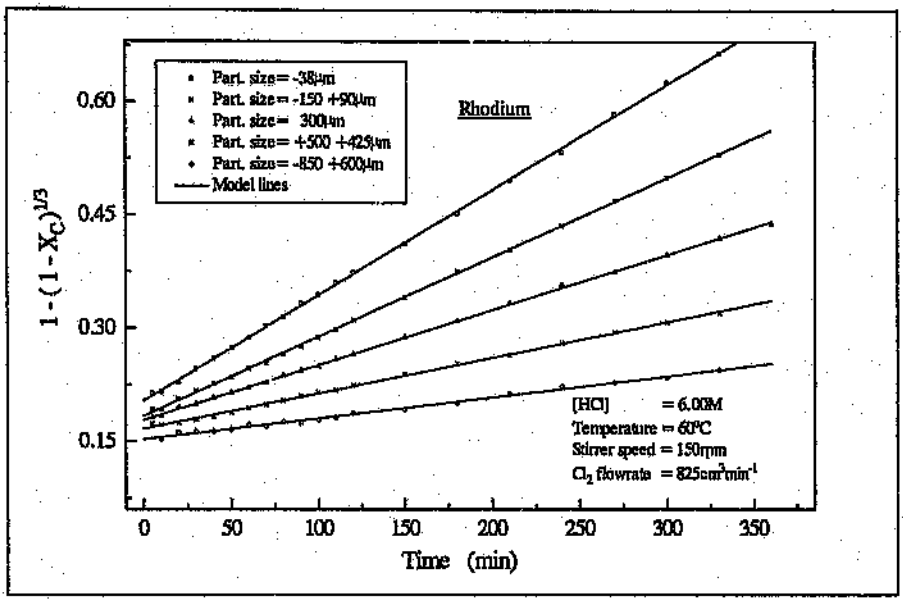


Fig. 5.38 Variation of the leaching rate with the initial particle size for Cl_2 soluble Rh.

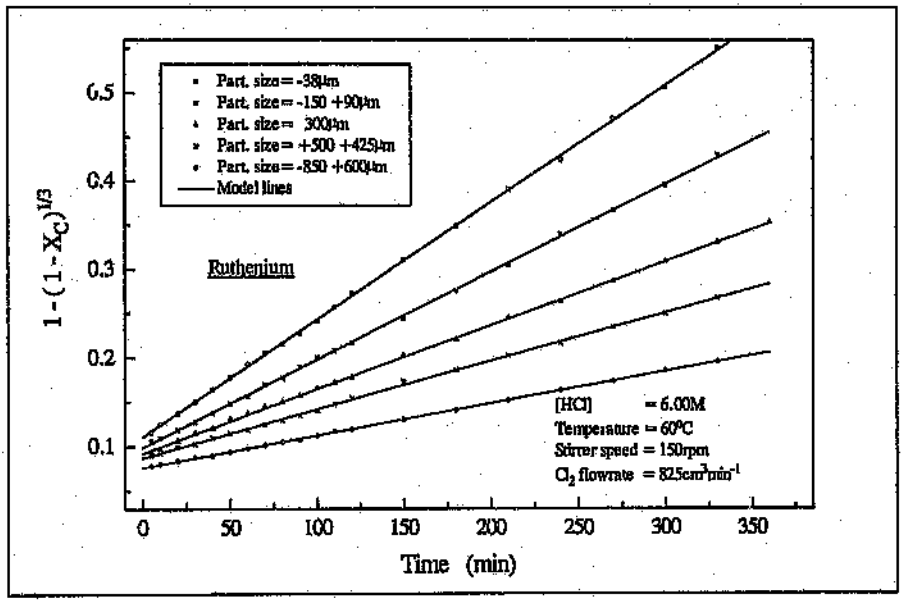


Fig.5.39 Variation of the leaching rate with the initial particle size for Cl_2 soluble Ru.

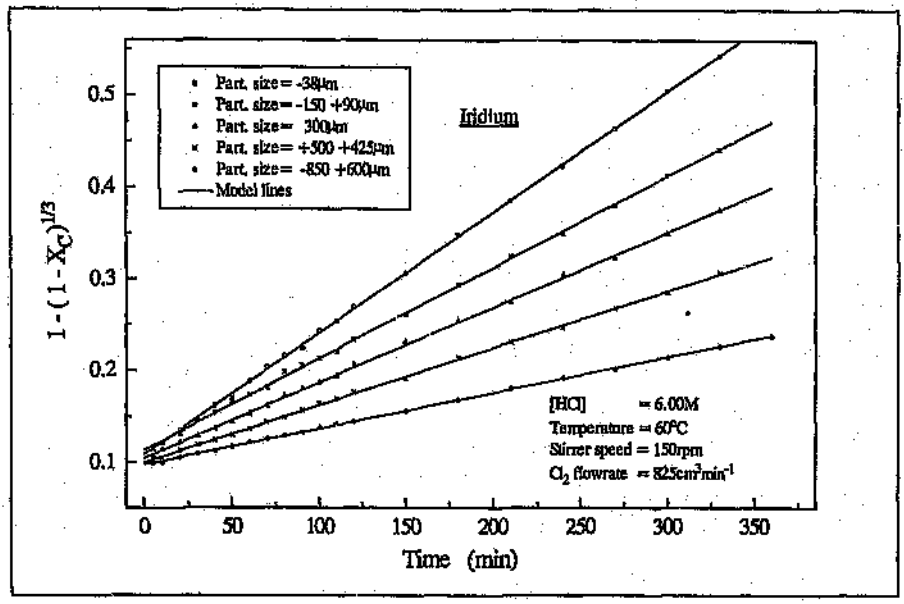


Fig. 5.40 Variation of the leaching rate with the initial particle size for Cl_2 soluble Ir.

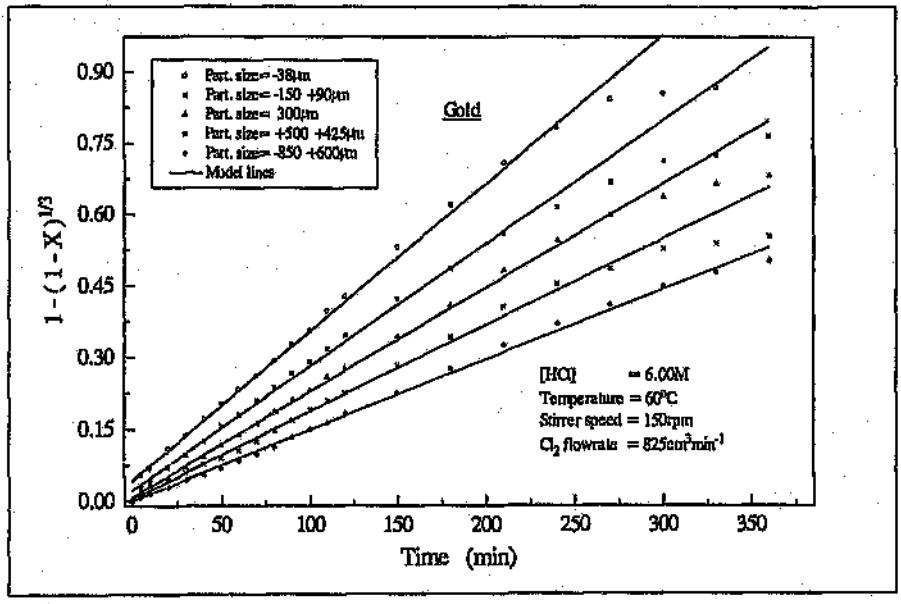


Fig. 5.41 Variation of the leaching rate with the initial particle size for the Gold.

are shown in Figures 5.36 to 5.41 for the chlorine soluble PGMs and gold. The apparent rate constants, k_s^+, determined from the gradients are plotted against the reciprocal of the initial particle diameter, d_o, and is presented as Figure 5.42.

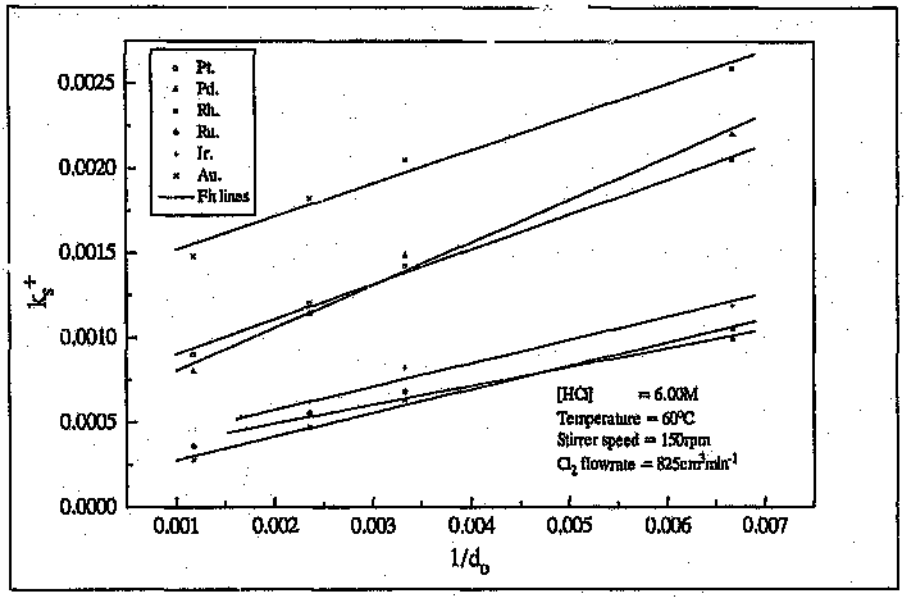


Fig. 5.42 A plot of the reaction rate constant versus the inverse of the initial particle diameter for the Chlorine soluble PGMs and the Au.

From the Figure 5.42, the correlation coefficients which express the linearity of the plots were determined by regression analysis. The -38 μm points were eliminated since they deviated from the trend. The correlation coefficients were found to be more than 0.98. This really implies a good linear fit. In view of the high values of correlation coefficient, it is reasonable to conclude that the chemical reaction control model at the surface of the particle gives a good representation of the chlorine soluble PGMs data. The linear relationship between the k_s^+ and $1/d_o$ again confirms that the proposed surface chemical reaction control of the shrinking particle model is indeed the rate limiting step in the PGMs dissolution process.

5.7 Analysis of Acid soluble PGMs to the Fit of the Shrinking particle Model

The results from the acid soluble PGM dissolution were also analysed with the chemical reaction control of the shrinking particle model expressed in equation 5.7. The rate model ($[1-(1-X_A)^{1/3}]$ vs t) plots for the individual acid-soluble platinum-group metals indicated that their dissolution depends on the leaching temperature, hydrochloric acid concentration and the particle size. There was negligible amount of acid soluble gold in the concentrate material.

(i) Dependence of Temperature on the dissolution of the Acid-soluble PGMs

The acid soluble PGMs results at different dissolution temperatures also satisfy the chemical reaction control of the shrinking particle model and were plotted as Figures 5.43 to 5.47. The values of the apparent rate constants, k_c, obtained from the gradients of the lines of fit of these rate model ($[1-(1-X_A)^{1/3}]$ vs t) plots were used to establish the Arrhenius plot for the acid soluble PGMs. This is presented in Figure 5.48. The regression analysis of all the rate model graphs together with the Arrhenius plot exhibited a good linear relationship with correlation coefficient of more than 0.98.

From Figure 5.48, the activation energies for the acid soluble PGMs were calculated. The activation energy of the acid soluble platinum was calculated to be 23.05 $kJmol^{-1}$, the acid soluble palladium was 19.59 $kJmol^{-1}$, rhodium was 23.82 $kJmol^{-1}$, ruthenium was 18.76 $kJmol^{-1}$ and iridium was calculated to be 18.22 $kJmol^{-1}$. The low activation energies for the acid soluble PGMs indicate that their dissolution is controlled by diffusion. The increase in the dissolution rates with temperature would be a result of the higher diffusion rates of the metals in the leaching solution at higher temperatures. The value of A_o which is the $\ln(k_c)$ intercept on the Arrhenius plot is analogous to the rate of diffusion (cm^2min^{-1}). This also supports the assumption that the acid solubles are oxides in the form of salts.

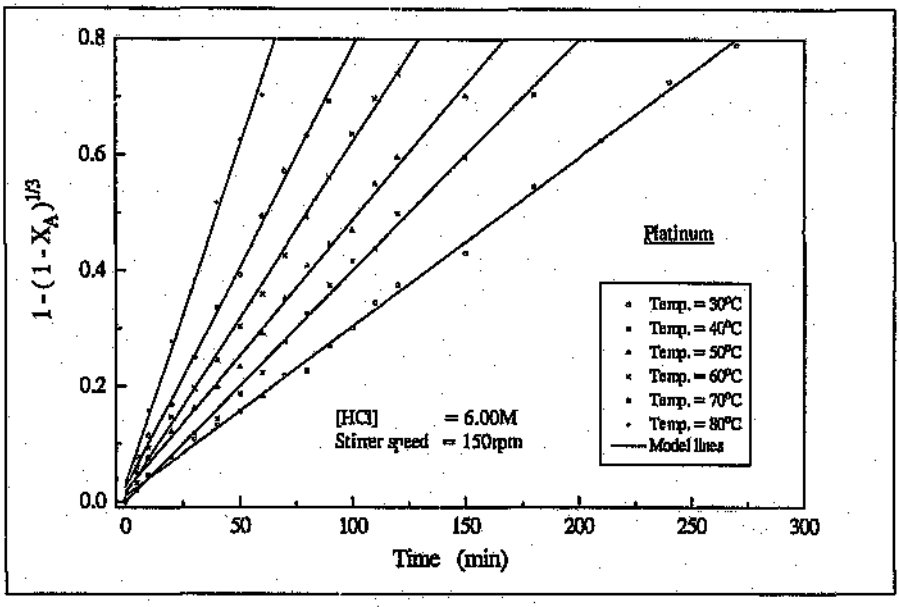


Fig. 5.43 Chemical reaction control model plot for the Acid soluble Pt. dissolution.

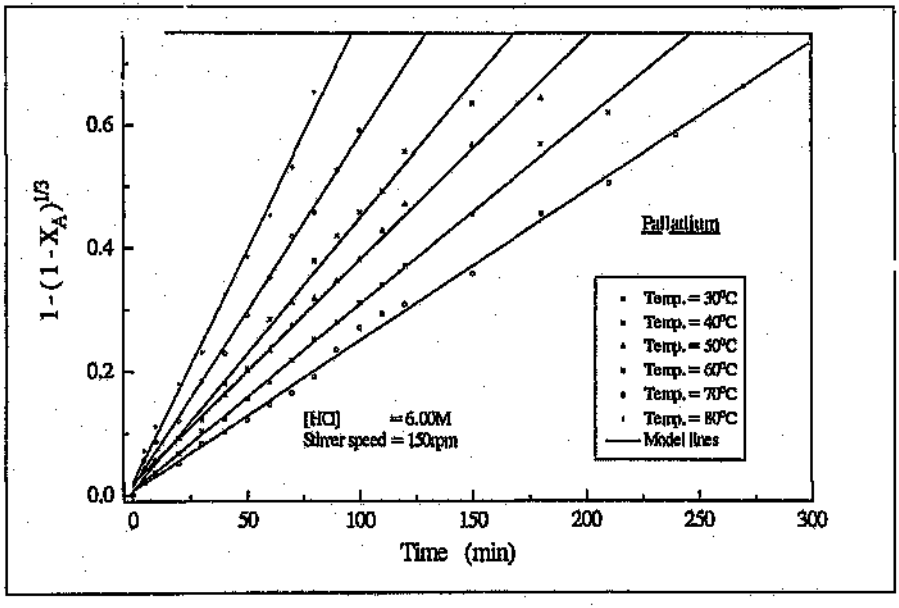


Fig. 5.44 Chemical reaction control model plot for the Acid soluble Pd. dissolution.

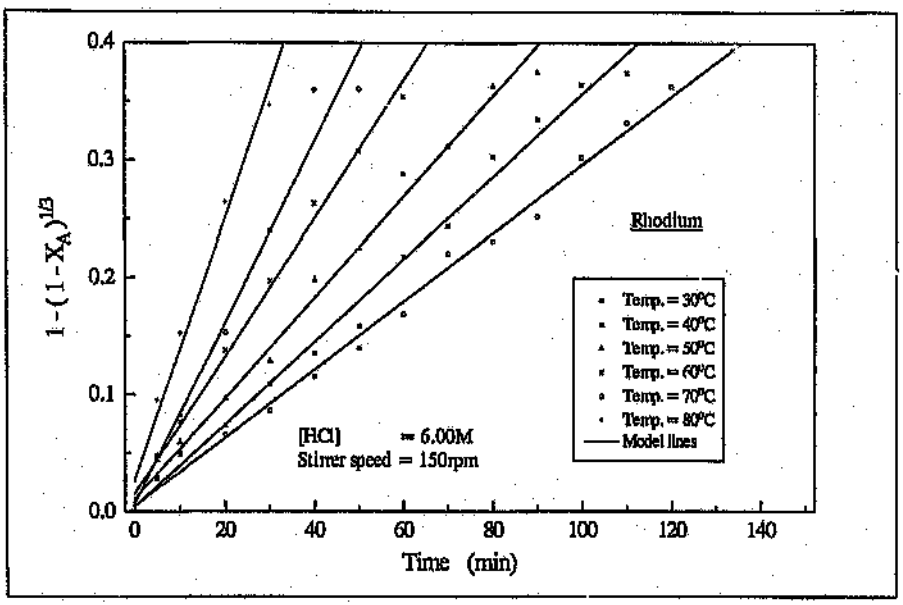


Fig. 5.45 Chemical reaction control model plot for the Acid soluble Rh. dissolution.

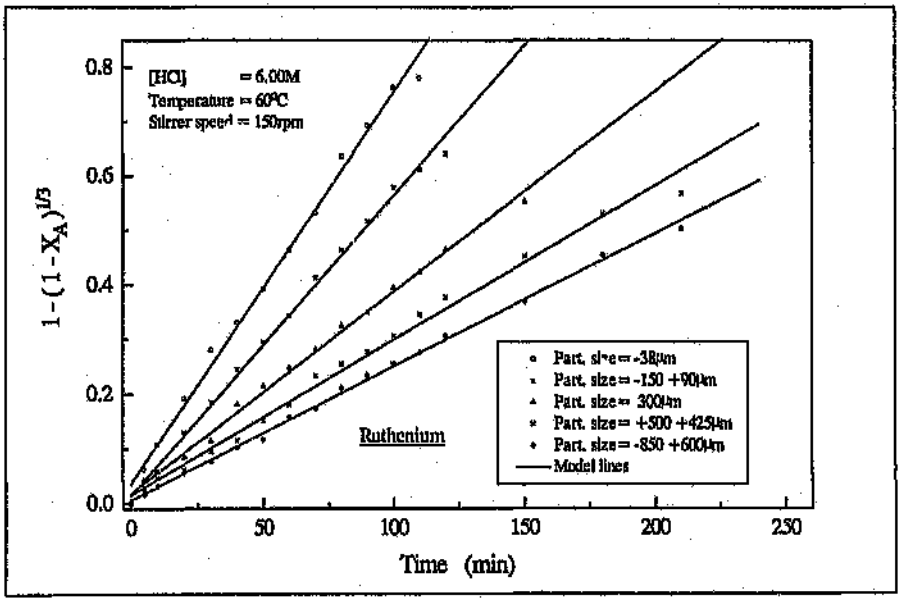


Fig. 5.46 Chemical reaction control model plot for the Acid soluble Ru. dissolution.

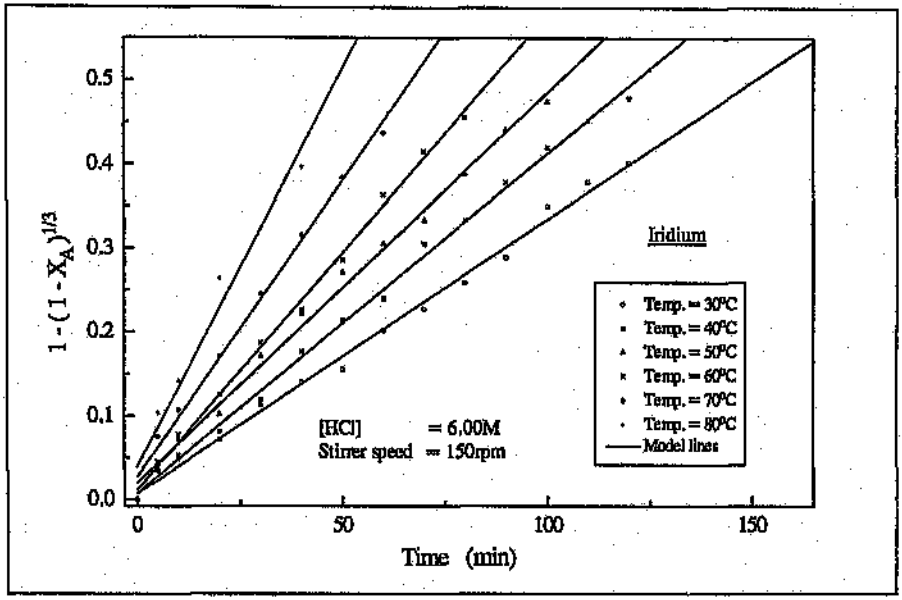


Fig. 5.47 Chemical reaction control model plot for the Acid soluble Ir. dissolution.

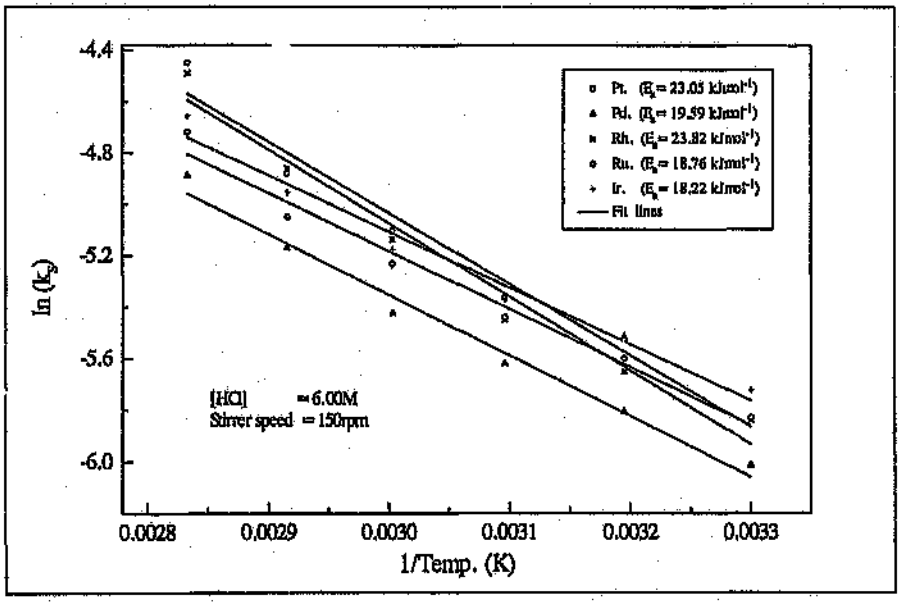


Fig. 5.48 Arrhenius plot for Acid soluble PGMs and Au dissolution in HCl/Cl_2 media.

(ii) Dependence of HCl conc. on dissolution of the Acid-soluble PGMs

The results obtained for the dissolution of the acid soluble PGMs under different hydrochloric acid concentrations were fitted into the surface chemical reaction control of the shrinking particle model expressed in equation 5.10. The model [1-(1-X_A) vs t] plots which are shown in Figures 5.49 to 5.53 are in good linear relationship for all the metals with a high correlation coefficient of more than 0.98. The apparent rate constants, k'_s were determined by regression analysis and a plot of ln(k'_s) against ln[HCl] were also established to determine the reaction orders of the acid soluble PGMs with respect to the hydrochloric acid concentration.

The reaction order of the acid soluble platinum was determined to be 0.56 with respect to the HCl concentration. The acid soluble palladium has an order of 0.58 with rhodium being 0.66 whereas ruthenium is 0.60. The order of reaction with respect to the HCl concentration for the acid soluble iridium is 0.56.

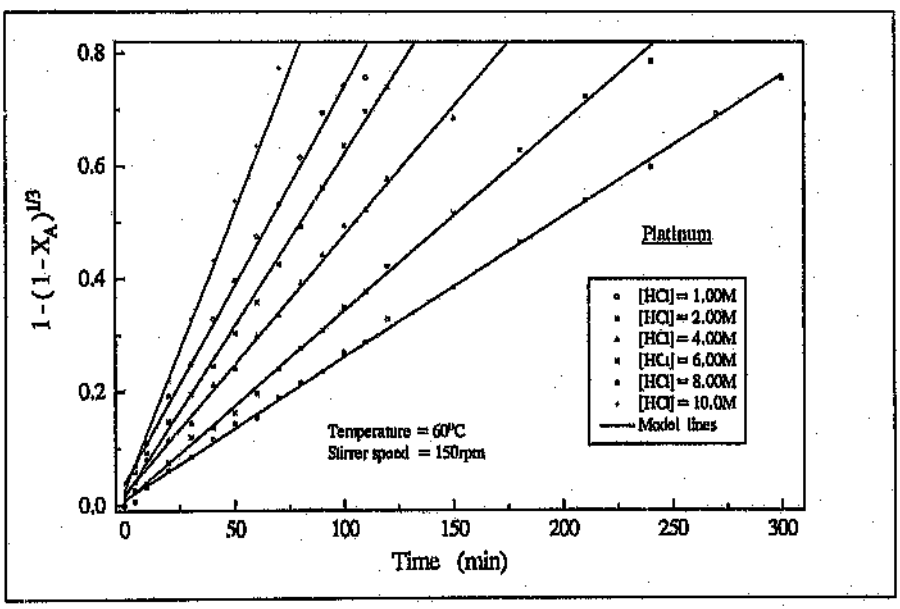


Fig. 5.49 Effect of HCl concentration on the Acid soluble P . dissolution rate.

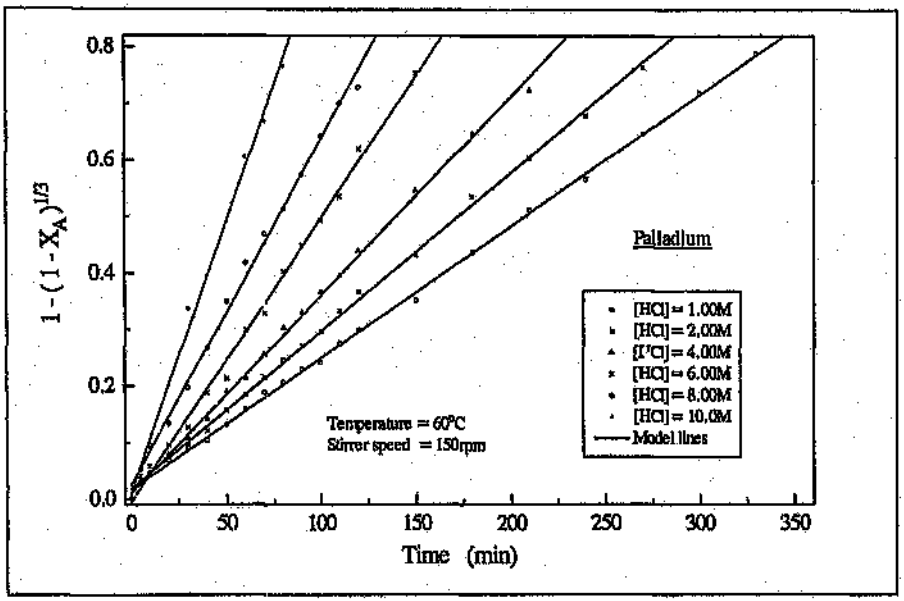


Fig. 5.50 Effect of HCl concentration on the Acid soluble Pd. dissolution rate.

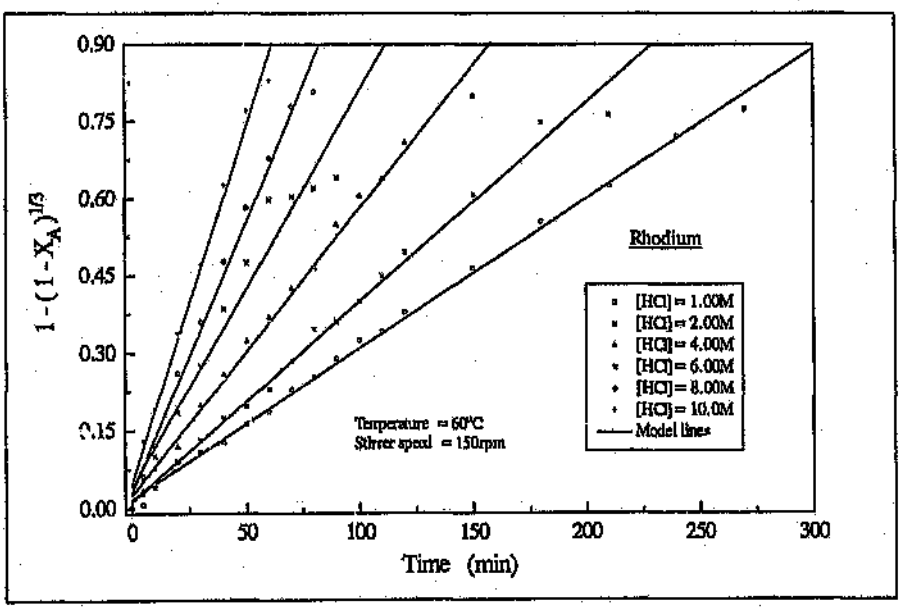


Fig. 5.51 Effect of HCl concentration on the Acid soluble Rh. dissolution rate.

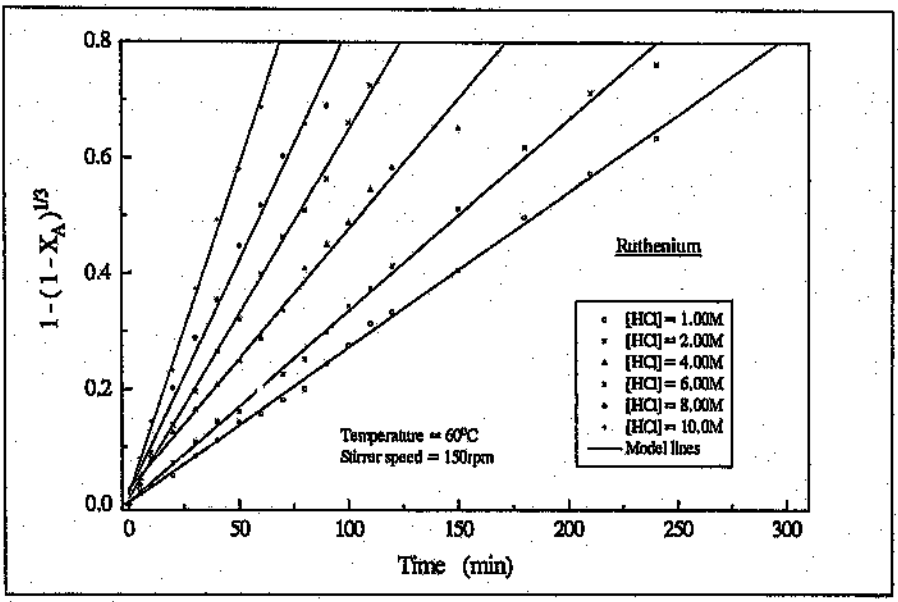


Fig. 5.52 Effect of HCl concentration on the Acid soluble Ru. dissolution rate.

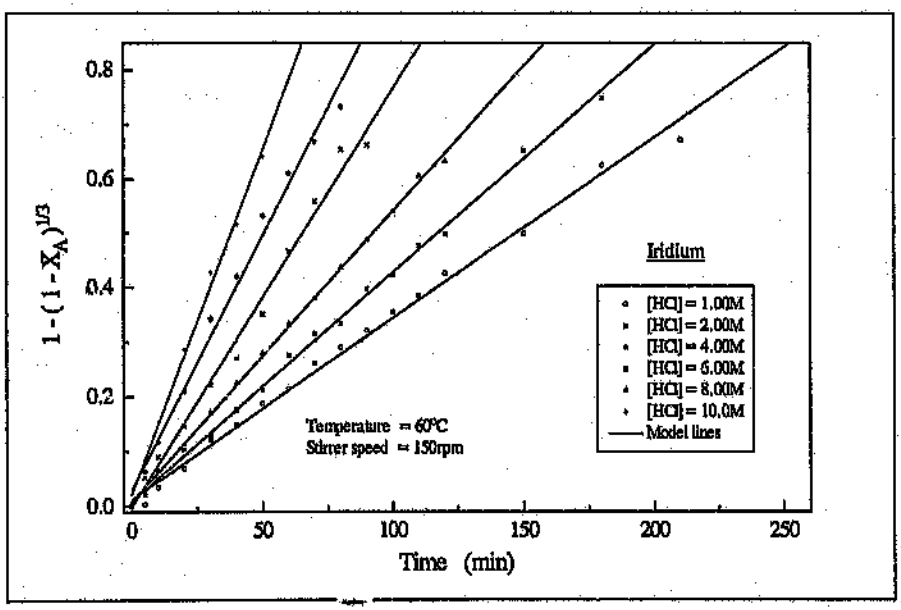


Fig. 5.53 Effect of HCl concentration on the Acid soluble Ir. dissolution rate.

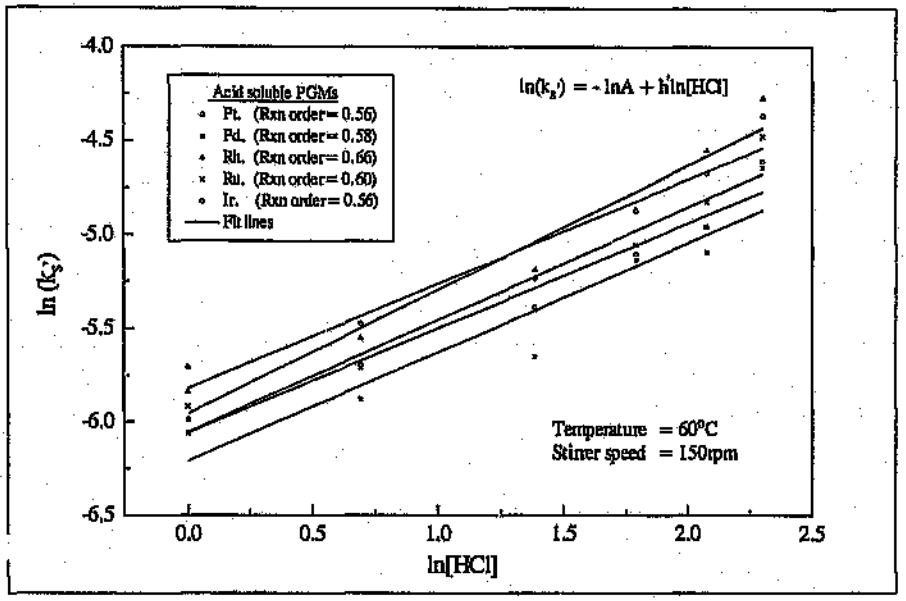


Fig. 5.54 Order of Reaction with respect to HCl conc. for the Acid soluble PGMs

(iii) Dependence of Initial Particle size on dissolution of Acid-soluble PGMs

The chemical reaction control of the shrinking particle model was also applied on the leaching data obtained for the effect of initial particle size on the rate of dissolution of the acid soluble PGMs. From the model rate equation 5.20, $1-(1-X_A)^{1/3}$ was plotted against t for the different initial particle sizes and the graphs for the individual platinum-group metals are presented as Figures 5.55 to 5.59. The apparent rate constants, k^+_s, determined from the gradients of the lines were plotted against the inverse of the initial particle diameter, d_o and is shown in Figure 5.60.

The linearity of the k^+_s and $1/d_o$ plots with high average correlation coefficients of 0.99 indicate a good relationship with the model. Therefore, it is concluded from the graphs that the proposed chemical reaction control of the shrinking particle model is really the rate determining step which also controls the dissolution of the acid soluble PGMs.

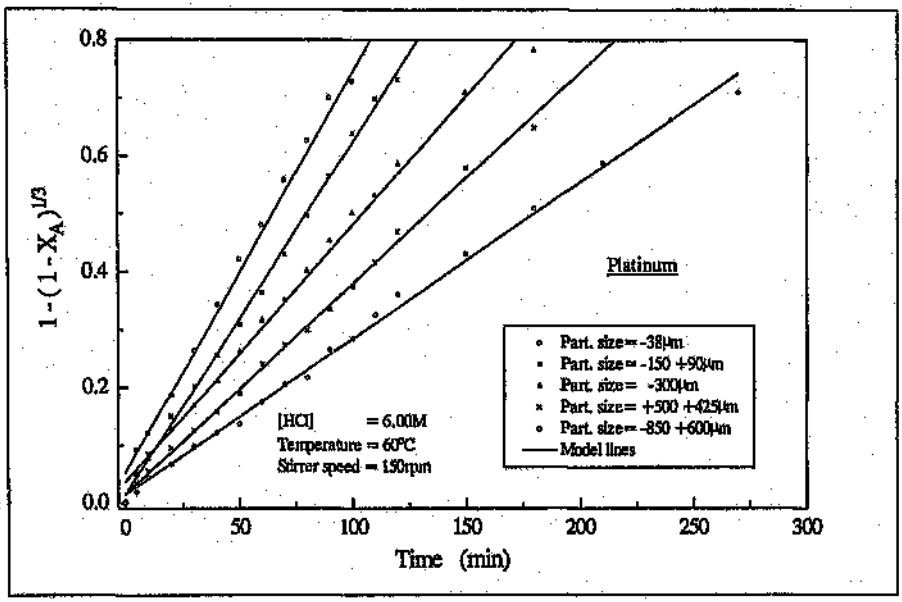


Fig. 5.55 Effect of initial particle size on dissolution rate for Acid soluble Platinum.

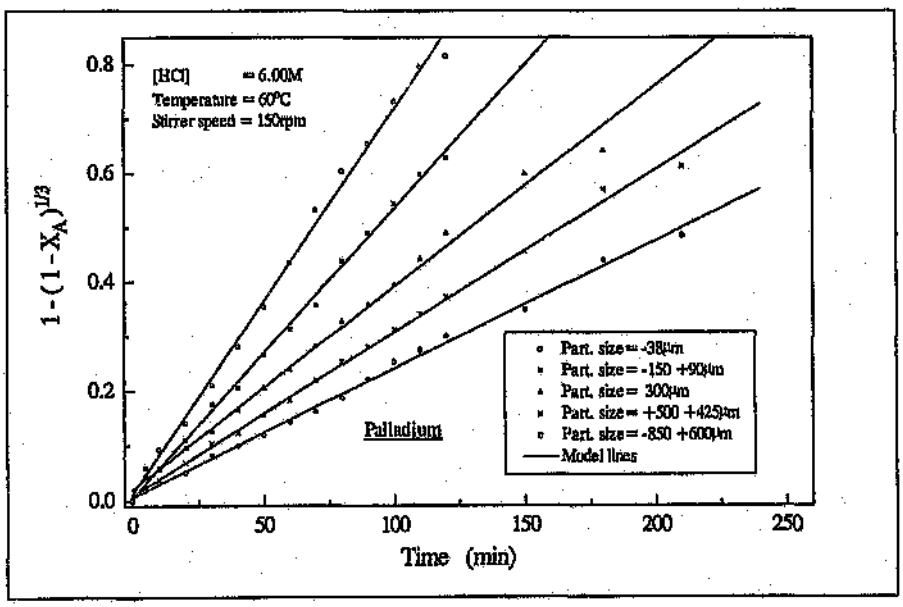


Fig. 5.56 Effect of initial particle size on dissolution rate for Acid soluble Palladium.

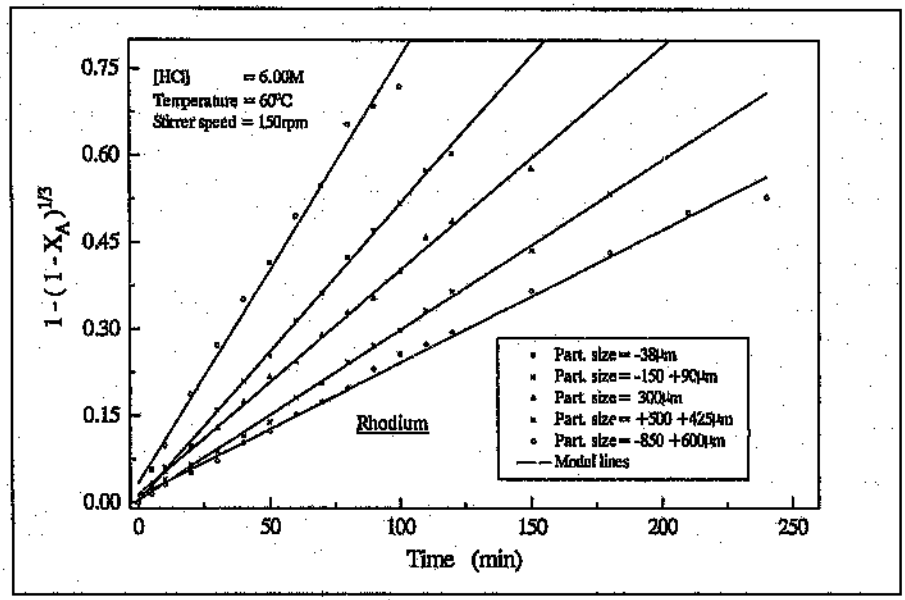


Fig. 5.57 Effect of initial particle size on dissolution rate for Acid soluble Rhodium.

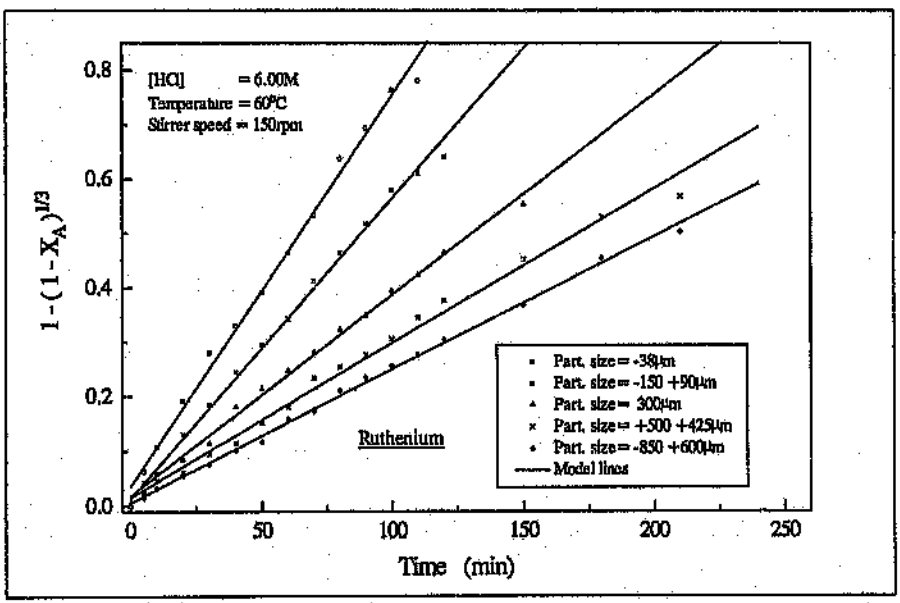


Fig. 5.58 Effect of initial particle size on dissolution rate for Acid soluble Ruthenium.

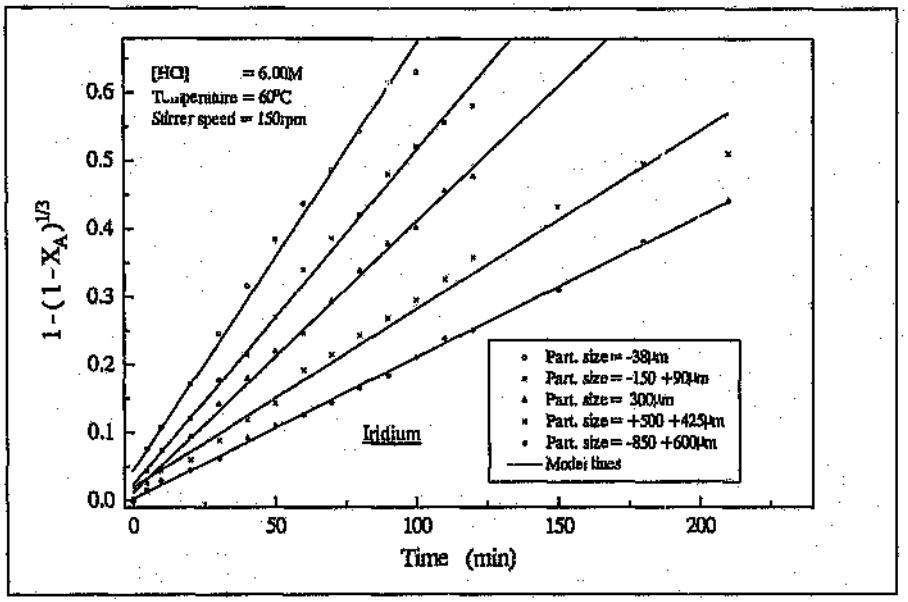


Fig. 5.59 Effect of initial particle size on dissolution rate for Acid soluble Iridium.

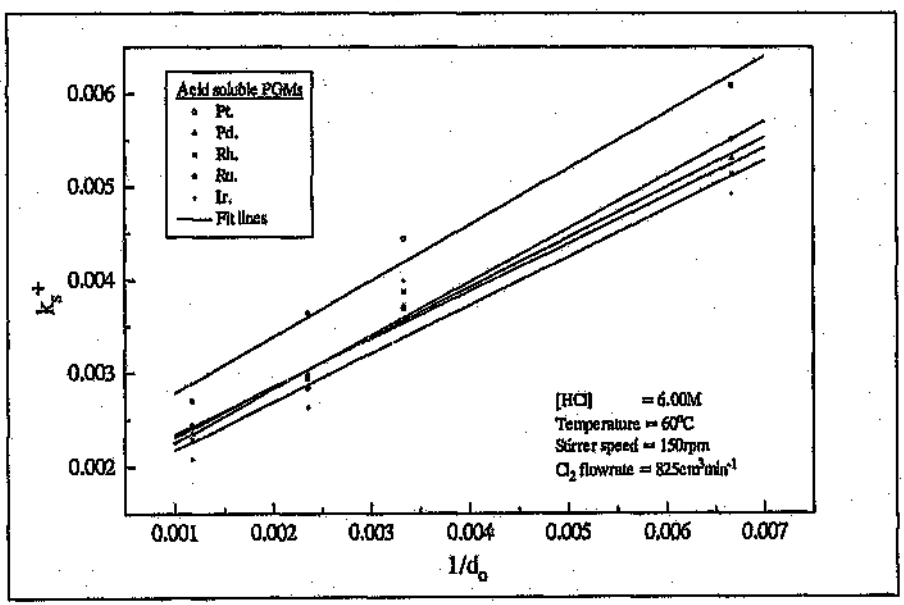


Fig. 5.60 A plot of the reaction rate constant versus $1/d_o$ for the Acid soluble PGMs.

5.8 Comparison between the Experimental Results and the Plant Tests Results for the Fit of the Proposed Models

The plant leach test which was conducted with a 6.00 M hydrochloric acid solution at 70°C and agitation speed of 140 rpm was compared with the laboratory test with the same experimental conditions. The leaching extractions of the plant and the laboratory tests were compared and their results are shown in Figures 5.61 and 5.62. The results

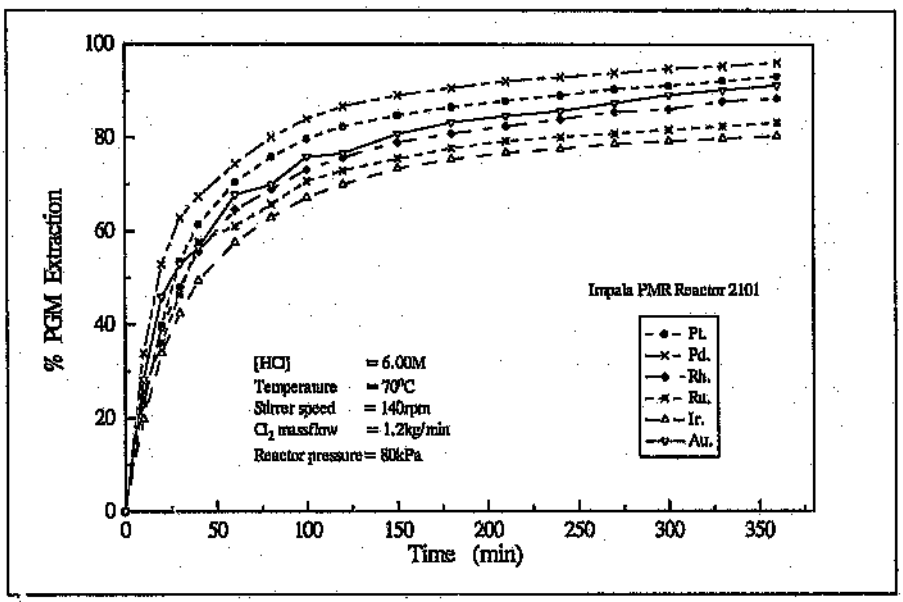


Fig. 5.61 PGM dissolution in 6.00 M HCl solution with the Impala Reactor 2101.

indicated that the bench scale experiments are in very good agreement with the results from the plant test. The extent of extraction of the PGMs in the bench scale experiment follows the same order as that in the plant, although the extractions achieved in the bench scale experiments are higher than those achieved in the plant as presented in Table 5.3. The laboratory test work has shown that the leaching of the platinum group metals with 6.00 M hydrochloric acid solution at 70°C and a stirrer speed of 150 rpm

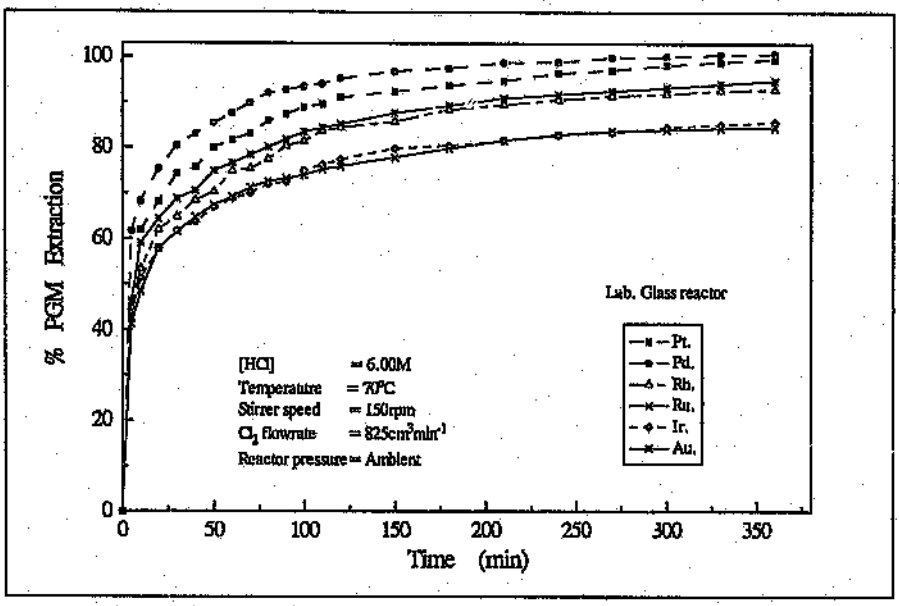


Fig. 5.62 PGM dissolution in 6.00 M HCl solution with the Laboratory reactor at ambient pressure.

achieved a good extraction from the concentrate.

Table 5.3 Comparison of the PGM dissolutions with the laboratory reactor and Impala plant reactor 2101.

Condition: *[HCl]= 6.00M, Temperature= 70°C, Agitation speed= 140 and 150 rpm*

6 hour PGM Dissolution in HCl	% Final Extraction					
	Pt	Pd	Rh	Ru	Ir	Au
Lab. Reactor dissolut. (*2-L Glass reactor*)	99.48	100.7	92.87	84.52	85.71	94.79
Impala Reactor dissol. (*1500-L Glass lined reactor*)	93.22	96.14	88.49	83.24	80.35	91.28

The improvement of the bench scale dissolution of the platinum group metals may be due to the fact that the solid-liquid ratio of 1:100 which was used for the laboratory

tests was far dilute as compared to about 1:4 used at the plant operations, therefore the consumption of chlorine in the laboratory reactor had minor effect on the rate of the PGMs dissolution. The higher dissolution at the bench scale may also come from the higher chlorine mass transfer coefficient obtained in the laboratory reactor, together with an increase in the stirrer speed of 150 rpm as compared to the 140 rpm used during the plant leach test.

The apparent decrease in ruthenium extraction in both reactors is possibly explained by the volatile nature of the ruthenium tetroxide during acid dissolution. It is therefore believed that some of the ruthenium is oxidised to the tetroxide form which then escape from the reactor. The sodium hydroxide scrubbers used during all the laboratory experiments were analysed for ruthenium and osmium. The concentrations of ruthenium and osmium in the six litre caustic solution used during the laboratory test run 21 was 18.60 ppm and 24.37 ppm respectively. From these concentrations, the mass of the ruthenium and osmium metals in the scrubbers are 0.112 g and 0.146 g respectively. Therefore, the mass balance for the ruthenium in this test is tabulated below.

Table 5.4 Ruthenium mass balance for the laboratory PGM leach test 21.

Condition: *[HCl]= 6.00M, Temperature= 60°C, Agitation speed= 80 rpm*

Metal	Mass in Sample (g)	Mass leached (g)	Mass escaped into NaOH (g)	Mass in residue (g)
Ru	1.02	0.720	0.112	0.289

The accountability of ruthenium in this particular leaching test is 98.90%. This implies that the total amount of ruthenium leached into solution and the residue is less than what was in the sample leached. Therefore, the difference is the amount of ruthenium escaped into the sodium hydroxide scrubber during the leaching.

5.9 Overall Leaching rate Model for the PGM dissolution.

The surface chemical reaction control of the shrinking particle model which was proposed in Chapter 2 as the probable leaching kinetic rate model to describe the dissolution of the PGMs in the various concentrations of hydrochloric acid solution at different chlorine concentrations and temperatures were successfully applied on the leaching results. From the results of the rate model [$1-(1-X)^{1/3}=k_s t$] plots above, the order of reactions with respect to HCl and chlorine concentrations together with the activation energies for the individual PGMs and gold were obtained to establish the overall leaching kinetic equations which is written as

$$1-(1-X)^{1/3} = k_o d_o^{-1}[HCl]^{0.70}[Cl_2]^{0.49}\exp\left[\frac{-42360}{RT}\right]t \qquad 5.21$$

for platinum. The final leaching rate expressions for both the chlorine soluble PGMs and the acid soluble PGM fractions and the total gold are presented in the Tables 6.3 and 6.4 of Chapter 6.

The overall rate constant, k_o, in the rate model equation 5.21 can be calculated from the relationship that exists between the apparent rate constants, k_s, and the various experimental parameters that affect the dissolution of the platinum group metals which is shown by the following function:

$$k_s = k_o d_o^{-1}[HCl]^a[Cl_2]^b\exp\left[-E_a/RT\right] \qquad 5.22$$

Now, from equation 5.22, a plot of k_s against $\{ d_o^{-1}[HCl]^a[Cl_2]^b\exp[-E_a/RT] \}$ for all the parameters produces a straight line expected from the origin. The graph of this relation is shown as Figure 5.63 for the chlorine soluble platinum. The average rate constant, k_o, value from the temperature, HCl and chlorine concentration lines were taken for all the metals. The k_o values obtained from the particle size lines were discarded since they differ from the rest. The value of the rate constant, k_o, for the chlorine soluble platinum

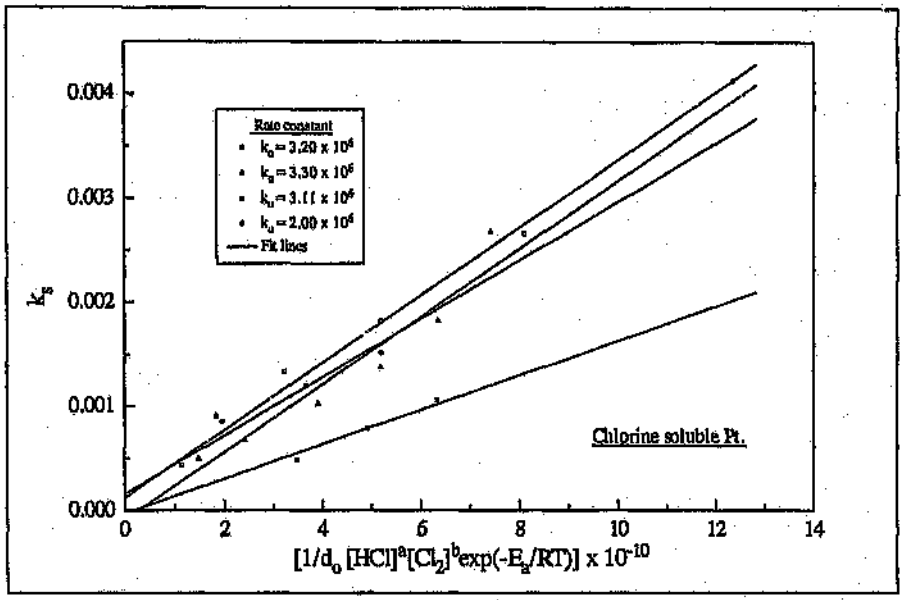


Fig. 5.63 Determination of the overall rate constant, k_o, for the chlorine soluble Pt.

is 3.20 x 10^6 min^{-1} and the average k_o values for the rest of the chlorine soluble PGMs, the acid soluble PGMs and gold are given in the Table 5.5 below. These rate constants are put in the overall rate model equations presented in the conclusion of this work.

Table 5.5 Values of k_o for the Chlorine soluble and Acid soluble PGMs and gold.

Platinum-Group Metals	Values of the Overall rate constants, k_o	
	Chlorine soluble PGM (min^{-1})	Acid soluble PGM (min^{-1})
Pt.	3.20×10^6	2.96×10^3
Pd.	4.15×10^6	7.20×10^2
Rh.	1.30×10^7	3.73×10^3
Ru.	2.90×10^7	5.65×10^2
Ir.	2.30×10^7	5.65×10^2
Au.	1.80×10^6	-

5.10 Combined Model for the Plant Reactor

The surface chemical reaction control of the shrinking particle model used to describe all the laboratory dissolution of the chlorine soluble and the acid soluble PGM fractions were combined with the energy balance and the chlorine mass balance from the plant reactor to generate a scale-up overall leaching model for the plant. The plant reactor modelling exercise involved in assembling differential rate equations and solving them.

The energy balance equation used in this plant reactor modelling expression is

$$\frac{dT}{dt} = \frac{\left[U_{ht}A\left(T_{steam} - T\right) + \sum_i \Delta H_{R_i}\frac{dX_i}{dt}(initial \cdot moles)\right]}{\sum_i N_i C_{p_i}} \qquad 5.23$$

where

T_{steam} = Temperature of the steam,

T = Temperature at time t,

ΔH_{Ri} = Heat of reaction of the i^{th} reaction,

X_i = Conversion of the PGE from the i^{th} reaction,

and the rest of the symbols have their usual meanings explained at the Nomenclature.

$\sum_i \Delta H_{R_i}\frac{dX_i}{dt}(initial\ moles)$ is the heat generated by the reactions.

The chlorine mass balance equation applied in this modelling is expressed as follows

$$\frac{dCl_2}{dt} = k_{la}A\left(Cl_{2(Sat)} - Cl_2\right) + \sum_i \upsilon_i \frac{dX_i}{dt}(initial\ moles) \qquad 5.24$$

where

k_{la} = Chlorine mass transfer coefficient,

υ_i = Stoichiometric coefficient, and

$\sum_i \upsilon_i \frac{dX_i}{dt}(initial\ moles)$ is the amount of chlorine consumed by the reaction. The meaning of the rest of the symbols are explained at the Nomenclature.

The differential equation of the shrinking particle model applied on the chlorine soluble PGM fractions used for the C++ computer program on the plant model is expressed as

$$\frac{dX_C}{dt} = 3k_{s,C}(1 - X_C)^{2/3} \qquad 5.25$$

which becomes $1-(1-X_C)^{1/3}=k_{s,C}t$ after integration. The same equation was applied for the acid soluble PGMs, where X_C is changed to X_A and $X=f_CX_C+(1-f_C)X_A$.

The data obtained for the dissolution of the PGM concentrate leached in the Impala plant reactor was modelled to generate an overall expression to describe the kinetics and mechanism of the leaching. The energy balance and the chlorine mass balance results were automatically put in the C++ computer program written by Frank Crundwell to solve the 14 differential equations for the development of the overall leaching model for the Impala plant reactor. All these equations are incorporated in the C++ computer program shown in the Appendix E.

In the computer program, a distinction is made between the sub-models that compute the energy balance, the chlorine mass balance and the rate of conversion of the platinum-group metals from both the chlorine soluble PGM and acid soluble PGM fractions. The known values from the Impala plant testwork are supplied to the C++ computer program which runs the data through the differential equations and the combine model to provide the final output of the total extractions for the platinum group metals in the plant reactor. This combined model computes the total extractions of the individual PGMs, the temperature profile and the chlorine concentrations during the leaching process as a function of time for the plant batch process.

The data obtained during the Impala refinery plant tests were used to run the model of the computer program named **Yaw cpp** and the output is presented below. The graph for the conversion of all the PGMs and gold from the output of the computer program is shown as Figure 5.64 and is compared with the plant leach test.

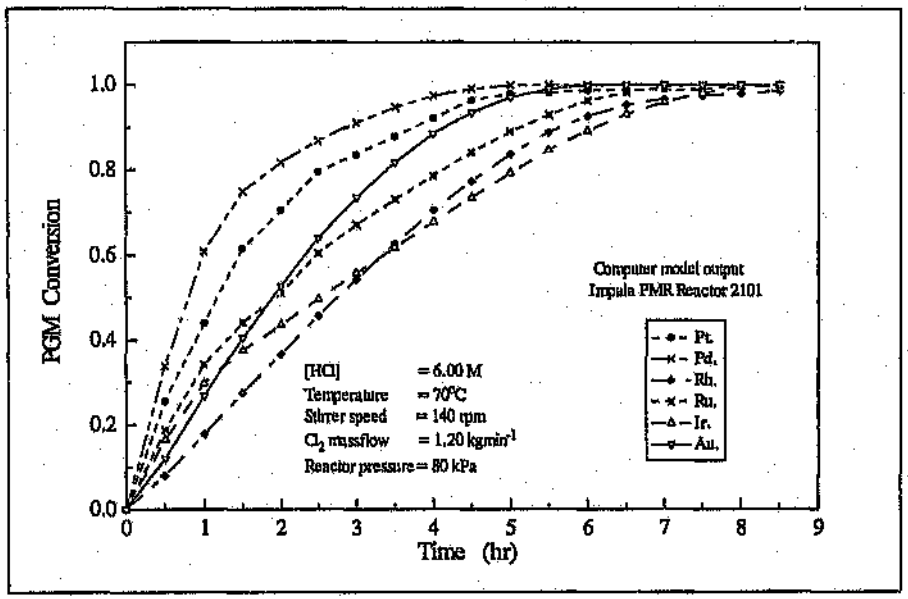


Fig. 5.64 A Plot of the PGMs conversion from the computer program output for the Impala plant test results.

The C++ computer program results for the conversion of the PGMs and gold for the Impala plant leach as shown in Figure 5.64 is compared with the results obtained from the actual Impala plant leach test which is also shown in Figure 5.61 to check the overall computer model. The results were almost the same for all the platinum group metals and gold. This proves that the C++ computer model developed from this work for the PGMs dissolution in the Impala plant reactor is good for the implementation on the industrial level. This model scaled up the laboratory test to the industrial scale which can be used to estimate the PGMs conversions during the plant leach by supplying the necessary initial leach data.

YAW ASAMOAH-BEKOE

* PGM Chlorine Leach *

by F. K. Crundwell

University of the Witwatersrand, Johannesburg

Program solves 14 differential equations for the leaching reactions, the energy balance and the chlorine mass balance.

Press the ENTER key

OUTPUT

Hours	Temp	Pt	Pd	Rh	Ru	Ir	Au	Base	Cl2
0	32	0	0	0	0	0	0	0	0
0.5	80.929	0.255	0.338	0.08	0.187	0.165	0.12	0.05	0.008
1	81.028	0.44	0.608	0.178	0.341	0.297	0.268	0.117	0.009
1.5	80.12	0.515	0.749	0.274	0.431	0.375	0.405	0.184	0.009
2	80.192	0.555	0.817	0.366	0.492	0.435	0.527	0.25	0.011
2.5	80.162	0.595	0.868	0.457	0.552	0.496	0.639	0.317	0.012
3	80.788	0.636	0.911	0.543	0.611	0.557	0.735	0.382	0.014
3.5	81.324	0.678	0.947	0.626	0.671	0.617	0.817	0.446	0.016
4	80.487	0.722	0.974	0.704	0.73	0.678	0.885	0.511	0.018
4.5	81.576	0.764	0.991	0.773	0.786	0.735	0.935	0.573	0.022
5	82.29	0.808	0.999	0.837	0.841	0.793	0.971	0.636	0.024
5.5	80.976	0.851	1	0.889	0.89	0.847	0.991	0.696	0.028
6	80.161	0.888	1	0.927	0.93	0.892	0.999	0.751	0.031
6.5	80.961	0.923	1	0.954	0.963	0.932	1	0.803	0.033
7	81.075	0.949	1	0.968	0.983	0.96	1	0.846	0.039
7.5	85.978	0.972	1	0.976	0.996	0.982	1	0.888	0.041
8	84.172	0.988	1	0.981	1	0.995	1	0.925	0.044
8.5	82.612	0.996	1	0.986	1	0.999	1	0.95	0.048

Press the ENTER key

CHAPTER 6

6.0 CONCLUSION AND RECOMMENDATIONS

In this chapter a summary of all the conclusions made in this project is given. Recommendations are also made for industrial implementation which may be beneficial for the optimum control strategy of the primary PGM leach. Further study in this field is recommended to look at the electrochemical aspect of the PGMs dissolution in detail to give a broader spectrum to this research.

6.1 Conclusion

The studies on the chemical and mineralogical effects on the dissolution of the Impala PGM concentrate have developed the ability to manipulate the factors that affect leaching and the conditions used in this project for the benefit of improving the plant recovery. From the analysis of the results of this investigation, the following conclusions can be drawn.

1. The SEM photomicrographs indicated the presence of silver chloride in the residue. Therefore, there is a likelihood that the silver chloride precipitate formed in the reactor during the leaching may coats the PGM particles and passivates them to prevent their total dissolution in the hydrochloric acid solution with chlorine.

2. The chlorine concentration in the PGM leach solution can be calculated from an equation similar to the Nernst equation with the relationship between the chlorine concentration and the redox potential of the solution.

3. The dissolution of PGMs in the concentrate sample in HCl solution without chlorine or any oxidant revealed the presence of acid soluble PGM fractions which do not require chlorine or any form of oxidant to dissolve them. The results are shown in

Table 6.1. the results indicated that there were no acid soluble gold in the concentrate material. It was also shown that when the acid soluble PGMs extraction is subtracted from the total PGMs extraction, the resulting value is the extraction of the chlorine soluble PGMs.

Table 6.1 Comparison of the dissolution of the PGMs with and without chlorine

Condition: *[HCl]= 6.00M, Temperature= 60°C, Agitation speed= 150rpm*

6 hour PGM Dissolution in HCl	% Final Extraction					
	Pt	Pd	Rh	Ru	Ir	Au
No Cl_2 dissolution (*Acid soluble PGMs*)	40.36	56.58	23.60	26.88	20.74	0.79
With Cl_2 dissolution (*Total PGMs in Sample*)	98.48	99.82	90.34	82.15	81.07	93.57

4. The dissolution of the platinum-group metals and gold is electrochemical in nature. Therefore, the dissolution of PGMs can be modelled by a shrinking particle model and electrochemical rate expression could also be considered.

5. The use of the various kinetic models of the shrinking-particle to analyse the PGMs dissolution results made it clear that the concentrate material was so porous that the diffusion through the material pores had no effect on the rate of dissolution. This supported the assumption that the dissolution process leaves no product layer after the reaction. The chlorine dissolution rate in the HCl solution was quite fast so the leach solutions were saturated with chlorine before the concentrate samples were added so the reactants diffusion through the leach solution never controlled the reaction rate.

6. The results obtained by the application of the kinetic models indicated that the rate of dissolution is controlled by the chemical reaction of the shrinking particle model. Therefore, this PGMs leaching investigation explained that the reacting chloride solution penetrates through the silica matrix of the material to the reacting PGM surface for a chemical reaction to take place.

7. The dissolution data for the chlorine soluble PGM fractions fit the surface chemical reaction control of the shrinking particle model very well with a non-zero intercept which is equal to the final dissolution rate of the acid soluble PGMs. This is confirmed by the dissolution results for the acid soluble PGM fractions also obeying the applied shrinking particle model from the origin of the plots.

8. It is concluded from the results that platinum, palladium, and gold in the concentrate material can be completely dissolved in the HCl/Cl_2 media under a controlled condition with a good redox potential value. The redox potential of the leach solution plays a major role in the PGM dissolution process. The rate of chemical reaction of the PGM dissolution increases with an increase in the solution redox potential and must be more than 1000 mV (vs Ag/AgCl) to maintain a good chlorine concentration in the reactor to ensure their total dissolution. In view of this, a total PGM dissolution was achieved for most of the metals by reducing the particle size below 38 μm with a temperature of 80°C at a stirrer speed of 450 rpm.

9. The activation energy for the chlorine dissolution in 11.50 M hydrochloric acid solution was found to be 16.34 $kJmol^{-1}$. The values for the 6.00 M HCl was calculated to be 24.38 $kJmol^{-1}$ and 26.71 $kJmol^{-1}$ was obtained for the 2.00 M. This shows that the activation energy for the dissolution increases with reduction in the acid concentration.

10. The dissolution rates of the PGMs were significantly dependant on the temperature. The values of the activation energy for the chlorine soluble PGMs and gold calculated from the reaction rate constants supported the fact that chemical reaction mechanism is the rate-limiting step throughout the leaching process. The low activation energies obtained for the acid soluble PGMs indicated that their dissolution is controlled by diffusion of the metal ions in the leach solution. All the activation energies are presented in Table 6.2.

11. The results of this investigation have shown that the rate of dissolution of the

PGMs and gold is dependent on the initial concentration of the hydrochloric acid solution. The concentration of chlorine gas in the leach solution also has a great influence on the rate of PGMs dissolution. The PGMs order of reactions with respect to the concentration of HCl and that of chlorine are summarised in Table 6.2 below.

Table 6.2 A summary of activation energies, the order of reactions with respect to HCl and Cl_2 concentrations for the PGMs fractions and gold.

Platinum-Group Metals	Based on the Chlorine soluble PGM Extraction		
	Activation Energy ($kJmol^{-1}$)	Order of Reaction with respect to [HCl]	Order of reaction with respect to [Cl_2]
Pt.	42.36	0.70	0.49
Pd.	40.19	0.94	0.78
Rh.	44.56	0.81	0.77
Ru.	46.62	0.68	0.79
Ir.	47.60	0.75	0.71
Au.	40.44	0.76	0.50
PGMs	Based on the Acid soluble PGM Extraction		
Pt.	23.05	0.56	-
Pd.	19.59	0.58	-
Rh.	23.82	0.66	-
Ru.	18.76	0.60	-
Ir.	18.22	0.56	-

12. The dissolution rate for all the PGMs were increased by reducing the initial particle size of the concentrate sample. The smaller particles of below 38 μm dissolved much faster than the large particle sizes. The linear relationship between the rate constant, k_s^+ and the inverse initial particle diameter was also observed.

13. The rates of PGM dissolution at stirrer speed above 300 rpm are independent of the agitation. Therefore, agitation speed had no remarkable effect on the rate of the

PGM dissolution if all the particles are in suspension. The effect experienced with the change of agitation speed is to lift all the particles into suspension. It was observed that all the particles are kept in suspension with the agitation speed of above 300 rpm.

14. The overall leaching rate expressions developed from this work for both the chlorine soluble and acid soluble PGM fractions are given in Tables 6.3 and 6.4 below.

Table 6.3 Summary of the leaching rate expressions for the Cl_2 soluble PGMs and Au

Platinum-Gr. Metals	Based on the Chlorine soluble PGM Extractions	
	Act. Energy ($kJmol^{-1}$)	General Rate equation for the leaching $r=k_o d_o^{-1}[HCl]^a[Cl_2]^b\exp(-E_a/RT)$
Pt.	42.36	$1-(1-X_C)^{1/3}=3.20\times10^6 d_o^{-1}[HCl]^{0.70}[Cl_2]^{0.49}\exp(-42.36/RT)t$
Pd.	40.19	$1-(1-X_C)^{1/3}=4.15\times10^6 d_o^{-1}[HCl]^{0.94}[Cl_2]^{0.78}\exp(-40.19/RT)t$
Rh.	44.56	$1-(1-X_C)^{1/3}=1.30\times10^7 d_o^{-1}[HCl]^{0.81}[Cl_2]^{0.77}\exp(-44.56/RT)t$
Ru.	46.62	$1-(1-X_C)^{1/3}=2.90\times10^7 d_o^{-1}[HCl]^{0.68}[Cl_2]^{0.79}\exp(-46.62/RT)t$
Ir.	47.60	$1-(1-X_C)^{1/3}=2.30\times10^7 d_o^{-1}[HCl]^{0.73}[Cl_2]^{0.71}\exp(-47.60/RT)t$
Au.	40.44	$1-(1-X)^{1/3}=1.80\times10^6 d_o^{-1}[HCl]^{0.76}[Cl_2]^{0.50}\exp(-40.44/RT)t$

Table 6.4 A summary of the leaching rate expressions for the Acid soluble PGMs.

Platinum-Gr. Metals	Based on the Acid soluble PGM Extraction	
	Activation Ener. ($kJmol^{-1}$)	General Rate equation for the leaching $r=k_o d_o^{-1}[HCl]^a\exp(-E_a/RT)$
Pt.	23.05	$1-(1-X_A)^{1/3}=2.96\times10^3 d_o^{-1}[HCl]^{0.56}\exp(-23.05/RT)t$
Pd.	19.59	$1-(1-X_A)^{1/3}=7.20\times10^2 d_o^{-1}[HCl]^{0.58}\exp(-19.59/RT)t$
Rh.	23.82	$1-(1-X_A)^{1/3}=3.73\times10^3 d_o^{-1}[HCl]^{0.66}\exp(-23.82/RT)t$
Ru.	18.76	$1-(1-X_A)^{1/3}=5.65\times10^2 d_o^{-1}[HCl]^{0.60}\exp(-18.76/RT)t$
Ir.	18.22	$1-(1-X_A)^{1/3}=5.65\times10^2 d_o^{-1}[HCl]^{0.56}\exp(-18.22/RT)t$

The shrinking particle model which combined the activation energies of the metals predicted the leaching rates for all the individual PGMs in this Impala concentrate.

15. The C++ computer program developed to run the overall platinum group metals conversion model from the energy balance and chlorine mass balance of the plant reactor as shown in section 5.10 was successfully done to scale up the laboratory test results to the plant level. The output obtained from the computer run was in agreement with the actual plant results. This is a good leach model which can be used at the industrial level to predict the extraction of the PGMs from the initial data from the reactor and the reactants. The Impala plant operators can also apply this model to check the dissolution efficiencies of the PGMs.

6.2 Recommendation

1. The possibility of the PGMs leaching kinetics being modelled with an electrochemical rate expression cannot be ruled out on the basis of this project. It is therefore recommended that platinum-group elements electrodes be designed to give a true account of the surface potential of the PGMs in the ore and also to investigate the electrochemical aspect of the dissolution that this research could not touch.

2. The effect of galvanic interactions or charge transfer due to the PGM particles coming into direct contact with other base metals can be investigated to determine the role that some of these metals can play to enhance the platinum group metals dissolution rate. This may be a good source of information for the initial prediction of the PGM dissolution operation at the plant level.

3. The platinum-group metals dissolution with chlorine gas at atmospheric pressure as most of this tests were done released the excess chlorine in the reactor out through a scrubber into the atmosphere, therefore, it is suggested that leaching in a closed reactor or a pressurized reactor would be better for the most effective utilisation of chlorine.

4. It might be worth doing some more experiments by leaching pure platinum-

group metals in hydrochloric acid solutions with chlorine to investigate the applicability of the shrinking particle model on the obtained data from the direct dissolutions. This will draw the distinction between the nature of the acid soluble PGMs and the chlorine soluble fractions of the PGMs experienced in the concentrate sample used for this experiments. It might be possible also to give a better explanation to the presence and the nature of the acid soluble PGMs fraction in the concentrate sample used. This will spell out clearly how the various metals respond to both the diffusion and surface chemical reaction control mechanisms of the shrinking particle models.

5. The work was done with a more dilute solid to liquid ratio of 1:100 for a constant leaching period of 6 hours so different solid to liquid ratios can be used to determine the effect of this on the rate and extent of dissolution of PGMs in hydrochloric acid solution with a constant chlorine concentration. The leaching duration may also be varied to establish an optimum period which would yield the highest extraction or a total dissolution of all the PGMs.

BIBLIOGRAPHY

1. Loebenstein J.R (1985): Mineral Facts and Problems. Bulletin 675, US Bureau of Mines.

2. Hoffmann J E (1989): Recovery of Platinum group metals from Automotive catalysts. Precious and Rare metal Technologies (1989), Torma A.E and Gundiler I.H. (Edit.), Elsevier Science publishers, pp 345 - 362.

3. Vermaak C.F. (1995): Platinum-group Metals: A global perspective. MINTEK publication. pp.85-91

4. Wadsworth M.E. (1989): Precious Metal industries and the role of cyanide. Precious and rare metal technologies. Proceedings of a symposium on Precious and rare metals, Albuquerque, N.M., USA, April 6-8 1988. Torma A.E and Gundiler I.H (Edit.), Elsevier Science publishers, pp 3 - 15.

5. Mishra R.K. (1993): A review of Platinum group metals recovery from Automobile catalytic converters. Precious Metals 1993. pp.449-471 (Intern. Precious Metals Institute).

6. Wisecarver K.D., Yang N., Kuo-Ying A.W. (1992): Dissolution of Platinum and Palladium from Automotive catalysts. Precious Metal 1992. pp. 29-37.

7. Bautista R.G., Yue L., Tyson D.R. (1987): Platinum and Palladium recovery from Spent Automobile catalysts leaching with (HCl):(HNO_3) in a packed and fluidised bed. Precious and Rare Metals Technologies. pp. 365-380.

8. Benner L.S., Suzuki S., Meguro K., Tanaka S. (Editors) (1991): Precious Metals Science and Technology. pp.375-399 (Intern. Precious Metals Institute)

9. Harris G.B. (1993): A Review of Precious Metals Refining. Precious Metals 1993. pp.351-368.

10. Bradford A.M.(1985): Recovery of Platinum and Rhodium from car exhaust catalysts, US Patent No. 3,985,954.

11. Jheelan A. and Lebakeng A. (1995): Extraction of Platinum-group metals from the NCR concentrate. Impala Platinum Refineries - Projects reports.

12. Llopis J., Tordesillas I.M. (1952): The passivation of Platinum in HCl solutions. Real. Scoedad Espan. Fis. Quim. (Madrid) Vol. 48B pp. 23-24.

13. Hawkins F A and Nicol M J (1976): An electrochemical investigation of the dissolution and passivation of Platinum in Acid solutions, NIM Report No. 1800, April 1976.

14. Edwards R.I.(1975): The refining of the Platinum-group Metals. National Institute for Metallurgy, Report no. 1744, 11th July, 1975

15. Weast R.C.(Editor)(1988): CRC Handbook of Chemistry and Physics. 69th Edition, CRC Press, 1988

16. Kirk-Othmer (1980): Encyclopedia of Chemical Technology, Vol. 12, 3rd Edition, Wiley-Interscience Publication, 1980

17. Osseo-Asare K. (1986): Hydrometallurgical Stability Diagrams: Visual Aids for Process Design and Analysis. Presented at the 115th AIME Annual Meeting, New Orleans.

18. Luo R., Osseo-Asare K. (1988): Heterogeneous Equilibria in the systems, Pt-H_2O, Pt-, Pd-, Au-Cl-H_2O, Pt-, Pd-, Au-NH_3-H_2O and Pt-, Pd-, Au-Cl-NH_3-

H_2O.

19. Habashi F.(1970): Principles of Extractive Metallurgy, Vol.2, Hydrometallurgy, Gordon and Breach, New York.

20. D'Aniello M.J. (1982): Noble Metal Recovery from Spent Automotive Catalysts. Recycling of Automotive Catalysts. SP-508, Society of Automotive Engineers, Inc., 1982. pp. 7

21. Ginzburg S.I., Ezerskaya N.A., Prokof'eva I.V., Fedorenko N.V. (1990): Analytical Chemistry of the Platinum metals edited by Shelnitz P. John Wiley and Sons, New York, pp.10 - 80.

22. Khan M.A and Morris D.F.C (1968), Talanta 15, 1301

23. Levenspiel O. (1972): Chemical Reaction Engineering 2nd Ed. John Wiley and Sons, New York, N.Y. pp 357 - 369.

24. Dry M.J. and Bryson A.W. (1987): Kinetics of leaching of a Low-grade Fe-Ni-Cu Matte in Ferric sulphate solution. Hydrometallurgy, 18; pp 155 - 181.

25. Crundwell F.K. and Verbaan B. (1987): Kinetics and mechanism of the non-oxidative dissolution of sphalerite, Hydrometallurgy 17, pp 369

26. Crundwell F.K. (1985): MSc Thesis, University of the Witwatersrand, Johannesburg.

27. Pletcher D. (1991): A First course in Electrode Processes. First Edition. Electrochemical Consultancy, Hants.

28. Bard A.J., Faulkner L.R. (1980): Electrochemical Methods. Wiley, New York,

1990.

29. Wadsworth M.E. (1979): Hydrometallurgical Processes, in Sohn H.Y and Wadsworth M.E (Eds.), Rate Processes of Extraction Metallurgy. Plenum press, New York, N Y, pp 133 - 186.

30. Crundwell F.K. and Verbaan B. (1986): An electrochemical model for the leaching of a sphalerite concentrate, Hydrometallurgy 16, pp 345.

31. Froment G.F and Bischoff K.B (1979): Chemical Reactor analysis and Design John Wiley & Sons, New York.

32. Smith J.M. (1981): Chemical Engineering Kinetics. 3rd Ed. McGraw-Hill.

33. Lindsay N M (1988): The processing and recovery of the Platinum-group elements. PhD Thesis, University of the Witwatersrand, Johannesburg.

34. Nicol M.J., Needles C.R.S and Finkelstein N.P. (1975): Electrochemical model for the leaching of Uranium dioxide. Burkin A.R (Ed.) Leaching and Reduction in Hydrometallurgy IMM, London.

35. Nicol M.J (1983): The non-oxidative Leaching of oxides and sulphides - an electrochemical approach in K Osseo-Asare and J.D. Miller (Ed.) Proc. 3rd Intern. Symp. On Hydrometallurgy 177.

36. Crundwell F K and Ashok J (1994): Calculation of Heat Transfer Duties for the 1500L and 3000L Ti Leaching Vessel. Impala Platinum Refineries report (1994).

37. Jones D A and Paul A J P (1994): Galvanic Interactions between alloys and minerals in sulphuric acid. Corrosion, 50, pp. 516 1994.

38. Llopis J (1969): Corrosion of Platinum Metals and Chemisorption. Catalysis Reviews, Vol. 2, 1969.

39. Dick J G (1973): Analytical Chemistry. McGraw-Hill, New York, 1973.

40. Vogel A I (1989): Textbook of Quantitative Chemical Analysis. Essex Longman Scientific Technical, New York, 1989.

APPENDICES

Appendix A

Some Physical Properties of the Platinum-Group Metals

Table A1: **Some Physical Properties of the Platinum-Group Metals**

Property	Light Group			Heavy Group		
	Ruthenium Ru	Rhodium Rh	Palladium Pd	Osmium Os	Iridium Ir	Platinum Pt
Atomic number	44	45	46	76	77	78
Atomic mass	101.07	102.91	106.40	190.20	192.22	195.07
Boiling point, *°C*	4150	3695	2963	5012	4428	3825
Bonding energy, *eV*	6.63	5.76	3.91	8.20	6.94	5.65
Brinell hardness	220	139	49	400	164	47
Bulk modulus, *kPa*	28.40	27.40	18.63	37.20	37.20	27.40
Coeff. of linear expansion, $10^{6}K^{-1}$	5.05	8.30	11.80	2.60	6.80	9.10
Density (at 20°C), gcm^{-3}	12.450	12.414	12.020	22.583	22.650	21.450
Ductility, *%*	1.70	1.80	4.10	1.70	1.80	4.50
Electrical resistivity, $10^{8}\Omega$-*m*	6.80	4.33	9.93	8.12	4.71	9.85
Enthalpy of fusion, $kJmol^{-1}$	38.59	26.59	16.74	57.85	41.12	22.17
Hardness (Mohs)	6.50	5.70	4.80	7.00	6.50	4.30
Heat of evaporation, $kJmol^{-1}$	568.15	495.72	376.81	628.02	563.96	510.79
Latent heat of fusion, $kJmol^{-1}$	26.00	21.60	17.60	31.70	26.40	19.70
Mean specific heat, Jkg^{-1}	234.0	243.0	247.0	130.0	130.6	134.4
Melting point, *°C*	2334.0	1964.0	1554.9	3033.0	2446.0	1768.4
Normal elastic modulus, *MPa*	4.81	3.26	1.28	5.91	5.30	1.77
Specific heat capacity, $J(g\text{-}K)^{-1}$	0.238	0.243	0.244	0.130	0.131	0.133
Standard entropy at 25°C, $Jmol^{-1}$	28.50	31.50	37.90	32.60	35.50	41.60
Thermal conductivity, $W(m\text{-}K)^{-1}$	107.50	150.00	73.00	73.80	147.50	72.10
Thermal expansion at 25°C, $10^{6}K^{-1}$	6.40	8.20	11.80	5.10	6.40	8.80
Work function, *eV*	4.71	4.98	5.12	4.83	5.40	5.65

Appendix B

Raw Data for the Chlorine dissolution tests

Table B1: **Raw Data for the Chlorine Dissolution**

Effect of Temperature on Cl_2 dissolution in HCl solution

[HCl] = 11.50M
Stirrer speed= 125rpm
Cl_2 flowrate = 825cm^{3}min^{-1}

Time	Temp.= 30°C			Temp.= 40°C			Temp.= 50°C			Temp.= 60°C			Temp.= 70°C		
(min)	Titr.Val (ml)	$[Cl_2]$ M	ln (1-C/C$_s$)	TitrVal (ml)	$[Cl_2]$ M	ln (1-C/C$_s$)	TitrVal (ml)	$[Cl_2]$ M	ln (1-C/C$_s$)	Titr.Val (ml)	$[Cl_2]$ M	ln (1-C/C$_s$)	TitrVal (ml)	$[Cl_2]$ M	ln (1-C/C$_s$)
0	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000
10	11.80	0.0288	-0.4232	9.10	0.0222	-0.4227	7.40	0.0181	-0.4680	5.20	0.0127	-0.4520	4.50	0.0110	-0.5897
20	17.40	0.0425	-0.7109	13.80	0.0337	-0.7397	11.20	0.0274	-0.8340	8.20	0.0200	-0.8519	6.70	0.0164	-1.0887
30	21.00	0.0513	-0.9521	17.30	0.0423	-1.0652	13.90	0.0340	-1.2108	10.40	0.0254	-1.2991	8.50	0.0208	-1.8424
40	24.00	0.0586	-1.2099	19.60	0.0479	-1.3565	16.10	0.0393	-1.6775	11.90	0.0291	-1.7845	9.10	0.0222	-2.3123
50	26.60	0.0650	-1.5042	21.60	0.0528	-1.7049	17.30	0.0423	-2.0696	12.90	0.0315	-2.3232	9.60	0.0235	-3.0052
60	28.20	0.0689	-1.7407	22.80	0.0557	-1.9927	17.90	0.0437	-2.3442	13.40	0.0327	-2.7647	9.80	0.0239	-3.5156
70	29.80	0.0728	-2.0509	23.80	0.0581	-2.3182	18.60	0.0454	-2.8039	13.80	0.0337	-3.3517	9.95	0.0243	-4.2079
80	30.80	0.0752	-2.3089	24.50	0.0598	-2.6320	18.90	0.0462	-3.0918	14.00	0.0342	-3.8614	10.01	0.0245	-4.7176
90	31.50	0.0769	-2.5395	25.00	0.0611	-2.9375	19.20	0.0469	-3.4976	14.05	0.0344	-4.1263	10.05	0.0246	-5.3030
100	32.20	0.0787	-2.8398	25.40	0.0620	-3.2743	19.40	0.0474	-3.9037	14.15	0.0346	-4.6203	10.07	0.0246	-5.8103
110	32.70	0.0799	-3.1278	25.70	0.0628	-3.6316	19.50	0.0476	-4.1919	14.20	0.0347	-5.1753	10.08	0.0246	-6.2114
120	33.00	0.0806	-3.3512	25.85	0.0631	-3.8729	19.60	0.0479	-4.5986	14.25	0.0348	-5.6389	10.09	0.0246	-6.8915
130	33.30	0.0813	-3.6393	26.00	0.0635	-4.1919	19.65	0.0480	-4.8874	14.27	0.0349	-6.1385	10.10	0.0247	-
140	33.50	0.0818	-3.8911	26.10	0.0638	-4.4804	19.70	0.0481	-5.2952	14.28	0.0349	-6.5301	10.10	0.0247	-
150	33.70	0.0823	-4.2285	26.20	0.0640	-4.8874	19.75	0.0482	-5.6549	14.30	0.0349	-	10.10	0.0247	-
160	33.80	0.0826	-4.4524	26.40	0.0645	-	19.80	0.0484	-	14.30	0.0349	-	10.10	0.0247	-
170	34.20	0.0835	-	26.40	0.0645	-	19.80	0.0484	-	14.30	0.0349	-	10.10	0.0247	-
180	34.20	0.0835	-	26.40	0.0645	-	19.80	0.0484	-	14.30	0.0349	-	10.10	0.0247	-

Effect of Temperature on Cl_2 dissolution in HCl solution

[HCl] = 6.00M
Stirrer speed = 125rpm
Cl_2 flowrate = 825cm^{3}min^{-1}

Time	Temp.= 30°C			Temp.= 40°C			Temp.= 50°C			Temp.= 60°C			Temp.= 70°C		
(min)	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$
0	0.00	0.00000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000
2	4.80	0.01172	-0.1911	-	-	-	-	-	-	-	-	-	-	-	-
4	7.50	0.01832	-0.3171	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	5.80	0.0142	-0.3250	3.90	0.00953	-0.2965	4.20	0.01026	-0.4699	4.20	0.01026	-0.6700
6	8.70	0.02125	-0.3787	-	-	-	-	-	-	-	-	-	-	-	-
8	9.60	0.02345	-0.4275	-	-	-	-	-	-	-	-	-	-	-	-
10	10.70	0.02613	-0.4905	8.50	0.0208	-0.5220	7.20	0.01759	-0.6418	5.90	0.01441	-0.7480	5.80	0.01417	-1.1217
12	11.50	0.02809	-0.5390	-	-	-	-	-	-	-	-	-	-	-	-
14	12.20	0.02980	-0.5835	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	10.10	0.0247	-0.6602	8.60	0.02101	-0.8341	7.80	0.01905	-1.1918	6.80	0.01661	-1.5632
16	12.80	0.03126	-0.6232	-	-	-	-	-	-	-	-	-	-	-	-
18	13.40	0.03273	-0.6646	-	-	-	-	-	-	-	-	-	-	-	-
20	14.10	0.03444	-0.7152	11.60	0.0283	-0.8097	10.20	0.02491	-1.1116	8.60	0.02101	-1.4599	7.30	0.01783	-1.8882
25	-	-	-	13.10	0.0320	-0.9856	11.50	0.02809	-1.4126	9.30	0.02272	-1.7734	7.90	0.01930	-2.5061
30	17.80	0.04348	-1.0355	14.50	0.0354	-1.1834	12.10	0.02955	-1.5895	10.00	0.02443	-2.2324	8.10	0.01978	-2.8415
40	20.10	0.04909	-1.3030	16.40	0.0401	-1.5356	13.50	0.03297	-2.1898	10.50	0.02565	-2.7705	8.40	0.02052	-3.7524
50	21.90	0.05349	-1.5775	17.80	0.0435	-1.9082	14.20	0.03468	-2.7198	10.90	0.02662	-3.6147	8.53	0.02083	-4.7857
60	23.20	0.05667	-1.8365	19.10	0.0467	-2.4516	14.60	0.03566	-3.2296	11.05	0.02699	-4.3026	8.57	0.02093	-5.6000
70	24.60	0.06009	-2.2196	19.60	0.0479	-2.7769	14.90	0.03639	-3.9201	11.12	0.02716	-4.9221	8.59	0.02098	-6.5910
80	25.20	0.06155	-2.4429	20.10	0.0491	-3.2621	15.00	0.03664	-4.3250	11.16	0.02726	-5.5959	8.60	0.02101	-
90	25.80	0.06302	-2.7307	20.40	0.0498	-3.7317	15.10	0.03688	-5.0084	11.18	0.02731	-6.2515	8.60	0.02101	-
100	26.20	0.06399	-2.9823	20.60	0.0503	-4.2417	15.14	0.03698	-5.5089	11.20	0.02736	-	8.60	0.02101	-
110	26.60	0.06497	-3.3191	20.70	0.0505	-4.6461	15.16	0.03703	-5.9016	11.20	0.02736	-	8.60	0.02101	-
120	26.80	0.06546	-3.5426	20.75	0.0507	-4.9327	15.18	0.03708	-6.5576	11.20	0.02736	-	8.60	0.02101	-
130	27.00	0.06595	-3.8308	20.80	0.0508	-5.3361	15.19	0.03710	-7.1803	11.20	0.02736	-	8.60	0.02101	-
140	27.20	0.06644	-4.2374	20.85	0.0509	-6.0230	15.20	0.03713	-	11.20	0.02736	-	8.60	0.02101	-
150	27.30	0.06668	-4.5262	20.86	0.0510	-6.2430	15.20	0.03713	-	11.20	0.02736	-	8.60	0.02101	-
160	27.40	0.06692	-4.9339	20.87	0.0510	-6.5255	15.20	0.03713	-	11.20	0.02736	-	8.60	0.02101	-
170	27.60	0.06741	-	20.90	0.0511	-	15.20	0.03713	-	11.20	0.02736	-	8.60	0.02101	-
180	27.60	0.06741	-	20.90	0.0511	-	15.20	0.03713	-	11.20	0.02736	-	8.60	0.02101	-

Effect of Temperature on Cl_2 dissolution in HCl solution

[HCl] = 2.00M
Stirrer speed = 125rpm
Cl_2 flowrate = 825cm^{3}min^{-1}

Time	Temp.= 30°C			Temp.= 40°C			Temp.= 50°C			Temp.= 60°C			Temp.= 70°C		
(min)	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$	TitrVal (ml)	$[Cl_2]$ M	ln $(1-C/C_s)$
0	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000
5	7.10	0.0173	-0.4527	5.70	0.0139	-0.4404	4.30	0.0105	-0.4581	3.60	0.0088	-0.5034	3.50	0.0086	-0.7729
10	10.10	0.0247	-0.7297	7.90	0.0193	-0.6807	6.30	0.0154	-0.7731	5.50	0.0134	-0.9271	4.90	0.0120	-1.4011
15	11.60	0.0283	-0.9035	9.80	0.0239	-0.9480	7.70	0.0188	-1.0731	6.70	0.0164	-1.3324	5.70	0.0139	-2.0933
20	12.90	0.0315	-1.0833	11.20	0.0274	-1.2040	8.80	0.0215	-1.3946	7.60	0.0186	-1.8021	6.10	0.0149	-2.7846
25	14.30	0.0349	-1.3217	12.10	0.0296	-1.4116	9.70	0.0237	-1.7660	8.10	0.0198	-2.2071	6.30	0.0154	-3.4740
30	15.20	0.0371	-1.5117	13.00	0.0318	-1.6740	10.20	0.0249	-2.0535	8.40	0.0205	-2.5632	6.40	0.0156	-4.1596
40	16.50	0.0403	-1.8717	14.10	0.0344	-2.1308	10.80	0.0264	-2.5638	8.80	0.0215	-3.4081	6.47	0.0158	-5.3295
50	17.50	0.0427	-2.2771	14.80	0.0362	-2.5903	11.30	0.0276	-3.3733	9.00	0.0220	-4.4982	6.50	0.0159	-
60	18.10	0.0442	-2.6337	15.20	0.0371	-2.9958	11.50	0.0281	-4.0637	9.06	0.0221	-5.3955	6.50	0.0159	-
70	18.50	0.0452	-2.9700	15.50	0.0379	-3.4659	11.60	0.0283	-4.7515	9.10	0.0222	-	6.50	0.0159	-
80	18.80	0.0459	-3.3265	15.70	0.0384	-3.9768	11.65	0.0285	-5.4341	9.10	0.0222	-	6.50	0.0159	-
90	19.00	0.0464	-3.6627	15.80	0.0386	-4.3824	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
100	19.20	0.0469	-4.1730	15.90	0.0388	-5.0758	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
110	19.30	0.0471	-4.5777	16.00	0.0391	-	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
120	19.35	0.0473	-4.8647	16.00	0.0391	-	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
130	19.40	0.0474	-5.2687	16.00	0.0391	-	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
140	19.50	0.0476	-	16.00	0.0391	-	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
150	19.50	0.0476	-	16.00	0.0391	-	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
160	19.50	0.0476	-	16.00	0.0391	-	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
170	19.50	0.0476	-	16.00	0.0391	-	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-
180	19.50	0.0476	-	16.00	0.0391	-	11.70	0.0286	-	9.10	0.0222	-	6.50	0.0159	-

Effect of Cl_2 concentration on dissolution in HCl solution

[HCl] = 6.00M
Temperature= 50°C
Stirrer speed= 125rpm

Time (min)	No Nitrogen Cl_2 flowrate= 720cm^{3}min^{-1}			N_2 flowrate= 90cm^{3}min^{-1} Cl_2 flowrate= 720cm^{3}min^{-1}			N_2 flowrate= 200cm^{3}min^{-1} Cl_2 flowrate= 720cm^{3}min^{-1}			N_2 flowrate= 310cm^{3}min^{-1} Cl_2 flowrate= 720cm^{3}min^{-1}		
	Titr Val (ml)	$[Cl_2]$ (M)	ln $(1-C/C_s)$	Titr Val (ml)	$[Cl_2]$ (M)	ln $(1-C/C_s)$	Titr Val (ml)	$[Cl_2]$ (M)	ln $(1-C/C_s)$	Titr Val (ml)	$[Cl_2]$ (M)	ln $(1-C/C_s)$
0	0.00	0.00000	0.0000	0.00	0.00000	0.0000	0.00	0.00000	0.0000	0.00	0.0000	0.0000
5	3.90	0.00953	-0.2965	3.50	0.00855	-0.2617	2.80	0.00684	-0.2036	1.70	0.00415	-0.1186
10	7.20	0.01759	-0.6418	6.00	0.01466	-0.5020	5.20	0.01270	-0.4187	4.00	0.00977	-0.3053
15	8.60	0.02101	-0.8341	7.50	0.01832	-0.6800	6.70	0.01636	-0.5811	5.20	0.01270	-0.4187
20	10.20	0.02491	-1.1116	8.70	0.02125	-0.8494	7.80	0.01905	-0.7197	6.30	0.01539	-0.5352
25	11.50	0.02809	-1.4126	9.80	0.02394	-1.0347	8.50	0.02076	-0.8191	7.00	0.01710	-0.6171
30	12.30	0.03004	-1.6561	10.50	0.02565	-1.1735	9.00	0.02198	-0.8966	7.60	0.01856	-0.6930
40	13.50	0.03297	-2.1898	11.60	0.02833	-1.4400	9.90	0.02418	-1.0534	8.50	0.02076	-0.8191
50	14.20	0.03468	-2.7198	12.40	0.03029	-1.6912	10.50	0.02565	-1.1735	9.10	0.02223	-0.9129
60	14.60	0.03566	-3.2296	12.90	0.03151	-1.8878	11.00	0.02687	-1.2859	9.50	0.02320	-0.9807
70	14.90	0.03639	-3.9201	13.40	0.03273	-2.1327	11.40	0.02784	-1.3860	9.90	0.02418	-1.0534
80	15.00	0.03664	-4.3230	13.70	0.03346	-2.3149	11.70	0.02858	-1.4682	10.20	0.02491	-1.1116
90	15.10	0.03688	-5.0084	13.90	0.03395	-2.4578	12.00	0.02931	-1.5578	10.60	0.02589	-1.1950
100	15.14	0.03698	-5.5089	14.10	0.03444	-2.6247	12.30	0.03004	-1.6561	10.90	0.02662	-1.2624
110	15.16	0.03703	-5.9016	14.30	0.03493	-2.8250	12.60	0.03078	-1.7653	11.20	0.02736	-1.3347
120	15.18	0.03708	-6.5576	14.40	0.03517	-2.9426	12.80	0.03126	-1.8453	11.40	0.02784	-1.3860
130	15.19	0.03710	-7.1803	14.50	0.03542	-3.0758	13.10	0.03200	-1.9787	11.70	0.02858	-1.4682
140	15.20	0.03713	-	14.60	0.03566	-3.2296	13.30	0.03249	-2.0787	11.90	0.02907	-1.5270
150	15.20	0.03713	-	14.70	0.03590	-3.4114	13.40	0.03273	-2.1327	12.10	0.02955	-1.5895
160	15.20	0.03713	-	14.80	0.03615	-3.6338	13.60	0.03322	-2.2504	12.30	0.03004	-1.6561
170	15.20	0.03713	-	14.90	0.03639	-3.9201	13.80	0.03371	-2.3838	12.50	0.03053	-1.7276
180	15.20	0.03713	-	15.00	0.03664	-	13.90	0.03395	-2.4578	12.80	0.03126	-1.8453

Effect of Stirrer speed on Cl_2 dissolution in HCl solution

[HCl] = 6.00M
Temperature= 40 °C
Cl_2 flowrate = 825cm^{3}min^{-1}

Time (min)	Stirrer speed = 150rpm			Stirrer speed = 190rpm			Stirrer speed = 300rpm			Stirrer speed = 500rpm		
	Titr Val (ml)	$[Cl_2]$ (M)	ln $(1-C/C_s)$	Titr Val (ml)	$[Cl_2]$ (M)	ln $(1-C/C_s)$	Titr Val (ml)	$[Cl_2]$ (M)	ln $(1-C/C_s)$	Titr Val (ml)	$[Cl_2]$ (M)	ln $(1-C/C_s)$
0	0.00	0.00000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.00000	0.0000
5	5.80	0.01417	-0.2834	6.10	0.01490	-0.3005	6.50	0.01588	-0.3238	7.50	0.01832	-0.3844
10	8.50	0.02076	-0.4489	9.50	0.02320	-0.5179	9.80	0.02394	-0.5396	11.60	0.02833	-0.6804
15	10.10	0.02467	-0.5617	11.20	0.02736	-0.6474	12.00	0.02931	-0.7146	14.20	0.03468	-0.9270
20	11.60	0.02833	-0.6804	12.80	0.03126	-0.7867	13.80	0.03371	-0.8848	15.90	0.03884	-1.1288
25	13.10	0.03200	-0.8152	14.30	0.03493	-0.9378	15.40	0.03761	-1.0651	17.50	0.04274	-1.3652
30	14.50	0.03542	-0.9597	15.70	0.03835	-1.1028	16.50	0.04030	-1.2110	18.60	0.04543	-1.5677
40	16.40	0.04006	-1.1969	17.60	0.04299	-1.3820	18.30	0.04470	-1.5083	20.00	0.04885	-1.9041
50	17.80	0.04348	-1.4165	19.10	0.04665	-1.6753	19.60	0.04787	-1.7959	20.50	0.05007	-2.0583
60	19.10	0.04665	-1.6753	19.90	0.04861	-1.8760	20.10	0.04909	-1.9331	20.60	0.05032	-2.0922
70	19.90	0.04861	-1.8760	20.20	0.04934	-1.9630	20.20	0.04934	-1.9630	20.70	0.05056	-2.1273
80	20.20	0.04934	-1.9630	20.50	0.05007	-2.0583	20.40	0.04983	-2.0255	20.72	0.05061	-2.1344
90	20.40	0.04983	-2.0255	20.60	0.05032	-2.0922	20.50	0.05007	-2.0583	20.74	0.05066	-2.1416
100	20.60	0.05032	-2.0922	20.70	0.05056	-2.1273	20.60	0.05032	-2.0922	20.76	0.05071	-2.1489
110	20.70	0.05056	-2.1273	20.80	0.05080	-2.1636	20.70	0.05056	-2.1273	20.80	0.05080	-2.1636
120	20.75	0.05068	-2.1453	20.90	0.05105	-	20.80	0.05080	-2.1636	20.82	0.05085	-2.1710
130	20.80	0.05080	-2.1636	20.90	0.05105	-	20.90	0.05105	-	20.84	0.05090	-2.1785
140	20.85	0.05093	-2.1823	20.90	0.05105	-	20.90	0.05105	-	20.86	0.05095	-2.1861
150	20.86	0.05095	-2.1861	20.90	0.05105	-	20.90	0.05105	-	20.88	0.05100	-2.1937
160	20.87	0.05098	-2.1899	20.90	0.05105	-	20.90	0.05105	-	20.90	0.05105	-
170	20.90	0.05105	-	20.90	0.05105	-	20.90	0.05105	-	20.90	0.05105	-
180	20.90	0.05105	-	20.90	0.05105	-	20.90	0.05105	-	20.90	0.05105	-

Comparison of Redox potential and Cl_2 concentration in HCl solution

[HCl] = 6.00M
Stirrer speed = 125rpm
Cl_2 flowrate = 825cm^3min^{-1}

Time (min)	Temperature = 30°C			Temperature = 50°C			Temperature = 60°C		
	Titr. Value (ml)	$[Cl_2]$ (M)	Redox Pot. (mV)	Titr. Value (ml)	$[Cl_2]$ (M)	Redox Pot. (mV)	Titr. Value (ml)	$[Cl_2]$ (M)	Redox Pot. (mV)
0.0	0.00	0.00000	961.0	0.00	0.0000	954.3	0.00	0.0000	950.1
5.0	8.10	0.01978	1031.2	3.90	0.00953	1019.8	3.60	0.00879	1017.4
10.0	11.20	0.02736	1035.4	6.80	0.01661	1027.5	5.80	0.01417	1023.6
15.0	13.20	0.03224	1037.3	8.60	0.02101	1030.7	7.40	0.01807	1027.1
20.0	15.10	0.03688	1039.4	10.20	0.02491	1033.1	8.50	0.02076	1029.0
25.0	16.90	0.04128	1040.9	11.50	0.02809	1034.5	9.20	0.02247	1030.0
30.0	18.20	0.04445	1042.1	12.30	0.03004	1035.4	9.80	0.02394	1031.2
40.0	20.40	0.04983	1043.6	13.50	0.03297	1036.8	10.50	0.02565	1032.1
50.0	22.10	0.05398	1044.7	14.20	0.03468	1037.5	10.90	0.02662	1032.2
60.0	23.60	0.05764	1045.6	14.60	0.03566	1037.7	11.05	0.02699	1032.3
70.0	24.80	0.06057	1046.0	14.90	0.03639	1037.8	11.12	0.02716	1032.5
80.0	25.60	0.06253	1046.2	15.00	0.03664	1037.9	11.16	0.02726	1032.7
90.0	26.20	0.06399	1046.4	15.10	0.03688	1038.0	11.18	0.02731	1032.9
100.0	26.60	0.06497	1046.5	15.14	0.03698	1038.2	11.20	0.02736	1033.1
110.0	26.90	0.06570	1046.6	15.16	0.03703	1038.3	11.20	0.02736	1033.3
120.0	27.10	0.06619	1046.7	15.18	0.03708	1038.5	11.20	0.02736	1033.5
130.0	27.20	0.06644	1046.8	15.19	0.03710	1038.6	11.20	0.02736	1033.7
140.0	27.30	0.06668	1046.9	15.20	0.03713	1038.9	11.20	0.02736	1033.8
150.0	27.40	0.06692	1047.2	15.20	0.03713	1039.5	11.20	0.02736	1034.1
160.0	27.50	0.06717	1047.5	15.20	0.03713	1039.9	11.20	0.02736	1034.3
170.0	27.60	0.06741	1047.6	15.20	0.03713	1040.1	11.20	0.02736	1034.5
180.0	27.60	0.06741	1047.6	15.20	0.03713	1040.1	11.20	0.02736	1034.8

Appendix C

Results of the Leaching experiments of the Platinum-Group Metals

Raw Data:

(i) Experimental measurements

(ii) Mass balances

(iii) Extractions versus time and redox potential data

RUN 1

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 30°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C1.1 Raw Data for the Leaching Experiment I.

Time (min)	Sample Vol. (ml)	Sample Analysis results in % and ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	0.072	0.0623	157	156	45	42
15	15	0.100	0.0702	194	176	59	46
20	15	0.110	0.0753	210	213	62	51
30	15	0.125	0.0812	225	249	69	58
40	15	0.135	0.0851	235	260	72	57
50	15	0.145	0.0878	248	277	75	63
60	15	0.152	0.0926	260	288	77	65
70	15	0.158	0.0954	266	293	79	67
80	15	0.163	0.1000	277	301	81	68
90	15	0.169	0.1034	282	308	83	69
100	15	0.175	0.1056	288	311	84	71
110	15	0.179	0.1078	292	322	85	72
120	15	0.184	0.1090	295	328	86	73
150	15	0.192	0.1140	306	339	88	76
180	15	0.200	0.1180	310	346	90	78
210	15	0.203	0.1200	314	351	91	80
240	15	0.208	0.1207	319	355	92	82
270	15	0.210	0.1225	320	359	93	83
300	15	0.215	0.1235	324	368	94	84
330	15	0.218	0.1242	328	376	95	85
360	15	0.220	0.1258	329	379	96	86
Pregn.		0.220	0.1258	329	379	96	86
Wash A	in (ppm)	66	56	14	8	3	2
Wash B	in (ppm)	1	<1	<1	1	<1	<1
Residue	in (%)	7.96	1.18	3.84	6.28	2.38	1.12

Liquids

Volume of liq. (HCl) into Leach = 2.00 L
Volume of liq. (HCl) ex-leach = 1.680 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C1.2: Assay values for Leach 1 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	7.96	1.18	3.84	6.28	2.38	1.12
Solids in sample	0.56	0.31	0.50	0.78	0.29	0.48

Masses Recorded

Sample into Leach	= 20.0 g
Residue	= 4.51 g
Solids in sample	= 0.52 g
Solids dissolved in solution	= 14.97 g

Table C1.3: Mass Balance for Leach 1

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.3590	0.0532	0.1732	0.2832	0.1073	0.0505
Solids in sample	0.0029	0.0016	0.0026	0.0041	0.0015	0.0025
Pregn. Solution	3.6960	2.1134	0.5527	0.6367	0.1613	0.1445
Wash A Liquor	0.0330	0.0280	0.0070	0.0040	0.0015	0.0010
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.4970	0.3028	0.0818	0.0896	0.0240	0.0205
Total Out	4.5894	2.5006	0.8188	1.0191	0.2971	0.2205
Mass Balance % (Out/In)	99.77	100.02	99.85	99.91	99.04	100.22
% Extraction	92.11	97.81	78.53	71.81	63.37	75.96

Table C1.4: Extraction vs time data for Leach 1.

Time	% Extraction						RedoxPot.
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1018.0
5	31.304	49.840	38.293	30.588	30.000	38.182	1019.6
15	43.387	56.113	47.249	34.480	39.263	41.791	1020.2
20	47.670	60.131	51.093	41.627	41.233	46.268	1022.0
30	54.044	64.745	54.670	48.527	45.795	49.823	1022.8
40	58.262	67.772	57.035	50.619	47.735	51.586	1022.8
50	62.447	69.851	60.087	53.827	49.660	55.961	1023.5
60	65.353	73.518	62.882	55.887	50.933	58.566	1024.2
70	67.825	75.640	64.269	56.816	52.197	60.289	1024.7
80	69.869	79.099	66.791	58.290	53.450	61.143	1025.4
90	72.301	81.636	67.928	59.570	54.693	61.991	1026.4
100	74.714	83.264	69.282	60.114	55.310	63.673	1027.5
110	76.310	84.879	70.177	61.014	55.922	64.507	1028.0
120	78.288	85.752	70.843	63.155	56.528	65.334	1029.1
150	81.427	89.362	73.264	65.102	57.732	67.796	1029.8
180	84.547	26	74.137	66.330	58.925	69.423	1031.1
210	85.698	46	75.003	67.200	59.517	71.036	1031.7
240	87.611	94.139	76.076	67.890	60.103	72.636	1033.5
270	88.570	95.395	76.289	68.575	60.685	73.430	1034.1
300	90.250	96.087	77.133	70.101	61.262	74.216	1034.5
330	91.369	96.567	77.970	71.446	61.833	74.996	1035.3
360	92.108	97.656	78.177	71.946	62.400	75.768	1037.1

RUN 2

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 40°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C2.1: Raw Data for the Leaching Experiment 2.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	738	537	145	148	44	42
15	15	1079	689	196	190	64	50
20	15	1220	770	218	220	70	56
30	15	1365	841	231	266	74	60
40	15	1457	897	240	276	78	62
50	15	1540	920	250	294	81	66
60	15	1610	972	266	300	84	69
70	15	1672	1006	270	311	85	71
80	15	1710	1045	283	321	88	72
90	15	1777	1070	290	324	90	73
100	15	1820	1080	295	332	91	75
110	15	1865	1110	302	335	92	76
120	15	1908	1129	307	341	94	78
150	15	1980	1165	316	350	95	80
180	15	2043	1201	318	355	96	81
210	15	2090	1213	326	370	97	83
240	15	2135	1224	330	374	98	84
270	15	2170	1236	338	380	99	86
300	15	2212	1241	341	381	100	87
330	15	2227	1258	343	382	101	88
360	15	2247	1267	346	386	102	89
Pregn.		2247	1267	346	386	102	89
Wash A	in (ppm)	48	54	15	15	2	3
Wash B	in (ppm)	1	<1	<1	<1	<1	<1
Residue	in (%)	5.98	0.96	3.46	6.32	2.35	1.07

Liquids

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.674 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C2.2: Assay values for Leach 2 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	5.98	0.96	3.46	6.32	2.35	1.07
Solids in sample	0.54	0.28	0.41	0.77	0.26	0.32

Masses Recorded

Sample into Leach = 20.0 g
Residue = 4.24 g
Solids in sample = 0.45 g

Solids dissolved in solution = 15.31 g

Table C2.3: Mass Balance for Leach 2

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.2536	0.0407	0.1467	0.2680	0.0996	0.0454
Solids in sample	0.0024	0.0013	0.0019	0.0035	0.0012	0.0014
Pregn. Solution	3.7615	2.1210	0.5792	0.6462	0.1708	0.1490
Wash A Liquor	0.0240	0.0270	0.0075	0.0075	0.0010	0.0015
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5193	0.3091	0.0841	0.0938	0.0258	0.0216
Total Out	4.5622	2.5005	0.8208	1.0204	0.2999	0.2204
Mass Balance % (Out/In)	99.18	100.02	100.10	100.03	99.96	100.18
% Extraction	94.39	98.32	81.90	73.40	66.38	78.76

Table C2.4: Extraction vs time data for Leach 2.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1021.7
5	32.087	42.960	35.366	29.020	29.333	38.182	1021.7
15	46.802	55.029	47.712	37.193	42.567	45.400	1027.9
20	52.840	61.412	52.997	42.987	46.507	50.773	1030.2
30	59.003	66.964	56.096	51.804	49.113	54.327	1032.6
40	62.883	71.309	58.226	53.706	51.700	56.091	1032.6
50	66.356	73.080	60.573	57.103	53.625	59.591	1033.9
60	69.263	77.053	64.300	58.227	55.535	62.196	1034.6
70	71.817	79.630	65.224	60.270	56.167	63.918	1035.2
80	73.370	82.563	68.205	62.113	58.047	64.773	1035.5
90	76.086	84.428	69.797	62.662	59.290	65.621	1036.0
100	77.816	85.168	70.925	64.113	59.907	67.302	1036.3
110	79.611	87.370	72.492	64.6525	60.518	68.136	1036.7
120	81.312	88.753	73.601	65.723	61.732	69.791	1037.2
150	84.137	91.353	75.582	67.316	62.333	71.432	1037.3
180	86.589	93.930	76.019	68.193	62.930	72.246	1038.3
210	88.402	94.782	77.751	70.80	[illegible]2	73.859	1039.4
240	90.124	95.557	78.609	71.494	64.108	74.659	1039.5
270	91.452	96.394	80.312	72.520	64.690	76.246	1039.9
300	93.031	96.740	80.945	72.690	65.267	77.032	1043.8
330	93.591	97.906	81.363	72.858	65.838	77.811	1043.8
360	94.330	98.518	81.985	73.525	66.405	78.584	1043.8

RUN 3

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C3.1: Raw Data for the Leaching Experiment 3.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	837	654	161	175	55	47
15	15	1224	750	204	207	67	58
20	15	1348	848	227	255	74	63
30	15	1482	911	245	282	81	68
40	15	1540	947	257	302	84	72
50	15	1660	975	264	311	87	74
60	15	1707	990	272	325	89	77
70	15	1754	1045	284	330	92	79
80	15	1850	1078	289	338	95	81
90	15	1861	1091	297	346	97	82
100	15	1910	1118	298	347	98	84
110	15	1938	1136	308	352	101	86
120	15	1970	1155	312	363	102	88
150	15	2041	1172	323	369	104	90
180	15	2080	1204	334	378	107	92
210	15	2138	1225	338	390	107	94
240	15	2190	1232	342	393	109	96
270	15	2216	1246	346	400	109	97
300	15	2265	1254	348	401	111	98
330	15	2290	1263	350	404	112	99
360	15	2325	1275	354	406	113	100
Pregn.		2325	1275	354	406	113	100
Wash A	in (ppm)	51	57	17	14	7	5
Wash B	in (ppm)	1	1	1	<1	<1	<1
Residue	in (%)	3.20	0.52	3.25	5.74	1.98	0.62

Liquids

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.670 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C3.2: **Assay values for Leach 3 solids**

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	3.20	0.52	3.25	5.74	1.98	0.62
Solids in sample	0.49	0.23	0.43	0.74	0.23	0.25

Masses Recorded

Sample into Leach = 20.0 g
Residue = 4.01 g
Solids in sample = 0.39 g

Solids dissolved in solution = 15.60 g

Table C3.3: **Mass Balance for Leach 3**

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.1283	0.0209	0.1303	0.2302	0.0794	0.0249
Solids in sample	0.0019	0.0009	0.0017	0.0029	0.0009	0.0010
Pregn. Solution	3.8828	2.1293	0.5912	0.6780	0.1887	0.1670
Wash A Liquor	0.0255	0.0285	0.0085	0.0070	0.0035	0.0025
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5445	0.3194	0.0870	0.1000	0.0282	0.0244
Total Out	4.5845	2.5004	0.8202	1.0196	0.3022	0.2212
Mass Balance % (Out/In)	99.66	100.02	100.02	99.96	100.74	100.55
% Extraction	97.16	99.13	83.91	77.14	73.43	88.32

Table C3.4: **Extraction vs time data for Leach 3.**

Time (min)	% Extraction						RedoxPot (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1032.6
5	36.391	52.320	39.268	34.314	36.667	42.727	970.0
15	53.091	59.942	49.677	40.541	44.607	52.652	976.5
20	58.402	67.665	55.203	49.812	49.203	57.130	990.6
30	64.097	72.591	59.495	54.987	53.765	61.573	1000.6
40	66.543	75.385	62.334	58.791	55.705	65.100	1003.8
50	71.565	77.541	63.977	60.489	57.630	66.850	1005.5
60	73.516	78.687	65.840	63.111	58.903	69.455	1006.1
70	75.452	82.856	68.613	64.040	60.798	71.177	1008.5
80	79.376	85.338	69.760	65.514	62.678	72.886	1008.3
90	79.822	86.307	71.579	66.977	63.922	73.734	1009.5
100	81.792	88.305	71.804	67.158	64.538	75.416	1010.2
110	82.909	89.627	74.043	68.058	66.373	77.084	1010.7
120	84.175	91.010	74.931	70.021	66.980	78.739	1011.8
150	86.961	92.237	77.352	71.082	68.183	80.380	1012.2
180	88.479	94.528	79.753	72.662	69.973	82.007	1012.6
210	90.717	96.019	80.619	74.750	69.973	83.621	1014.4
240	92.707	96.512	81.477	75.268	71 147	85.221	1015.3
270	93.693	97.489	82.329	76.465	71.147	86.014	1015.9
300	95.536	98.043	82.751	76.635	72.300	86.800	1017.4
330	96.468	98.660	83.169	77.139	72.872	87.580	1018.5
360	97.761	99.476	83.998	77.473	73.438	88.352	1020.8

RUN 4

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C4.1: Raw Data for the Leaching Experiment 4.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	898	711	180	192	59	49
15	15	1333	802	221	227	71	60
20	15	1469	895	241	275	80	66
30	15	1596	960	253	298	87	71
40	15	1682	995	265	314	90	73
50	15	1730	1024	281	328	93	77
60	15	1802	1059	291	340	97	81
70	15	1840	1088	298	348	98	83
80	15	1904	1114	305	356	101	85
90	15	1960	1136	315	361	104	87
100	15	1974	1149	321	365	106	89
110	15	2014	1161	328	371	110	90
120	15	2055	1176	337	376	113	92
150	15	2080	1205	350	387	116	95
180	15	2145	1230	361	396	117	98
210	15	2180	1240	365	406	119	100
240	15	2213	1243	370	413	120	102
270	15	2242	1256	373	418	121	103
300	15	2283	1265	375	422	122	104
330	15	2312	1271	378	424	124	105
360	15	2332	1274	381	431	125	106
Pregn.		2332	1274	381	431	125	106
Wash A	in (ppm)	45	52	14	12	5	4
Wash B	in (ppm)	1	2	1	1	<1	<1
Residue	in (%)	2.10	0.42	2.20	4.78	1.50	0.36

Liquids

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.668 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C4.2. Assay values for Leach 4 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	2.10	0.42	2.20	4.78	1.50	0.36
Solids in sample	0.45	0.24	0.36	0.71	0.21	0.20

Masses Recorded

Sample into Leach = 20.0 g
Residue = 3.72 g
Solids in sample = 0.38 g

Solids dissolved in solution = 15.90 g

Table C4.3: Mass Balance for Leach 4

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0781	0.0156	0.0818	0.1778	0.0558	0.0134
Solids in sample	0.0017	0.0009	0.0014	0.0027	0.0008	0.0008
Pregn. Solution	3.8898	2.1250	0.6355	0.7189	0.2085	0.1768
Wash A Liquor	0.0225	0.0260	0.0070	0.0060	0.0025	0.0020
Wash B Liquor	0.0015	0.0030	0.0015	0.0015	0.0015	0.0015
Samples	0.5657	0.3297	0.0931	0.1053	0.0307	0.0257
Total Out	4.5593	2.5003	0.8203	1.0122	0.2998	0.2201
Mass Balance % (Out/In)	99.11	100.01	100.04	99.23	99.94	100.05
% Extraction	98.25	99.34	89.86	82.17	81.12	93.57

Table C4.4: Extraction vs time data for Leach 4.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1024.6
5	39.044	56.880	43.902	37.647	39.333	44.546	980.3
15	57.815	64.105	53.827	44.458	47.273	54.471	1005.7
20	63.639	71.434	58.632	53.729	53.183	59.843	1007.2
30	69.037	76.517	61.493	58.137	57.745	64.286	1009.1
40	72.664	79.233	64.332	61.180	59.685	66.050	1008.9
50	74.672	81.466	68.088	63.823	61.610	69.550	1008.6
60	77.662	84.140	70.418	66.070	64.157	73.023	1012.6
70	79.227	86.338	72.035	67.556	64.788	74.741	1015.2
80	81.843	88.293	73.640	69.030	66.668	76.455	1011.5
90	84.113	89.934	75.915	69.945	68.533	78.150	1015.2
100	84.676	90.896	77.268	70.670	69.767	79.832	1015.3
110	86.272	91.777	78.835	71.750	72.213	80.566	1016.1
120	87.894	92.969	80.832	72.642	74.033	82.321	1021.6
150	88.875	94.963	83.694	74.588	75.838	84.782	1016.8
180	91.405	96.753	86.095	76.168	76.435	87.223	1014.6
210	92.755	97.463	86.961	77.908	77.618	88.836	1018.6
240	94.018	97.674	88.034	79.116	78.205	90.436	1019.3
270	95.118	98.582	88.673	79.971	78.787	91.230	1019.8
300	96.660	99.204	89.095	80.650	79.363	92.016	1020.3
330	97.741	99.616	89.722	80.986	80.507	92.796	1020.5
360	98.480	99.820	90.344	82.153	81.073	93.568	1020.8

RUN 5

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 70°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C5.1: Raw Data for the Leaching Experiment 5.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	967	771	184	210	65	51
15	15	1426	854	219	247	77	65
20	15	1574	944	255	296	87	71
30	15	1716	1009	267	315	93	76
40	15	1750	1043	282	332	96	78
50	15	1854	1073	290	346	101	83
60	15	1896	1102	310	356	104	85
70	15	1927	1132	312	367	106	87
80	15	1995	1160	321	374	109	89
90	15	2032	1170	334	378	110	91
100	15	2071	1180	338	382	114	93
110	15	2088	1188	349	389	116	94
120	15	2125	1204	352	393	118	95
150	15	2160	1226	358	404	122	98
180	15	2192	1235	370	415	123	100
210	15	2221	1253	375	425	125	102
240	15	2265	1255	380	433	127	103
270	15	2282	1269	384	437	128	104
300	15	2311	1272	386	439	130	105
330	15	2331	1278	390	441	131	106
360	15	2346	1282	391	442	132	107
Pregn.		2346	1282	391	442	132	107
Wash A	in (ppm)	41	41	25	28	8	6
Wash B	in (ppm)	1	1	1	1	<1	<1
Residue	in (%)	2.23	0.11	1.53	4.18	1.13	0.29

Liquids

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.665 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C5.2: Assay values for Leach 5 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	2.23	0.11	1.53	4.18	1.13	0.29
Solids in sample	0.38	0.06	0.33	0.62	0.18	0.18

Masses Recorded

Sample into Leach = 20.0 g
Residue = 3.72 g
Solids in sample = 0.39 g

Solids dissolved in solution = 15.89 g

Table C5.3: Mass Balance for Leach 5

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0830	0.0041	0.0569	0.1555	0.0420	0.0108
Solids in sample	0.0013	0.0002	0.0013	0.0024	0.0007	0.0007
Pregn. Solution	3.9067	2.1345	0.6510	0.7359	0.2198	0.1782
Wash A Liquor	0.0205	0.0205	0.0125	0.0140	0.0040	0.0030
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5878	0.3393	0.0968	0.1107	0.0327	0.0266
Total Out	4.6001	2.5001	0.8201	1.0200	0.3008	0.2208
Mass Balance % (Out/In)	100.00	100.01	100.01	100.00	100.25	100.36
% Extraction	98.17	99.83	92.90	84.52	85.79	94.80

Table C5.4: Extraction vs time data for Leach 5.

Time (min)	% Extraction						PedoxPot (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1012.2
5	42.044	61.680	44.878	41.177	43.333	46.364	988.5
15	61.850	68.270	53.351	48.377	51.273	58.996	997.2
20	68.189	75.362	61.999	57.841	57.840	64.368	1002.5
30	74.224	80.445	64.860	61.482	61.750	68.811	1007.8
40	75.658	83.084	68.409	64.716	63.690	70.575	1008.0
50	80.010	85.394	70.287	67.358	66.898	74.950	1008.9
60	81.754	87.609	74.946	69.230	68.808	76.686	1009.5
70	83.031	89.883	75.408	71.274	70.072	78.409	1008.6
80	85.810	91.989	77.471	72.564	71.952	80.118	1009.2
90	87.310	92.735	80.428	73.296	72.573	81.814	1010.6
100	88.878	93.475	81.331	74.021	75.040	83.496	1011.0
110	89.557	94.062	83.792	75.280	76.263	84.330	1011.8
120	91.020	95.227	84.458	75.994	77.477	85.157	1012.5
150	92.394	96.815	85.779	77.941	79.883	87.618	1014.2
180	93.639	97.460	88.398	79.171	80.480	89.246	1014.4
210	94.758	98.738	89.481	81.611	81.663	90.859	1015.2
240	96.442	98.878	90.554	82.992	82.837	91.659	1016.4
270	97.086	99.856	91.405	83.676	83.418	92.452	1017.8
300	98.177	100.06	91.827	84.015	84.572	93.239	1017.9
330	98.923	100.48	92.663	84.352	85.143	94.018	1017.8
360	99.477	100.75	92.871	84.518	85.710	94.791	1017.6

RUN 6

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 80°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C6.1: Raw Data for the Leaching Experiment 6.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1009	820	195	227	71	48
15	15	1624	908	225	268	84	66
20	15	1730	992	261	316	92	72
30	15	1829	1035	275	331	98	78
40	15	1900	1091	295	351	102	83
50	15	1965	1112	304	362	108	86
60	15	1998	1147	318	374	113	90
70	15	2025	1160	324	385	115	92
80	15	2088	1191	335	392	118	94
90	15	2120	1200	342	396	120	95
100	15	2137	1213	349	400	122	97
110	15	2167	1216	358	407	123	98
120	15	2199	1234	360	412	125	99
150	15	2223	1246	371	422	126	101
180	15	2243	1257	380	433	128	103
210	15	2264	1264	389	445	130	104
240	15	2297	1268	392	454	132	106
270	15	2314	1273	394	459	134	107
300	15	2344	1281	398	462	136	108
330	15	2368	1286	402	464	138	109
360	15	2370	1290	407	466	139	110
Pregn.		2370	1290	407	466	139	110
Wash A	in (ppm)	43	10	32	38	12	8
Wash B	in (ppm)	1	<1	1	1	1	<1
Residue	in (%)	0.82	0.12	0.73	2.96	0.77	0.14

Liquids

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.660 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C6.2: Assay values for Leach 6 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	0.82	0.12	0.73	2.96	0.77	0.14
Solids in sample	0.32	0.06	0.30	0.58	0.19	0.11

Masses Recorded

Sample into Leach	= 20.0 g
Residue	= 3.70 g
Solids in sample	= 0.36 g
Solids dissolved in solution	= 15.94 g

Table B6.3: Mass Balance for Leach 6

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0303	0.0044	0.0270	0.1095	0.0285	0.0052
Solids in sample	0.0012	0.0002	0.0011	0.0021	0.0007	0.0004
Pregn. Solution	3.9342	2.1414	0.6756	0.7736	0.2307	0.1826
Wash A Liquor	0.0210	0.0050	0.0160	0.0190	0.0060	0.0040
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.6127	0.3479	0.1000	0.1164	0.0347	0.0275
Total Out	4.6009	2.5005	0.8212	1.0221	0.3021	0.2212
Mass Balance % (Out/In)	100.02	100.02	100.15	100.20	100.715	100.55
% Extraction	99.32	99.81	96.58	89.08	90.34	97.48

Table C6.4: Extraction vs time data for Leach 6.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1038.3
5	43.870	65.6	47.561	44.510	47.333	43.636	954.2
15	70.408	72.587	54.823	52.489	55.935	59.877	973.5
20	74.948	79.206	63.472	61.759	61.188	65.250	979.2
30	79.155	82.569	66.810	64.634	65.098	70.582	981.8
40	82.150	86.915	71.542	68.438	67.685	74.991	980.6
50	84.870	88.532	73.654	70.514	71.535	77.616	979.5
60	86.240	91.206	76.915	72.761	74.718	81.089	980.7
70	87.352	92.191	78.302	74.805	75.982	82.811	994.0
80	89.927	94.522	80.824	76.095	77.862	84.521	993.0
90	91.224	95.194	82.416	76.827	79.105	85.368	994.5
100	91.908	96.156	83.995	77.552	80.338	87.050	993.1
110	93.105	96.376	86.009	78.811	80.950	87.884	998.4
120	94.371	97.686	86.453	79.703	82.163	88.711	999.1
150	95.313	98.553	88.874	81.473	82.765	90.352	1001.2
180	96.091	99.340	90.839	83.403	83.958	91.980	1002.4
210	96.901	99.837	92.787	85.492	85.142	92.786	1002.8
240	98.164	100.12	93.431	87.045	86.315	94.386	1003.5
270	98.809	100.47	93.857	87.900	87.478	95.180	1005.3
300	99.937	101.02	94.701	88.409	88.632	95.966	1007.6
330	100.83	101.36	95.537	88.745	89.775	96.746	1008.2
360	100.91	101.64	96.574	89.078	90.342	97.518	1009.6

RUN 7

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 1.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C7.1 Raw Data for the Leaching Experiment 7.

Time (min)	Sample Vol. (ml)	Sample Analysis results in % and ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	0	0	0	0	0	0
5	15	490	570	94	99	19	26
15	15	840	694	160	160	31	44
20	15	1020	790	186	190	48	53
30	15	1230	824	204	210	54	58
40	15	1340	890	215	230	62	62
50	15	1410	904	235	253	66	64
60	15	1470	960	242	268	68	67
70	15	1530	981	254	272	70	69
80	15	1590	1008	262	282	72	71
90	15	1620	1015	270	288	75	72
100	15	1669	1034	274	292	77	74
110	15	1700	1050	277	296	78	76
120	15	1720	1065	280	308	79	77
150	15	1780	1090	285	321	80	79
...	15	1820	1100	290	332	81	81
210	15	1840	1100	295	340	82	83
240	15	1860	1110	300	345	83	85
270	15	1880	1120	305	350	84	87
300	15	1900	1130	310	355	85	88
330	15	1930	1140	315	360	87	89
360	15	1950	1150	320	365	89	90
Pregn.		1950	1150	320	365	89	90
Wash A	in (ppm)	15	9	6	4	2	1
Wash B	in (ppm)	1	<1	<1	1	<1	<1
Residue	in (%)	9.23	3.20	2.21	3.54	1.42	0.43

Liquids

Volume of liq. (HCl) into Leach = 2.00 L
Volume of liq. (HCl) ex-leach = 1.665 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C7.2: Assay values for Leach 7 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	9.23	3.20	2.21	3.54	1.42	0.43
Solids in sample	2.86	1.62	1.85	1.94	0.98	1.49

Masses Recorded

Sample into Leach	= 20.0 g
Residue	= 8.62 g
Solids in sample	= 0.61 g
Solids dissolved in solution	= 10.77 g

Table C7.3: Mass Balance for Leach 7

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.7956	0.2758	0.1905	0.3052	0.1224	0.0371
Solids in sample	0.0175	0.0099	0.0113	0.0118	0.0060	0.0091
Pregn. Solution	3.2462	1.9148	0.5328	0.6077	0.1482	0.1499
Wash A Liquor	0.0075	0.0045	0.0030	0.0020	0.0010	0.0005
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.4595	0.2936	0.0758	0.0833	0.0207	0.0211
Total Out	4.5283	2.5001	0.8149	1.0115	0.2998	0.2191
Mass Balance % (Out/In)	98.44	100.00	99.38	99.16	99.93	99.58
% Extraction	82.04	88.57	75.24	68.66	57.18	78.93

Table C7.4: Extraction vs time data for Leach 7.

Time (min)	% Extraction						RedoxPot. (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1126.9
5	21.304	45.600	22.927	19.412	12.667	23.636	1094.2
15	36.408	55.446	38.904	31.283	20.607	39.877	1092.5
20	44.116	63.010	45.150	37.077	31.770	47.936	1099.3
30	53.041	65.669	49.442	40.910	35.680	52.380	1092.6
40	57.680	70..91	52.044	44.714	40.853	55.907	1096.1
50	60.610	71.869	56.739	49.055	43.420	57.657	1095.8
60	63.101	76.147	58.370	51.864	44.693	60.261	1096.2
70	65.573	77.739	61.143	52.607	45.957	61.984	1096.5
80	68.025	79.769	62.977	54.450	47.210	63.693	1096.8
90	69.241	80.292	64.796	55.547	49.075	64.[illegible]	1097.2
100	70.850	81.698	65.699	56.273	50.308	66.223	1096.8
110	72.446	82.872	66.370	56.992	50.920	67.891	1096.6
120	73.237	83.964	67.036	59.133	51.527	68.718	1097.4
150	75.591	85.769	68.137	61.434	52.128	70.359	1099.1
180	77.148	86.485	69.228	63.364	52.725	71.986	1099.4
210	77.920	86.485	70.310	64.756	53.317	73.600	1098.9
240	78.685	87.189	71.384	65.619	53.903	75.200	1099.2
270	79.444	87.887	72.448	66.475	54.485	76.786	1099.3
300	80.196	88.579	73.502	67.323	55.062	77.573	1098.3
330	81.314	89.265	74.548	68.163	56.205	78.352	1099.6
360	82.053	89.945	75.585	68.997	57.338	79.125	1099.5

RUN 8

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 2.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C8.1: Raw Data for the Leaching Experiment 8.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	736	585	127	120	40	38
15	15	963	752	170	172	49	46
20	15	1190	805	198	202	56	56
30	15	1360	860	214	233	62	62
40	15	1480	920	228	246	66	65
50	15	1560	945	240	265	69	70
60	15	1640	980	250	271	72	72
70	15	1690	1000	260	280	75	74
80	15	1720	1020	266	291	77	76
90	15	1760	1031	276	295	80	78
100	15	1790	1042	280	300	81	80
110	15	1820	1060	284	310	83	81
120	15	1860	1080	290	316	85	82
150	15	1890	1115	297	330	88	84
180	15	1920	1140	304	336	90	86
210	15	1940	1160	308	348	92	88
240	15	1960	1175	313	355	94	89
270	15	1980	1190	318	364	96	90
300	15	2000	1205	323	369	98	91
330	15	2020	1220	326	374	100	92
360	15	2030	1240	329	378	102	93
Pregn.		2030	1240	329	378	102	93
Wash A	in (ppm)	28	13	11	8	5	4
Wash B	in (ppm)	1	<1	<1	<1	<1	<1
Residue	in (%)	7.98	1.35	2.18	3.46	1.22	0.40

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.670 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C8.2: **Assay values for Leach 8 solids**

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	7.98	1.35	2.18	3.46	1.22	0.40
Solids in sample	2.19	1.67	1.75	1.84	0.90	1.36

Masses Recorded:

Sample into Leach	= 20.0 g
Residue	= 8.05 g
Solids in sample	= 0.53 g
Solids dissolved in solution	= 11.42 g

Table C8.3: **Mass Balance for Leach 8**

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.6424	0.1087	0.1755	0.2785	0.0982	0.0322
Solids in sample	0.0116	0.0089	0.0093	0.0098	0.0048	0.0072
Pregn. Solution	3.3901	2.0708	0.5494	0.6313	0.1703	0.1553
Wash A Liquor	0.0140	0.0065	0.0055	0.0040	0.0025	0.0020
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.4992	0.3043	0.0791	0.0867	0.0233	0.0225
Total Out	4.5588	2.5006	0.8203	1.0117	0.3006	0.2207
Mass Balance % (Out/In)	99.10	100.02	100.03	99.19	100.21	100.33
% Extraction	85.65	95.30	77.48	71.51	65.74	82.15

Table C8.4: **Extraction vs time data for Leach 8.**

Time (min)	% Extraction						RedoxPot (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1094.6
5	32.000	46.800	30.976	23.529	26.667	34.546	1043.1
15	41.796	60.060	41.385	33.649	32.622	41.764	1050.6
20	51.517	64.236	48.112	39.443	37.218	50.718	1052.3
30	58.742	68.537	51.926	45.385	41.128	56.050	1054.2
40	63.803	73.193	55.238	47.857	43.715	58.696	1056.8
50	67.151	75.118	58.056	51.443	45.640	63.071	1055.4
60	70.473	77.792	60.385	52.567	47.550	64.807	1054.9
70	72.532	79.308	62.696	54.239	49.445	66.530	1055.0
80	73.758	80.812	64.071	56.266	50.698	68.239	1056.2
90	75.380	81.633	66.346	56.998	52.563	69.934	1056.1
100	76.587	82.447	67.248	57.904	53.180	71.616	1056.2
110	77.783	83.768	68.143	59.703	54.403	72.450	1055.6
120	79.366	85.224	69.475	60.774	55.617	73.277	10557
150	80.543	87.751	71.016	63.252	57.422	74.918	1056.4
180	81.711	89.541	72.544	64.304	58.615	76.546	1056.8
210	82.482	90.961	73.410	66.393	59.798	78.159	1056.5
240	83.248	92.017	74.483	67.601	60.972	78.959	1055.8
270	84.006	93.064	75.547	69.140	62.135	79.752	1056.2
300	84.758	94.102	76.602	69.988	63.288	80.539	1055.8
330	85.504	95.131	77.229	70.829	64.432	81.318	1056.6
360	85.874	96.491	77.851	71.496	65.565	82.091	1056.8

RUN 9

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 4.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C9.1: Raw Data for the Leaching Experiment 9.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	785	632	128	156	46	43
15	15	1120	736	180	195	60	54
20	15	1258	840	208	226	68	60
30	15	1442	900	225	248	72	66
40	15	1525	942	236	264	75	69
50	15	1628	975	252	274	78	73
60	15	1684	1018	264	282	80	76
70	15	1725	1045	270	290	82	77
80	15	1772	1070	275	298	84	78
90	15	1845	1095	286	308	85	80
100	15	1898	1110	290	317	86	82
110	15	1920	1128	294	320	88	84
120	15	1945	1143	300	328	90	86
150	15	1996	1170	308	336	93	88
180	15	2068	1193	314	345	96	89
210	15	2100	1209	318	356	98	90
240	15	2128	1218	322	364	100	91
270	15	2180	1230	326	372	104	92
300	15	2208	1238	330	384	105	93
330	15	2224	1250	334	390	107	94
360	15	2242	1258	338	396	109	95
Pregn.		2242	1258	338	396	109	95
Wash A	in (ppm)	45	27	19	11	10	7
Wash B	in (ppm)	1	1	1	<1	<1	<1
Residue	in (%)	4.28	1.01	2.56	4.02	1.36	0.45

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.670 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C9.2: Assay values for Leach 9 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	4.28	1.01	2.56	4.02	1.36	0.45
Solids in sample	1.74	1.02	1.15	1.17	0.81	1.31

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 6.17 g
Solids in sample = 0.51 g

Solids dissolved in solution = 13.32 g

Table C9.3: Mass Balance for Leach 9

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach,						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach,						
Residue	0.2641	0.0623	0.1580	0.2480	0.0839	0.0278
Solids in sample	0.0089	0.0052	0.0059	0.0060	0.0041	0.0067
Pregn. Solution	3.7441	2.1009	0.5645	0.6613	0.1820	0.1587
Wash A Liquor	0.0225	0.0135	0.0095	0.0055	0.0050	0.0035
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5318	0.3171	0.0819	0.0908	0.0255	0.0235
Total Out	4.5729	2.5005	0.8212	1.0131	0.3020	0.2216
Mass Balance % (Out/In)	99.41	100.02	100.14	99.33	100.68	100.72
% Extraction	94.03	97.30	80.05	74.93	70.85	84.45

Table C9.4: Extraction vs time data for Leach 9.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1032.6
5	34.130	50.560	31.220	30.588	30.667	39.091	1019.0
15	48.586	58.818	43.807	38.178	39.930	49.016	1006.2
20	54.496	67.013	50.534	44.165	45.183	54.389	1008.3
30	62.316	71.705	54.587	48.382	47.790	59.721	1009.5
40	65.817	74.964	57.190	51.425	49.730	62.366	1011.2
50	70.127	77.505	60.946	53.312	51.655	65.866	1012.7
60	72.452	80.790	63.741	54.810	52.928	68.471	1012.8
70	74.141	82.837	65.127	56.297	54.192	69.332	1013.2
80	76.062	84.717	66.274	57.771	55.445	70.186	1013.6
90	79.022	86.582	68.776	59.600	56.067	71.882	1014.4
100	81.154	87.692	69.678	61.232	56.683	73.564	1015.3
110	82.031	89.013	70.573	61.772	57.907	75.232	1015.9
120	83.020	90.105	71.905	63.199	59.120	76.886	1017.4
150	85.021	92.054	73.666	64.615	60.925	78.527	1018.5
180	87.823	93.701	74.976	66.194	62.715	79.341	1020.8
210	89.058	94.837	75.842	68.108	63.898	80.148	1024.2
240	90.129	95.471	76.700	69.489	65.772	80.948	1024.6
270	92.102	96.308	77.551	70.857	.398	81.741	1025.3
300	93.155	96.862	78.395	72.893	67.975	82.527	1026.3
330	93.751	97.685	79.232	73.902	69.118	83.307	1026.4
360	94.417	98.229	80.061	74.902	70.252	84.080	1026.5

RUN 10

Leaching Condition

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 8.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C10.1: Raw Data for the Leaching Experiment 10.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1400	850	242	248	66	73
15	15	1550	980	260	308	79	78
20	15	1670	1020	270	330	85	80
30	15	1750	1060	280		92	83
40	15	1840	1090	290	364	96	85
50	15	1930	1120	298	380	102	88
60	15	2010	1140	310	388	105	90
70	15	2050	1160	320	392	107	91
80	15	2090	1170	325	400	109	92
90	15	2120	1180	330	405	112	93
100	15	2140	1190	336	408	114	94
110	15	2170	1200	340	412	116	95
120	15	2200	1210	347	416	118	96
150	15	2230	1220	355	420	120	98
180	15	2250	1230	360	425	122	100
210	15	2280	1240	365	430	124	101
240	15	2310	1250	370	438	126	102
270	15	2320	1260	375	446	128	103
300	15	2330	1270	380	450	129	104
330	15	2350	1280	385	455	130	105
360	15	2360	1290	390	460	131	106
Pregn.		2360	1290	390	460	131	106
Wash A	in (ppm)	72	51	36	24	17	14
Wash B	in (ppm)	1	2	1	1	<1	<1
Residue	in (%)	0.13	0.01	2.23	4.73	1.96	0.37

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.670 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml

Table C10.2: Assay values for Leach 10 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	0.13	0.01	2.23	4.73	1.96	0.37
Solids in sample	0.12	0.01	2.50	3.94	0.68	0.95

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 2.15 g
Solids in sample = 0.45 g

Solids dissolved in solution = 17.40 g

Table C10.3: Mass Balance for Leach 10

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0028	0.0002	0.0480	0.1017	0.0421	0.0080
Solids in sample	0.0005	0.0001	0.0113	0.0177	0.0031	0.0043
Pregn. Solution	3.9412	2.1543	0.6513	0.7682	0.2188	0.1770
Wash A Liquor	0.0360	0.0255	0.0180	0.0120	0.0085	0.0070
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.6149	0.3468	0.0981	0.1180	0.0327	0.0278
Total Out	4.5969	2.5284	0.8281	1.0191	0.3067	0.2255
Mass Balance % (Out/In)	99.93	101.13	100.98	99.91	102.22	102.51
% Extraction	99.93	99.99	92.85	88.28	85.26	94.58

Table C10.4: Extraction vs time data for Leach 10.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1023.5
5	60.870	68.000	59.024	48.628	44.000	66.364	991.3
15	67.342	78.322	63.382	60.304	52.602	70.875	1002.8
20	72.482	81.474	65.784	64.553	56.542	72.666	1008.3
30	75.882	84.602	68.188	68.386	61.103	75.332	1012.8
40	79.677	86.930	70.534	71.049	63.690	77.096	1014.2
50	83.444	89.240	72.412	74.069	67.540	79.721	1017.2
60	86.765	90.768	75.207	75.567	69.450	81.457	1017.6
70	88.413	92.284	77.518	76.310	70.713	82.318	1020.8
80	90.048	93.036	78.665	77.784	71.967	83.173	1021.3
90	91.264	93.782	79.802	78.699	73.832	84.021	1021.8
100	92.069	94.522	81.156	79.243	75.065	84.861	1021.4
110	93.265	95.256	82.051	79.962	76.288	85.696	1021.6
120	94.452	95.984	83.604	80.676	77.502	86.523	1021.2
150	95.629	96.706	85.365	81.384	78.705	88.164	1022.6
180	96.408	97.422	86.457	82.261	79.898	89.791	1023.1
210	97.565	98.132	87.539	83.131	81.082	90.598	1022.4
240	98.713	98.836	88.612	84.512	82.255	91.398	1022.6
270	99.092	99.534	89.676	85.880	83.418	92.191	1022.4
300	99.469	100.226	90.731	86.559	83.995	92.977	1023.2
330	100.21	100.912	91.777	87.400	84.567	93.757	1023.4
360	100.58	101.592	92.813	88.233	85.133	94.530	1023.6

RUN 11

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 10.0 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C11.1: Raw Data for the Leaching Experiment 11.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1517	926	251	278	87	66
15	15	1595	980	275	318	96	75
20	15	1720	1022	289	332	100	78
30	15	1760	1030	292	356	102	81
40	15	1783	1063	306	362	104	84
50	15	1842	1092	310	368	106	85
60	15	1910	1095	314	372	108	86
70	15	1920	1147	316	376	109	87
80	15	1934	1151	318	378	110	88
90	15	1943	1167	320	380	111	89
100	15	1956	1171	322	383	112	90
110	15	1968	1180	324	386	113	91
120	15	2000	1188	326	389	113	92
150	15	2034	1198	330	395	114	93
180	15	2110	1206	335	400	114	94
210	15	2138	1212	338	402	115	95
240	15	2180	1223	342	404	116	96
270	15	2194	1230	344	406	117	97
300	15	2215	1240	346	408	118	98
330	15	2230	1250	350	410	119	99
360	15	2242	1262	355	412	120	100
Pregn.		2242	1262	355	412	120	100
Wash A	in (ppm)	84	69	47	42	29	21
Wash B	in (ppm)	1	1	1	1	<1	<1
Residue	in (%)	5.23	0.39	3.24	5.45	1.72	0.54

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.670 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C11.2: Assay values for Leach 11 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	5.23	0.39	3.24	5.45	1.72	0.54
Solids in sample	2.86	0.16	1.18	2.66	0.89	1.06

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 3.65 g
Solids in sample	= 0.42 g
Solids dissolved in solution	= 15.93 g

Table C11.3: Mass Balance for Leach 11

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.1909	0.0142	0.1183	0.1989	0.0628	0.0197
Solids in sample	0.0120	0.0007	0.0050	0.0112	0.00374	0.0045
Pregn. Solution	3.7441	2.1075	0.5929	0.6880	0.2004	0.1670
Wash A Liquor	0.0420	0.0345	0.0235	0.0210	0.0145	0.0105
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5842	0.3416	0.0952	0.1126	0.0328	0.0265
Total Out	4.5748	2.5000	0.8363	1.0332	0.3157	0.2296
Mass Balance % (Out/In)	99.45	100.00	101.99	101.29	105.23	104.37
% Extraction	95.56	99.40	85.27	79.67	78.93	89.48

Table C11.4: Extraction vs time data for Leach 11.

Time (min)	% Extraction						RedoxPot (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1028.6
5	65.957	74.080	61.219	54.510	58.000	60.000	996.8
15	69.322	78.368	67.029	62.294	63.955	68.121	964.2
20	74.676	81.677	70.393	64.998	66.582	70.807	1000.5
30	76.376	82.303	71.108	69.598	67.885	73.473	1006.7
40	77.346	84.864	74.420	70.739	69.178	76.118	1007.2
50	79.815	87.097	75.359	71.872	70.462	76.993	1011.2
60	82.638	87.326	76.291	72.621	71.735	77.861	1012.1
70	83.050	91.267	76.753	73.364	72.367	78.723	1012.4
80	83.622	91.568	77.212	73.732	72.993	79.577	1012.5
90	83.987	92.762	77.667	74.098	73.615	80.425	1013.4
100	84.510	93.058	78.118	74.642	74.232	81.266	1014.6
110	84.989	93.718	78.565	75.182	74.843	82.100	1013.8
120	86.255	94.301	79.009	75.717	74.843	82.927	1014.2
150	87.589	95.023	79.890	76.779	75.445	83.748	1014.6
180	90.546	95.596	80.981	77.656	75.445	84.561	1014.3
210	91.627	96.022	81.631	78.004	76.037	85.368	1014.8
240	93.234	96.796	82.489	78.350	76.623	86.168	1014.6
270	93.765	97.285	82.915	78.692	77.205	86.961	1015.2
300	94.555	97.977	83.337	79.031	77.782	87.748	1014.2
330	95.114	98.663	84.173	79.367	78.353	88.527	1015.3
360	95.557	99.479	85.210	79.701	78.920	89.300	1015.4

RUN 12

Leaching Condition

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= 825 cm^3min^{-1}
N_2 flowrate	= 310 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C12.1 Raw Data for the Leaching Experiment 12.

Time (min)	Sample Vol. (ml)	Sample Analysis results in % and ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	665	436	85	124	45	30
15	15	1025	637	115	163	56	41
20	15	1124	680	128	181	60	48
30	15	1242	761	146	206	67	54
40	15	1365	812	160	226	71	60
50	15	1428	852	172	246	76	64
60	15	1504	895	184	260	80	68
70	15	1567	916	191	274	83	70
80	15	1611	938	201	283	85	72
90	15	1686	970	206	292	87	74
100	15	1718	1000	215	302	89	76
110	15	1762	1020	221	310	90	77
120	15	1795	1042	228	317	92	79
150	15	1870	1092	242	334	94	82
180	15	1918	1118	255	345	95	84
210	15	1952	1134	263	354	96	86
240	15	1980	1145	270	360	97	88
270	15	2004	1162	275	365	98	89
300	15	2038	1174	280	370	99	90
330	15	2072	1186	285	373	100	91
360	15	2098	1192	288	375	101	92
Pregn.		2098	1192	288	375	101	92
Wash A	in (ppm)	32	19	11	7	4	3
Wash B	in (ppm)	1	<1	<1	1	<1	<1
Residue	in (%)	8.38	2.85	3.99	4.49	1.55	0.57

Liquids:

Volume of liq. (HCl) into Leach = 2.00 L
Volume of liq. (HCl) ex-leach = 1.672 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C12.2: Assay values for Leach 12 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	8.38	2.85	3.59	4.49	1.55	0.57
Solids in sample	2.14	1.61	1.78	1.94	0.84	1.32

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 6.36 g
Solids in sample	= 0.48 g
Solids dissolved in solution	= 13.16 g

Table C12.3: Mass Balance for Leach 12

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.5330	0.1813	0.2538	0.2856	0.0986	0.0363
Solids in sample	0.0103	0.0077	0.0085	0.0093	0.0040	0.0063
Pregn. Solution	3.5079	1.9930	0.4815	0.6270	0.1689	0.1538
Wash A Liquor	0.0150	0.0095	0.0055	0.0035	0.0020	0.0015
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.4849	0.2844	0.0518	0.0853	0.0249	0.0214
Total Out	4.5535	2.4774	0.8127	1.0122	0.2999	0.2208
Mass Balance % (Out/In)	98.99	99.10	99.11	99.23	99.96	100.35
% Extraction	88.07	92.37	67.72	70.87	65.78	80.71

Table C12.4: Extraction vs time data for Leach 12.

Time	% Extraction						RedoxPot.
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1032.6
5	28.913	34.880	20.732	24.314	30.000	27.273	986.9
15	44.448	50.839	27.994	31.903	37.278	37.198	980.4
20	48.688	54.228	31.117	35.360	39.905	43.466	1000.4
30	53.703	60.562	35.409	40.172	44.467	48.798	1002.2
40	58.890	64.520	38.721	43.976	47.053	54.089	1003.5
50	61.526	67.600	41.538	47.750	50.262	57.589	1004.2
60	64.682	70.121	44.333	50.372	52.808	61.061	1005.1
70	67.277	72.471	45.951	52.973	54.703	62.784	1007.9
80	69.076	74.125	48.243	54.631	55.957	64.493	1011.2
90	72.116	76.512	49.381	56.277	57.200	66.189	1012.4
100	73.403	78.732	51.411	58.091	58.433	67.871	1012.9
110	75.159	80.200	52.754	59.530	59.045	68.705	1014.2
120	76.464	81.802	54.307	60.779	60.258	70.359	1015.4
150	79.407	85.412	57.389	63.787	61.462	72.821	1016.2
180	81.275	87.273	60.227	65.718	62.058	74.448	1017.5
210	82.587	88.409	61.959	67.284	62.650	76.061	1018.4
240	83.658	89.184	63.461	68.319	63.237	77.661	1018.6
270	84.569	90.370	64.525	69.175	63.818	78.455	1018.4
300	85.847	91.201	65.580	70.022	64.395	79.241	1018.1
330	87.115	92.024	66.626	70.527	64.967	80.021	1018.4
360	88.076	92.432	67.248	70.860	65.533	80.793	1018.4

RUN 13

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= 825 cm^3min^{-1}
N_2 flowrate	= 200 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C13.1: Raw Data for the Leaching Experiment 13.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	724	496	108	141	49	35
15	15	1096	680	146	182	64	49
20	15	1232	750	162	199	69	54
30	15	1344	828	180	234	74	60
40	15	1460	874	192	250	79	65
50	15	1528	914	207	268	84	68
60	15	1608	950	216	282	87	71
70	15	1658	972	223	299	90	74
80	15	1708	996	228	306	92	76
90	15	1765	1022	234	317	94	78
100	15	1788	1044	242	325	96	79
110	15	1830	1064	244	330	97	81
120	15	1860	1075	252	336	98	82
150	15	1942	1114	262	352	100	85
180	15	2010	1145	269	364	100	87
210	15	2050	1168	278	370	101	89
240	15	2090	1178	284	375	102	90
270	15	2120	1188	290	378	103	91
300	15	2130	1197	295	381	103	92
330	15	2140	1210	302	383	104	93
360	15	2150	1216	306	386	105	94
Pregn.		2150	1216	306	386	105	94
Wash A	in (ppm)	46	21	18	10	6	4
Wash B	in (ppm)	1	<1	<1	<1	<1	<1
Residue	in (%)	7.15	2.15	3.80	4.45	1.52	0.53

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.672 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C13.2: Assay values for Leach 13 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	7.15	2.15	3.80	4.45	1.52	0.53
Solids in sample	2.02	1.42	1.56	1.81	0.72	1.26

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 5.87 g
Solids in sample	= 0.54 g
Solids dissolved in solution	= 13.59 g

Table C13.3: Mass Balance for Leach 13

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.4197	0.1262	0.2221	0.2612	0.0892	0.0311
Solids in sample	0.0109	0.0077	0.0084	0.0098	0.0039	0.0068
Pregn. Solution	3.5948	2.0332	0.5116	0.6454	0.1756	0.1572
Wash A Liquor	0.0230	0.0105	0.0090	0.0050	0.0030	0.0020
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5112	0.2980	0.0692	0.0911	0.0268	0.0225
Total Out	4.5611	2.4770	0.8228	1.0140	0.3000	0.2211
Mass Balance % (Out/In)	99.15	99.08	100.35	99.41	99.99	100.49
% Extraction	90.56	94.60	71.87	73.27	68.96	82.85

Table C13.4: Extraction vs time data for Leach 13.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1026.7
5	31.478	39.680	26.342	27.647	32.667	31.818	1000.4
15	47.531	54.290	35.540	35.626	42.592	44.450	1001.2
20	53.355	59.806	39.384	38.909	45.875	48.927	1007.2
30	58.115	65.905	43.676	45.618	49.133	54.259	1005.6
40	63.007	69.475	46.515	48.661	52.367	58.668	1009.6
50	65.853	72.555	50.036	52.058	55.575	61.293	1012.9
60	69.050	75.305	52.132	54.679	57.485	63.898	1014.6
70	71.234	76.973	53.750	57.838	59.380	66.482	1012.2
80	73.277	78.778	54.896	59.128	60.633	68.191	1013.5
90	75.588	80.717	56.261	61.139	61.877	69.886	1014.0
100	76.513	82.345	58.066	62.590	63.110	70.727	1015.3
110	78.189	83.813	58.513	63.490	63.722	72.396	1016.7
120	79.375	84.614	60.289	64.560	64.328	73.223	1017.2
150	82.393	87.430	62.490	67.392	65.532	75.684	1017.3
180	85.239	89.649	64.018	69.498	65.532	77.311	1018.3
210	86.783	91.282	65.967	70.542	66.123	78.925	1019.4
240	88.313	91.986	67.254	71.404	66.710	79.725	1019.5
270	89.451	92.684	68.531	71.918	67.292	80.518	1019.9
300	89.827	93.307	69.586	72.427	67.292	81.305	1013.8
330	90.200	94.199	71.050	72.673	67.863	82.084	1013.8
360	90.570	94.607	71.879	73.263	68.430	82.857	1013.8

RUN 14

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= 825 cm^3min^{-1}
N_2 flowrate	= 90 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

C14.1: Raw Data for the Leaching Experiment 14.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	795	572	133	161	52	41
15	15	1178	740	178	217	68	54
20	15	1328	821	192	238	70	59
30	15	1468	905	208	273	76	65
40	15	1597	945	225	291	85	71
50	15	1662	992	236	310	87	74
60	15	1738	1022	246	326	89	76
70	15	1790	1040	255	336	94	78
80	15	1830	1068	260	342	96	80
90	15	1878	1084	265	348	98	82
100	15	1900	1106	270	354	99	83
110	15	1938	1126	274	358	100	84
120	15	2000	1138	278	365	101	85
150	15	2060	1170	286	370	102	87
180	15	2090	1196	294	378	103	89
210	15	2110	1208	300	384	104	91
240	15	2120	1216	305	390	105	93
270	15	2130	1226	314	396	106	94
300	15	2160	1231	320	400	107	95
330	15	2170	1236	324	408	108	96
360	15	2180	1240	328	412	109	97
Pregn.		2180	1240	328	412	109	97
Wash A	in (ppm)	52	25	20	12	7	5
Wash B	in (ppm)	1	1	1	<1	<1	<1
Residue	in (%)	6.69	1.36	3.49	4.11	1.65	0.51

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.670 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C14.2: Assay values for Leach 14 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	6.69	1.36	3.49	4.11	1.65	0.51
Solids in sample	1.97	1.28	1.48	1.78	0.69	1.19

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 5.12 g
Solids in sample	= 0.46 g
Solids dissolved in solution	= 14.42 g

Table C14.3: Mass Balance for Leach 14

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.3425	0.0696	0.1787	0.2104	0.0845	0.0261
Solids in sample	0.0091	0.0059	0.0068	0.0082	0.0032	0.0055
Pregn. Solution	3.6406	2.0708	0.5478	0.6880	0.1820	0.1620
Wash A Liquor	0.0260	0.0125	0.0100	0.0060	0.0035	0.0025
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5391	0.3156	0.0775	0.0997	0.0278	0.0237
Total Out	4.5588	2.4760	0.8222	1.0138	0.3024	0.2212
Mass Balance % (Out/In)	99.10	99.04	100.27	99.40	100.81	100.56
% Extraction	92.29	96.95	77.44	78.44	71.02	85.72

Table C14.4: Extraction vs time data for Leach 14.

Time (min)	% Extraction						RedoxPot (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1032.6
5	34.565	45.760	32.439	31.569	34.667	37.273	974.0
15	51.093	59.099	43.332	42.467	45.253	49.002	971.5
20	57.516	65.482	46.696	46.523	46.567	53.480	992.6
30	63.466	72.051	50.510	53.231	50.477	58.811	1005.6
40	68.907	75.155	54.532	56.654	56.297	64.102	1008.8
50	71.627	78.774	57.1146	60.240	57.580	66.727	1007.5
60	74.783	81.066	59.444	63.236	58.853	68.464	1011.1
70	76.925	82.430	61.524	65.094	62.012	70.186	1012.5
80	78.560	84.536	62.670	66.200	63.265	71.896	1012.3
90	80.506	85.729	63.807	67.297	64.508	73.591	1013.5
100	81.390	87.357	64.935	68.385	65.125	74.432	1014.2
110	82.906	88.825	65.831	69.105	65.737	75.266	1015.7
120	85.359	89.699	66.718	70.3**	66.343	76.093	1016.8
150	87.714	92.009	68.479	71.239	66.945	77.734	1017.2
180	88.881	93.871	70.226	72.643	67.542	79.361	1017.6
210	89.653	94.723	71.524	73.687	68.133	80.975	1017.4
240	90.035	95.286	72.598	74.722	68.720	82.575	1017.3
270	90.415	95.984	74.513	75.749	69.302	83.368	1016.9
300	91.543	96.330	75.779	76.427	69.878	84.155	1017.4
330	91.916	96.673	76.615	77.772	70.450	84.934	1018.5
360	92.285	96.945	77.445	78.439	71.017	85.707	1019.8

RUN 15

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= No Chlorine
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C15.1: Raw Data for the Leaching Experiment 15.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	480	300	42	52	12	0.1
15	15	600	405	54	78	17	0.1
20	15	650	432	63	86	20	0.2
30	15	710	460	72	98	22	0.2
40	15	760	500	80	104	24	0.3
50	15	790	520	85	110	26	0.3
60	15	820	544	88	114	27	0.4
70	15	860	564	90	117	28	0.5
80	15	880	572	92	121	29	0.6
90	15	895	586	93	126	30	0.7
100	15	910	598	94	128	30	0.8
110	15	920	607	95	131	30	0.9
120	15	930	618	96	133	31	1.0
150	15	935	641	97	134	31	1.0
180	15	937	658	98	135	31	1.0
210	15	939	675	98	136	31	1.0
240	15	940	692	98	137	32	1.0
270	15	940	703	98	138	32	1.0
300	15	940	712	98	138	32	1.0
330	15	940	720	98	139	32	1.0
360	15	940	725	98	140	32	1.0
Pregn.		940	725	98	140	32	1.0
Wash A	in (ppm)	45	52	14	12	5	4
Wash B	in (ppm)	1	2	1	1	<1	<1
Residue	in (%)	2.10	0.42	2.20	4.78	1.50	0.36

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.668 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C15.2: Assay values for Leach 15 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	2.10	0.42	2.20	4.78	1.50	0.36
Solids in sample	0.45	0.24	0.36	0.71	0.21	0.20

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 3.72 g
Solids in sample	= 0.38 g
Solids dissolved in solution	= 15.90 g

Table C15.3: Mass Balance for Leach 15

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0781	0.0156	0.0818	0.1778	0.0558	0.0134
Solids in sample	0.0017	0.0009	0.0014	0.0027	0.0008	0.0008
Pregn. Solution	3.8898	2.1250	0.6355	0.7189	0.208[illegible]	0.1768
Wash A Liquor	0.0225	0.0260	0.0070	0.0060	0.0025	0.0020
Wash B Liquor	0.0015	0.0030	0.0015	0.0015	0.0015	0.0015
Samples	0.5657	0.3297	0.0931	0.1053	0.0307	0.0257
Total Out	4.5593	2.5003	0.8203	1.0122	0.2998	0.2201
Mass Balance % (Out/In)	99.11	100.01	100.04	99.23	99.94	100.05
% Extraction	98.25	99.34	89.86	82.17	81.12	93.57

Table C15.4: Extraction vs time data for Leach 15.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	860.9
5	20.870	24.000	10.244	10.196	11.308	0.091	614.8
15	26.048	32.337	13.149	15.256	13.278	0.091	524.6
20	28.189	34.465	15.311	16.801	14.582	0.180	436.2
30	30.739	36.654	17.457	19.101	15.875	0.180	410.6
40	32.848	39.758	19.349	20.242	17.158	0.269	398.8
50	34.103	41.298	20.523	21.375	17.795	0.269	388.4
60	35.349	43.132	21.222	22.124	18.427	0.355	382.6
70	36.997	44.648	21.684	22.681	19.053	0.442	378.4
80	37.814	45.249	22.143	23.418	19.675	0.527	380.1
90	38.422	46.294	22.370	24.332	19.675	0.612	380.0
100	39.026	47.182	22.596	24.695	19.675	0.696	380.1
110	39.425	47.842	22.820	25.253	20.282	0.779	385.4
120	39.820	48.643	23.042	25.592	20.282	0.862	390.1
150	40.016	50.304	23.262	25.769	20.282	0.862	392.5
180	40.094	51.521	23.480	25.944	20.282	0.862	392.8
210	40.171	52.728	23.480	26.118	20.282	0.862	392.6
240	40.210	53.925	23.480	26.291	20.868	0.862	392.8
270	40.210	54.693	23.480	26.462	20.868	0.862	394.2
300	40.210	55.315	23.480	26.462	20.868	0.862	394.4
330	40.210	55.864	23.480	26.630	20.868	0.862	394.8
360	40.210	56.204	23.480	26.797	20.868	0.862	395.6

RUN 16

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Particle size	= -38 μm
Total leaching period	= 6.00 hours

Table C16.1: Raw Data for the Leaching Experiment 16.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1793	1070	282	307	90	91
15	15	1890	1108	290	315	92	93
20	15	1925	1129	300	328	97	95
30	15	1965	1142	298	339	98	97
40	15	2003	1158	307	343	105	98
50	15	2024	1167	305	351	104	99
60	15	2042	1186	310	357	109	100
70	15	2074	1200	320	370	108	101
80	15	2088	1206	318	369	112	102
90	15	2086	1213	331	381	113	103
100	15	2136	1231	334	379	114	103
110	15	2130	1238	339	384	115	104
120	15	2160	1248	343	395	116	105
150	15	2192	1254	350	405	118	106
180	15	2218	1262	356	415	120	107
210	15	2242	1268	362	423	122	107
240	15	2265	1272	368	426	124	108
270	15	2286	1278	374	428	126	109
300	15	2306	1282	376	432	128	110
330	15	2338	1286	380	435	129	111
360	15	2342	1292	381	442	131	112
Pregn.		2342	1292	381	442	131	112
Wash A	in (ppm)	68	54	21	18	12	8
Wash B	in (ppm)	1	1	1	1	<1	<1
Residue	in (%)	0.32	0.06	2.70	5.95	1.62	0.08

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.665 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C16.2: **Assay values for Leach 16 solids**

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.[illegible]0	5.10	1.50	1.10
Residue	0.32	0.06	2.70	5.95	1.62	0.08
Solids in sample	0.26	0.09	1.28	0.94	0.85	0.05

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 2.54 g
Solids in sample	= 0.30 g
Solids dissolved in solution	= 17.16 g

Table C16.3: **Mass Balance for Leach 16**

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0081	0.0015	0.0686	0.1511	0.0412	0.0020
Solids in sample	0.0008	0.0003	0.0038	0.0028	0.0026	0.0002
Pregn. Solution	3.8994	2.1512	0.6344	0.7359	0.2181	0.1865
Wash A Liquor	0.0340	0.0270	0.0105	0.0090	0.0060	0.0040
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.6325	0.3630	0.0997	0.1137	0.0336	0.0307
Total Out	4.5763	2.5444	0.8184	1.0141	0.3029	0.2249
Mass Balance % (Out/In)	99.48	101.78	99.81	99.42	100.97	102.22
% Extraction	99.31	99.[illegible]	91.15	84.81	85.57	99.03

Table C16.4: **Extraction vs time data for Leach 16.**

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1023.5
5	77.957	85.600	68.781	60.[illegible]96	60.000	82.727	991.2
15	82.142	88.617	70.717	61.[illegible]3	61.323	84.532	1002.8
20	83.641	90.272	73.120	64.264	64.607	86.323	1008.3
30	85.341	91.289	72.643	66.372	65.258	88.100	1012.4
40	86.944	92.530	74.772	67.133	69.785	88.982	1011.9
50	87.823	93.223	74.302	68.643	69.143	89.857	1012.6
60	88.570	94.675	75.467	69.766	72.327	90.725	1017.2
70	89.888	95.736	77.778	72.181	71.695	91.586	1020.6
80	90.460	96.187	77.320	71.997	74.202	92.441	1016.2
90	90.379	96.709	80.276	74.191	74.823	93.289	1012.8
100	92.390	98.041	80.953	73.828	75.440	93.289	1012.5
110	92.151	98.555	82.072	74.728	76.052	94.123	1012.2
120	93.338	99.283	82.960	76.691	76.658	94.950	1014.3
150	94.594	99.716	84.501	78.460	77.862	95.771	1013.4
180	95.605	100.29	85.810	80.215	79.055	96.584	1015.2
210	96.531	100.72	87.109	81.607	80.238	96.584	1015.4
240	97.411	100.99	88.397	82.125	81.412	97.384	1015.1
270	98.208	101.42	89.674	82.467	82.575	98.177	1016.4
300	98.960	101.69	90.096	83.146	83.728	98.964	1017.2
330	100.15	101.97	90.932	83.650	84.300	99.743	1018.3
360	100.30	102.38	91.140	84.817	85.433	100.52	1018.6

RUN 17

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Particle size	= -150 +90 μm
Total leaching period	= 6.00 hours

Table C17.1 Raw Data for the Leaching Experiment 17.

Time (min)	Sample Vol. (ml)	Sample Analysis results in % and ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1525	1005	248	265	84	64
15	15	1676	1098	271	291	90	76
20	15	1790	1110	286	300	95	80
30	15	1885	1130	288	317	96	84
40	15	1938	1132	293	332	99	87
50	15	2016	1160	304	345	103	90
60	15	2024	1158	314	352	107	92
70	15	2048	1187	305	365	106	94
80	15	2072	1189	318	368	107	96
90	15	2093	1204	323	372	109	97
100	15	2106	1212	334	376	110	98
110	15	2138	1218	328	381	112	99
120	15	2160	1228	338	388	114	100
150	15	2186	1236	342	396	116	102
180	15	2215	1243	348	402	118	104
210	15	2230	1252	355	408	120	106
240	15	2242	1253	359	415	122	107
270	15	2256	1256	363	419	124	108
300	15	2274	1259	366	421	125	109
330	15	2300	1261	369	423	126	110
360	15	2304	1262	371	425	127	111
Pregn.		2304	1262	371	425	127	111
Wash A	in (ppm)	32	11	23	20	8	4
Wash B	in (ppm)	1	<1	<1	1	<1	<1
Residue	in (%)	1.68	0.08	2.34	4.80	1.29	0.07

Liquids:

Volume of liq. (HCl) into Leach = 2.00 L
Volume of liq. (HCl) ex-leach = 1.668 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C17.2: Assay values for Leach 17 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	1.68	0.08	2.34	4.80	1.29	0.07
Solids in sample	0.42	1.07	1.45	1.84	0.96	0.08

Masses Recorded :

Sample into Leach	= 20.0 g
Residu	= 3.76 g
Solids in sample	= 0.32 g
Solids dissolved in solution	= 15.92 g

Table C17.3: Mass Balance for Leach 17

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0632	0.0020	0.0880	0.1805	0.0485	0.0026
Solids in sample	0.0013	0.0034	0.0046	0.0059	0.0031	0.0003
Pregn. Solution	3.8431	2.1050	0.6188	0.7089	0.2118	0.1852
Wash A Liquor	0.0160	0.0055	0.0115	0.0100	0.0040	0.0020
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.6179	0.3569	0.0968	0.1100	0.0328	0.0286
Total Out	4.5430	2.4753	0.8212	1.0168	0.3017	0.2201
Mass Balance % (Out/In)	98.76	99.01	100.15	99.69	100.55	100.04
% Extraction	98.58	99.74	88.72	81.67	82.90	99.69

Table C17.4: Extraction vs time data for Leach 17.

Time (min)	% Extraction						RedoxPot. (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1025.8
5	66.304	80.400	60.488	51.961	56.000	58.182	986.3
15	72.820	87.784	66.056	57.021	59.970	69.009	989.9
20	77.703	88.730	69.659	58.759	63.253	72.591	1002.8
30	81.740	90.294	70.136	62.017	63.905	76.146	1007.8
40	83.975	90.449	71.319	64.870	65.845	78.791	1009.2
50	87.239	92.605	73.901	67.324	68.412	81.416	1009.4
60	87.572	92.452	76.231	68.634	70.958	83.152	1009.5
70	88.560	94.650	76.151	71.050	70.327	84.875	1010.2
80	89.541	94.801	77.131	71.603	70.953	86.584	1010.6
90	90.393	95.920	78.268	72.334	72.197	87.432	1011.2
100	90.915	96.512	80.750	73.059	72.813	88.273	1012.3
110	92.192	96.952	79.407	73.959	74.037	89.107	1012.5
120	93.062	97.680	81.627	75.208	75.250	89.934	1015.2
150	94.083	98.258	82.507	76.624	76.453	91.575	1016.3
180	95.211	98.759	83.817	77.677	77.647	93.202	1018.6
210	95.790	99.398	85.332	78.721	78.830	94.816	1020.1
240	96.249	99.468	86.191	79.928	80.003	95.616	1020.[illegible]
270	96.780	99.678	87.042	80.613	81.167	96.409	1021.[illegible]
300	98.209	99.885	87.675	80.952	81.743	97.196	1021.3
330	98.433	100.02	88.302	81.288	82.315	97.975	1020.4
360	98.581	100.09	88.717	81.622	82.882	98.748	1020.8

RUN 18

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Particle size	= 300 μm
Total leaching period	= 6.00 hours

Table C18.1: Raw Data for the Leaching Experiment 18.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1439	1005	260	285	80	64
15	15	1657	1042	280	298	85	72
20	15	1712	1062	284	312	88	75
30	15	1842	1097	292	326	90	80
40	15	1898	1115	300	336	93	84
50	15	1991	1132	305	343	96	86
60	15	2018	1145	310	350	98	88
70	15	2036	1151	314	362	100	90
80	15	2058	1173	315	361	102	92
90	15	2068	1186	318	368	103	94
100	15	2097	1192	324	374	104	96
110	15	2125	1204	328	378	106	97
120	15	2148	1210	330	382	107	98
150	15	2172	1218	336	390	110	100
180	15	2190	1230	340	394	112	102
210	15	2224	1238	346	399	114	103
240	15	2236	1247	351	402	115	105
270	15	2243	1260	355	406	116	106
300	15	2260	1261	360	410	118	107
330	15	2284	1262	361	413	119	108
360	15	2290	1264	362	415	120	109
Pregn.		2290	1264	362	415	120	109
Wash A	in (ppm)	35	25	21	16	7	4
Wash B	in (ppm)	1	<1	<1	<1	<1	<1
Residue	in (%)	2.37	0.07	2.65	5.09	1.54	0.16

Liquids:

Volume of liq (HCl) into Leach = 2.000 L

Volume of liq. (HCl) ex-leach = 1.667 L

Wash water volume (Wash A) = 500 ml

Wash water volume (Wash B) = 1500 ml.

Table C18.2: Assay values for Leach 18 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	2.37	0.77	2.65	5.09	1.54	0.16
Solids in sample	0.64	0.03	1.19	1.17	1.28	0.18

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 3.92 g
Solids in sample = 0.38 g

Solids dissolved in solution = 15.70 g

Table C18.3: Mass Balance for Leach 18

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0929	0.0027	0.1039	0.1995	0.0604	0.0063
Solids in sample	0.0024	0.0001	0.0045	0.0045	0.0049	0.0007
Pregn. Solution	3.8174	2.1071	0.6035	0.6918	0.2000	0.1817
Wash A Liquor	0.0175	0.0125	0.0105	0.0080	0.0035	0.0020
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.6105	0.3515	0.0961	0.1093	0.0308	0.0277
Total Out	4.5422	2.4754	0.8200	1.0146	0.3011	0.2199
Mass Balance % (Out/In)	98.74	99.02	100.00	99.47	100.37	99.94
% Extraction	97.90	99.88	86.78	79.90	78.34	96.84

Table C18.4: Extraction vs time data for Leach 18.

Time (min)	% Extraction						RedoxPot (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1028.4
5	62.565	80.400	63.415	55.882	53.333	58.182	993.2
15	71.972	83.338	68.256	58.412	56.642	65.400	1010.2
20	74.328	84.914	69.217	61.116	58.612	68.086	1018.3
30	79.853	87.651	71.124	63.800	59.915	72.530	1018.7
40	82.215	89.048	73.017	65.702	61.855	76.057	1019.2
50	86.106	90.357	74.191	67.023	63.780	77.807	1020.9
60	87.228	91.350	75.356	68.333	65.053	79.543	1024.1
70	87.969	91.735	76.280	70.563	66.317	81.266	1025.2
80	88.868	93.459	76.509	70.378	67.570	82.975	1022.8
90	89.274	94.429	77.192	71.658	68.192	84.671	1023.2
100	90.440	94.873	78.545	72.747	68.808	86.352	1019.6
110	91.557	95.754	79.440	73.466	70.032	87.186	1018.9
120	92.467	96.190	79.884	74.180	70.638	88.014	1019.7
150	93.409	96.768	81.205	75.596	72.443	89.655	1020.4
180	94.109	97.627	82.078	76.298	73.637	91.282	1021.6
210	95.421	98.195	83.377	77.168	74.820	92.089	1022.6
240	95.880	98.829	84.450	77.685	75.407	93.689	1022.6
270	96.146	99.736	85.301	78.370	75.988	94.482	1025.2
300	96.785	99.805	86.356	79.048	77.142	95.268	1024.0
330	97.680	99.874	86.565	79.553	77.713	96.048	1023.4
360	97.902	100.01	86.773	79.886	78.280	96.821	1024.1

RUN 19

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Particle size	= +500 -+425 μm
Total leaching period	= 6.00 hours

Table C19.1: Raw Data for the Leaching Experiment 19.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	962	610	140	186	56	46
15	15	1160	700	185	212	65	54
20	15	1316	780	200	248	72	60
30	15	1420	860	220	260	78	67
40	15	1510	920	235	284	81	70
50	15	1630	980	242	300	84	74
60	15	1680	1010	255	308	87	78
70	15	1710	1050	267	316	90	81
80	15	1780	1080	280	327	92	83
90	15	1810	1100	286	335	94	85
100	15	1840	1120	292	342	96	88
110	15	1870	1137	298	350	97	90
120	15	1920	1152	304	358	98	91
150	15	1980	1174	312	368	100	93
180	15	2020	1195	319	378	102	95
210	15	2070	1206	327	383	104	97
240	15	2120	1212	332	388	105	99
270	15	2160	1220	340	392	106	100
300	15	2200	1225	347	398	108	101
330	15	2230	1230	350	402	109	102
360	15	2260	1235	352	406	110	103
Pregn.		2260	1235	352	406	110	103
Wash A	in (ppm)	27	17	15	13	5	4
Wash B	in (ppm)	1	1	1	<1	<1	<1
Residue	in (%)	4.69	1.78	2.71	4.79	1.71	0.40

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.667 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C19.2: Assay values for Leach 19 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	4.69	1.78	2.71	4.79	1.71	0.40
Solids in sample	0.72	0.41	2.50	1.41	1.31	0.31

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 4.67 g
Solids in sample = 0.45 g

Solids dissolved in solution = 14.88 g

Table C19.3: Mass Balance for Leach 19

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.2190	0.0831	0.1266	0.2237	0.0799	0.0187
Solids in sample	0.0032	0.0019	0.0113	0.0064	0.0059	0.0014
Pregn. Solution	3.7674	2.0588	0.5868	0.6768	0.1834	0.1717
Wash A Liquor	0.0135	0.0085	0.0075	0.0065	0.0025	0.0020
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5308	0.3144	0.0830	0.0980	0.0274	0.0248
Total Out	4.5355	2.4681	0.8166	1.0129	0.3005	0.2201
Mass Balance % (Out/In)	98.60	98.73	99.58	99.30	100.16	100.04
% Extraction	95.10	96.56	93.12	77.29	71.46	90.88

Table C19.4: Extraction vs time data for Leach 19.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1026.0
5	41.826	48.800	34.146	36.471	37.333	41.818	1007.1
15	50.370	55.946	45.040	41.530	43.288	49.036	1009.7
20	57.051	62.250	48.643	48.483	47.885	54.409	1010.2
30	61.471	68.506	53.412	50.783	51.795	60.630	1012.3
40	65.267	73.162	56.960	55.348	53.735	63.275	1020.6
50	70.289	77.782	58.604	58.368	55.660	66.775	1025.1
60	72.365	80.074	61.632	59.866	57.570	70.248	1024.6
70	73.600	83.106	64.405	61.352	59.465	72.832	1024.3
80	76.461	85.362	67.385	63.379	60.718	74.541	1024.1
90	77.678	86.854	68.750	64.842	61.962	76.236	1021.3
100	78.884	88.334	70.104	66.112	63.195	78.759	1020.8
110	80.081	89.582	71.446	67.551	63.807	80.427	1020.1
120	82.059	90.674	72.778	68.978	64.413	81.255	1019.8
150	84.414	92.262	74.539	70.748	65.617	82.896	1018.8
180	85.970	93.766	76.067	72.503	66.810	84.523	1018.4
210	87.899	94.547	77.799	73.37?	67.993	86.136	1018.4
240	89.812	94.969	78.872	74.236	68.580	87.736	1018.4
270	91.330	95.528	80.574	74.920	69.162	88.530	1019.4
300	92.834	95.874	82.051	75.938	70.315	89.316	1019.5
330	93.953	96.217	82.670	76.610	70.887	90.096	1019.8
360	95.061	96.557	83.093	77.277	71.453	90.868	1019.5

RUN 20

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Particle size	= -850 +600 μm
Total leaching period	= 6.00 hours

Table C20.1: Raw Data for the Leaching Experiment 20.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	672	448	99	115	41	28
15	15	924	578	126	174	50	36
20	15	1012	670	158	190	58	47
30	15	1238	748	181	211	61	55
40	15	1360	812	195	228	69	62
50	15	1460	856	203	241	74	69
60	15	1540	880	211	250	77	74
70	15	1580	932	230	261	82	78
80	15	1632	964	244	272	83	82
90	15	1660	992	256	280	86	84
100	15	1710	1020	261	289	89	86
110	15	1760	1045	264	298	91	88
120	15	1790	1070	270	305	93	89
150	15	1872	1098	282	320	95	92
180	15	1942	1118	290	333	97	94
210	15	2026	1142	300	345	98	95
240	15	2040	1168	304	354	99	96
270	15	2100	1189	315	366	100	97
300	15	2115	1208	320	372	100	98
330	15	2130	1215	332	380	100	99
360	15	2150	1224	340	388	100	100
Pregn.		2150	1224	340	388	100	100
Wash A	in (ppm)	24	16	12	8	6	3
Wash B	in (ppm)	1	2	1	1	<1	<1
Residue	in (%)	7.97	2.21	2.98	4.92	1.83	0.41

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L

Volume of liq. (HCl) ex-leach = 1.668 L

Wash water volume (Wash A) = [illegible] ml

Wash water volume (Wash B) = [illegible] ml.

Table C20.2: Assay values for Leach 20 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	7.97	2.21	2.98	4.92	1.83	0.41
Solids in sample	2.64	1.76	1.03	1.06	1.19	0.82

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 5.46 g
Solids in sample = 0.52 g

Solids dissolved in solution = 14.02 g

Table C20.3: Mass Balance for Leach 20

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach,						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach,						
Residue	0.4352	0.1207	0.1627	0.2686	0.0999	0.0224
Solids in sample	0.0137	0.0092	0.0054	0.0055	0.0062	0.0043
Pregn. Solution	3.5862	2.0416	0.5671	0.6472	0.1668	0.1668
Wash A Liquor	0.0120	0.0080	0.0060	0.0040	0.0030	0.0015
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.4885	0.2873	0.0726	0.0838	0.0247	0.0232
Total Out	4.5370	2.4683	0.8153	1.0106	0.3021	0.2197
Mass Balance % (Out/In)	98.63	98.73	99.43	99.08	100.69	99.86
% Extraction	90.11	94.74	79.39	72.87	64.87	87.87

Table C20.4: Extraction vs time data for Leach 20.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1018.6
5	29.217	35.840	24.146	22.549	27.333	25.455	1015.3
15	40.092	46.162	30.682	34.031	33.288	32.673	1015.4
20	43.860	53.412	38.370	37.121	38.542	42.523	1016.2
30	53.465	59.511	43.854	41.146	40.497	49.632	1016.2
40	58.611	64.478	47.166	44.379	45.670	55.805	1016.6
50	62.795	67.866	49.044	46.833	48.878	61.930	1016.9
60	66.117	69.699	50.907	48.518	50.788	66.271	1017.2
70	67.765	73.641	55.298	50.562	53.947	69.716	1017.4
80	69.890	76.047	58.508	52.589	54.573	73.134	1017.5
90	71.025	78.136	61.237	54.052	56.438	74.830	1017.8
100	73.035	80.208	62.365	55.684	58.288	76.511	1017.2
110	75.031	82.043	63.037	57.303	59.512	78.180	1017.9
120	76.218	83.863	64.368	58.553	60.725	79.007	1017.8
150	79.435	85.885	67.010	61.207	61.928	81.468	1018.4
180	82.159	87.317	68.756	63.488	63.122	83.096	1019.4
210	85.401	89.021	70.921	65.577	63.713	83.902	1018.1
240	85.936	90.851	71.779	67.129	64.300	84.702	1017.4
270	88.212	92.317	74.120	69.182	64.882	85.496	1017.6
300	88.777	93.632	75.175	70.200	64.882	86.282	1018.1
330	89.336	94.112	77.685	71.545	64.882	87.061	1018.6
360	90.075	94.724	79.343	72.878	64.882	87.834	1018.2

RUN 21

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 80 rpm
Total leaching period	= 6.00 hours

Table C21.1: Raw Data for the Leaching Experiment 21.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	724	552	102	108	28	38
15	15	998	660	140	160	50	42
20	15	1120	725	170	187	54	48
30	15	1230	789	188	207	65	54
40	15	1346	842	201	226	69	59
50	15	1398	868	210	240	75	63
60	15	1534	915	225	248	78	66
70	15	1565	946	230	257	80	68
80	15	1625	960	242	270	82	70
90	15	1648	982	248	278	84	72
100	15	1698	1005	253	290	86	74
110	15	1736	1018	260	297	88	76
120	15	1758	1027	265	306	89	77
150	15	1798	1068	278	328	91	80
180	15	1841	1087	288	341	93	83
210	15	1868	1115	296	352	95	85
240	15	1892	1127	304	359	97	87
270	15	1913	1140	311	368	99	89
300	15	1945	1152	318	373	100	90
330	15	1960	1164	327	376	101	91
360	15	1970	1170	332	379	102	92
Pregn.		1970	1170	332	379	102	92
Wash A	in (ppm)	18	11	6	4	2	4
Wash B	in (ppm)	1	1	1	1	<1	<1
Residue	in (%)	9.11	2.56	2.07	3.42	1.19	0.42

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.670 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C21.2: Assay values for Leach 21 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	9.11	2.56	2.07	3.42	1.19	0.42
Solids in sample	2.36	1.57	1.74	1.03	0.58	1.35

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 8.27 g
Solids in sample	= 0.58 g
Solids dissolved in solution	= 11.15 g

Table C21.3: Mass Balance for Leach 21

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.7534	0.2117	0.1712	0.2828	0.0984	0.0347
Solids in sample	0.0137	0.0091	0.0101	0.0060	0.0034	0.0078
Pregn. Solution	3.2899	1.9539	0.5544	0.6329	0.1703	0.1536
Wash A Liquor	0.0090	0.0055	0.0030	0.0020	0.0010	0.0020
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.4740	0.2871	0.0728	0.0836	0.0241	0.0212
Total Out	4.5415	2.4689	0.8131	1.0088	0.2987	0.2209
Mass Balance % (Out/In)	98.73	98.75	99.15	98.90	99.56	100.40
% Extraction	83.11	91.06	77.70	71.37	65.92	80.73

Table C21.4: Extraction vs time data for Leach 21.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1019.5
5	31.478	44.160	24.878	21.177	18.667	34.546	970.3
15	43.302	52.735	34.077	31.296	33.223	38.155	1010.8
20	48.527	57.857	41.784	36.511	35.850	43.527	1012.3
30	53.202	62.862	45.57o	40.344	43.018	48.859	1012.9
40	58.094	66.975	48.651	43.958	45.605	53.268	1012.4
50	60.270	68.977	50.764	46.600	49.455	56.768	1013.4
60	65.917	72.568	54.258	48.098	51.365	59.373	1013.7
70	67.194	74.917	55.413	49.770	52.628	61.096	1016.4
80	69.646	75.970	58.165	52.166	53.882	62.805	1017.6
90	70.579	77.611	59.529	53.629	55.125	64.500	1017.1
100	72.590	79.313	60.657	55.805	56.358	66.182	1017.2
110	74.105	80.268	62.224	57.065	57.582	67.850	1016.8
120	74.976	80.923	63.334	58.671	58.188	68.677	1017.0
150	76.545	83.883	66.195	62.564	59.392	71.139	1016.9
180	78.219	85.243	68.378	64.845	60.585	73.580	1017.2
210	79.261	87.231	70.110	66.759	61.768	75.193	1017.1
240	80.179	88.076	71.827	67.967	62.942	76.793	1017.0
270	80.975	88.984	73.317	69.507	64.105	78.380	1017.2
300	82.179	89.814	74.793	70.355	64.682	79.166	1017.3
330	82.738	90.637	76.676	70.859	65.253	79.946	1017.4
360	83.108	91.045	77.712	71.359	65.82	80.718	1018.0

RUN 22

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 210 rpm
Total leaching period	= 6.00 hours

Table C22.1 Raw Data for the Leaching Experiment 22.

Time (min)	Sample Vol. (ml)	Sample Analysis results in % or ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	960	658	140	145	51	41
15	15	1120	752	175	178	58	52
20	15	1210	800	188	200	66	58
30	15	1345	850	208	224	73	63
40	15	1438	910	223	242	78	68
50	15	1520	928	241	272	82	73
60	15	1610	962	250	286	95	76
70	15	1685	980	260	295	[illegible]	79
80	15	1740	1012	270	305	89	82
90	15	1770	1042	278	314	91	84
100	15	1824	1068	285	325	93	86
110	15	1845	1072	292	332	94	88
120	15	1870	1086	300	338	95	90
150	15	1910	1132	310	353	98	93
180	15	1972	1150	320	362	100	96
210	15	1996	1163	330	369	103	98
240	15	2026	1181	336	375	106	100
270	15	2048	1188	340	380	108	102
300	15	2082	1193	345	386	109	103
330	15	2112	1208	350	390	110	104
360	15	2131	1217	354	393	111	105
Pregn.		2131	1217	354	393	111	105
Wash A	in (ppm)	46	21	11	7	4	6
Wash B	in (ppm)	1	<1	<1	1	<1	<1
Residue	in (%)	7.84	2.05	2.21	4.31	1.31	0.21

Liquids:

Volume of liq. (HCl) into Leach = 2.00 L
Volume of liq. (HCl) ex-leach = 1.670 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C22.2: Assay values for Leach 22 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	7.84	2.05	2.21	4.31	1.31	0.21
Solids in sample	1.87	1.31	1.65	1.84	1.90	1.05

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 5.78 g
Solids in sample	= 0.47 g
Solids dissolved in solution	= 13.75 g

Table C22.3: Mass Balance for Leach 22

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.4532	0.1185	0.1277	0.2497	0.0757	0.0121
Solids in sample	0.0088	0.0062	0.0078	0.0087	0.0089	0.0049
Pregn. Solution	3.5588	2.0324	0.5912	0.6563	0.1854	0.1754
Wash A Liquor	0.0230	0.0105	0.0055	0.0035	0.0020	0.0030
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5113	0.3050	0.0816	0.0911	0.0266	0.0245
Total Out	4.5565	2.4741	0.8153	1.0107	0.3002	0.2215
Mass Balance % (Out/In)	99.05	98.96	99.43	99.09	100.05	100.67
% Extraction	89.86	94.96	83.38	74.44	71.80	92.29

Table C22.4: Extraction vs time data for Leach 22.

Time	% Extraction						RedoxPot.
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1018.0
5	41.739	52.640	34.146	28.431	34.000	37.273	989.6
15	48.644	60.104	42.619	34.853	38 632	47.198	1004.6
20	52.498	63.886	45.742	39.103	43.885	52.571	1006.2
30	58.235	67.796	50.510	43.703	48.447	57.014	1007.0
40	62.158	72.452	54.059	47.126	51.680	61.423	1008.8
50	65.589	73.838	58.285	52.788	54.247	65.798	1008.8
60	69.326	76.436	60.381	55.409	56.157	68.402	1009.5
70	72.416	77.800	62.692	57.081	57.420	70.986	1011.4
80	74.664	80.206	64.985	58.925	58.673	73.550	1012.5
90	75.880	82.444	66.804	60.570	59.917	75.246	1013.0
100	78.052	84.368	68.384	62.565	61.150	76.927	1014.1
110	78.889	84.662	69.950	63.825	61.762	78.596	1015.8
120	79.878	85.681	71.726	64.895	62.368	80.250	1016.1
150	81.448	89.002	73.927	67.550	64.173	82.711	1015.7
180	83.861	90.291	76 110	69.129	65.367	85.152	1016.1
210	84.787	91.214	78.274	70.347	67.142	86.766	1017.1
240	85.935	92.481	79.562	71.382	68.902	88.36[illegible]	1017.5
270	86.769	92.970	80.413	72.238	70.065	89.952	1017.3
300	88.048	93.316	81.468	73.255	70.642	90.739	1018.1
330	89.166	94.345	82.51[illegible]	73 928	71.213	91.518	1018.4
360	89.868	94.957	83.343	74.428	71.780	92.291	1018.6

RUN 23

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 320 rpm
Total leaching period	= 6.00 hours

Table C23.1:Raw Data for the Leaching Experiment 23.

Time (min)	Samp. Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1050	712	148	180	58	45
15	15	1192	788	186	224	63	58
20	15	1298	853	198	248	70	65
30	15	1416	884	221	274	78	72
40	15	1492	932	240	286	82	75
50	15	1586	965	256	310	86	81
60	15	1642	1016	264	321	89	84
70	15	1732	1048	276	332	92	86
80	15	1784	1076	284	340	94	88
90	15	1830	1090	292	350	96	90
100	15	1880	1112	301	360	98	92
110	15	1915	1124	308	365	99	94
120	15	1942	1142	315	370	100	96
150	15	2010	1168	327	382	103	99
180	15	2065	1192	337	388	106	102
210	15	2108	1212	346	394	108	104
240	15	2150	1236	351	400	110	106
270	15	2184	1245	354	404	111	107
300	15	2226	1254	358	408	112	109
330	15	2265	1262	360	410	113	110
360	15	2300	1266	362	412	114	111
Pregn.		2300	1266	362	412	114	111
Wash A	in (ppm)	54	18	16	9	7	5
Wash B	in (ppm)	1	<1	<1	<1	<1	<1
Residue	in (%)	3.12	0.52	2.43	4.51	1.53	0.09

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl ex-leach = 1.668 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C23.2: Assay values for Leach 23 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	3.12	0.52	2.43	4.51	1.53	0.09
Solids in sample	1.54	0.89	1.21	1.39	1.81	0.21

Masses Recorded :

Sample into Leach	= 20.0 g
Residue	= 4.68 g
Solids in sample	= 0.39 g
Solids dissolved in solution	= 14.93 g

Table C23.3: Mass Balance for Leach 23

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex Leach.						
Residue	0.1460	0.0243	0.1137	0.2111	0.0716	0.0042
Solids in sample	0.0060	0.0035	0.0047	0.0054	0.0071	0.0008
Pregn. Solution	3.8364	2.1117	0.6038	0.6872	0.1902	0.1852
Wash A Liquor	0.0270	0.0090	0.0080	0.0045	0.0035	0.0025
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5365	0.3197	0.0858	0.1012	0.0280	0.0264
Total Out	4.5534	2.4697	0.8176	1.0109	0.3018	0.2206
Mass Balance % (Out/In)	98.99	98.79	99.71	99.11	100.61	100.28
% Extraction	96.66	98.87	85.51	78.58	73.94	97.72

Table C23.4: Extraction vs time data for Leach 23.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1024.7
5	45.652	56.950	36.098	35.294	38.667	40.909	973.9
15	51.780	62.994	45.296	43.857	41.975	52.639	1009.9
20	56.319	68.116	48.179	48.492	46.572	58.907	1010.2
30	61.334	70.541	53.663	53.476	51.785	65.127	1011.6
40	64.540	74.265	58.158	55.758	54.372	67.773	1012.6
50	68.473	76.806	61.914	60.287	56.938	73.023	1013.9
60	70.799	80.703	63.777	62.347	58.848	75.627	1014.6
70	74.506	83.128	66.551	64.391	60.743	77.350	1015.2
80	76 631	85.234	68.385	65.865	61.997	79.059	1015.5
90	78.496	86.278	70.204	67.694	63.240	80.755	1016.0
100	80.507	87.906	72.235	69.507	64.473	82.436	1016.3
110	81.903	88.787	73.801	70.407	65.085	84.105	1016.7
120	82.972	90.098	75.355	71.299	65.692	85.759	1017.2
150	85.640	91.975	77.996	73.423	67.497	88.221	1017.3
180	87.780	93.693	80.179	74.476	69.287	90.661	1018.3
210	89.439	95.113	82.127	75.520	70.470	92.275	1019.4
240	91.046	96.803	83.201	76.555	71.643	93.875	1019.5
270	92.336	97.431	83.839	77.239	72.225	94.668	1020.9
300	93.916	98.054	84.683	77.918	72.802	96.241	1021.8
330	95.370	98.603	85.101	78.254	73.373	97.021	1022.8
360	96.663	98.875	85.516	78.587	73.940	97.793	1022.8

RUN 24

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 60°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 450 rpm
Total leaching period	= 6.00 hours

Table C24.1: Raw Data for the Leaching Experiment 24.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1284	732	200	215	65	58
15	15	1411	882	242	280	82	62
20	15	1524	904	261	308	90	68
30	15	1652	972	270	324	98	75
40	15	1724	1012	285	336	102	78
50	15	1820	1045	302	342	108	84
60	15	1854	1072	312	360	112	88
70	15	1892	1118	321	372	115	92
80	15	1932	1140	332	379	116	94
90	15	1991	1162	340	384	118	96
100	15	2012	1173	345	390	120	98
110	15	2040	1186	351	395	121	100
120	15	2092	1204	356	405	122	102
150	15	2132	1230	362	418	123	104
180	15	2186	1248	367	427	124	106
210	15	2224	1252	370	434	125	108
240	15	2264	1266	372	438	126	109
270	15	2308	1269	374	445	127	110
300	15	2335	1272	376	449	128	111
330	15	2352	1276	378	451	129	112
360	15	2362	1280	380	453	130	113
Pregn.		2362	1280	380	453	130	113
Wash A	in (ppm)	62	20	18	11	8	6
Wash B	in (ppm)	1	1	1	<1	<1	<1
Residue	in (%)	0.04	0.01	2.19	4.11	1.43	0.01

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.667 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C24.2: Assay values for Leach 24 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	0.04	0.01	2.19	4.11	1.43	0.01
Solids in sample	0.06	0.01	2.50	2.12	0.15	0.02

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 3.15 g
Solids in sample = 0.28 g

Solids dissolved in solution = 16.57 g

Table C24.3: Mass Balance for Leach 24

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0013	0.0003	0.0690	0.1295	0.0451	0.0003
Solids in sample	0.0002	0.0000	0.0070	0.0059	0.0004	0.0000
Pregn. Solution	3.9375	2.1338	0.6335	0.7552	0.2167	0.1884
Wash A Liquor	0.0310	0.0100	0.0090	0.0035	0.0040	0.0030
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.5854	0.3362	0.0977	0.1133	0.0338	0.0278
Total Out	4.5568	2.4818	0.8177	1.0108	0.3015	0.2211
Mass Balance % (Out/In)	99.06	99.27	99.72	99.10	100.48	100.49
% Extraction	99.97	99.99	90.71	86.61	84.92	99.83

Table C24.4: Extraction vs time data for Leach 24.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1032.8
5	55.826	58.560	48.781	42.157	43.333	52.727	980.0
15	61.306	70.470	58.948	54.806	54.582	56.336	976.5
20	66.146	72.204	63.512	60.214	59.835	61.709	997.6
30	71.586	77.521	65.658	63.281	65.048	67.930	1008.6
40	74.622	80.625	69.207	65.563	67.635	70.575	1012.8
50	78.640	83.166	73.198	66.696	71.485	75.825	1012.5
60	80.051	85.229	75.527	70.066	74.032	79.298	1014.1
70	81.617	88.716	77.607	72.296	75.927	82.743	1015.5
80	83.252	90.370	80.129	73.586	76.553	84.452	1016.3
90	85.644	92.011	81.948	74.500	77.797	86.148	1018.5
100	86.488	92.825	83.076	75.588	79.030	87.830	1020.2
110	87.605	93.780	84.419	76.488	79.642	89.498	1022.7
120	89.663	95.090	85.529	78.272	80.248	91.152	1023.8
150	91.232	96.967	86.849	80.573	80.850	92.793	1024.2
180	93.334	98.256	87.941	82.152	81.447	94.421	1025.6
210	94.800	98.540	88.590	83.370	82.038	96.034	1026.4
240	96.330	99.526	89.020	84.060	82.625	96.834	1027.3
270	97.999	99.735	89.445	85.258	83.207	97.627	1028.9
300	99.015	99.943	89.867	85.936	83.783	98.414	1030.4
330	99.649	100.22	90.285	86.273	84.355	99.193	1032.5
360	100.02	100.49	90.700	86.606	84.922	99.966	1032.8

RUN 25

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Reactor pressure	= 345 KPa
Total leaching period	= 6.00 hours

Table C25.1: Raw Data for the Leaching Experiment 25.

Time (min)	Sample Vol. (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Rn	Ir	Au
0	-	-	-	-	-	-	-
5	15	1492	904	222	309	71	72
15	15	1624	990	262	336	79	79
20	15	1702	1032	284	354	83	82
30	15	1786	1082	298	370	87	87
40	15	1832	1110	310	387	91	91
50	15	1912	1138	323	397	94	94
60	15	1944	1154	330	406	97	96
70	15	1964	1168	337	412	99	98
80	15	2020	1192	343	418	101	100
90	15	2035	1198	347	424	102	101
100	15	2045	1212	352	428	105	102
110	15	2082	1225	356	433	106	103
120	15	2104	1238	360	438	108	104
150	15	2152	1253	366	444	110	105
180	15	2196	1261	372	450	112	106
210	15	2222	1264	377	456	113	107
240	15	2258	1268	380	459	114	108
270	15	2275	1273	384	461	115	109
300	15	2306	1276	388	464	116	110
330	15	2331	1278	391	466	117	111
360	15	2336	1280	395	470	118	112
Pregn.		2336	1280	39.	470	118	112
Wash A	in (ppm)	37	12	25	21	8	9
Wash B	in (ppm)	1	2	1	1	<1	<1
Residue	in (%)	0.61	0.01	1.14	2.44	1.76	0.01

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.672 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C25.2: Assay values for Leach 25 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	0.61	0.01	1.14	2.44	1.76	0.01
Solids in sample	0.45	0.01	1.27	1.41	1.15	0.01

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 3.76 g
Solids in sample = 0.32 g

Solids dissolved in solution = 15.92 g

Table C25.3: Mass Balance for Leach 25

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0229	0.0004	0.0429	0.0917	0.0662	0.0004
Solids in sample	0.0014	0.0000	0.0041	0.0045	0.0037	0.0000
Pregn. Solution	3.9058	2.1402	0.6604	0.7858	0.1973	0.1873
Wash A Liquor	0.0185	0.0060	0.0125	0.0105	0.0040	0.0045
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.6042	0.3527	0.1017	0.1247	0.0303	0.0295
Total Out	4.5544	2.5008	0.8231	1.0188	0.3030	0.2232
Mass Balance % (Out/In)	99.01	100.03	100.38	99.88	100.98	101.43
% Extraction	99.46	99.98	94.30	90.55	76.94	99.82

Table C25.4: Extraction vs time data for Leach 25.

Time	% Extraction						RedoxPot
(min)	Pt	Pd	Rh	Ru	Ir	Au	(mV)
0	0.000	0.000	0.000	0.000	0.000	0.000	1023.6
5	64.870	72.320	54.146	60.588	47.333	65.455	1007.3
15	70.566	79.148	63.829	65.843	52.627	71.771	1016.7
20	73.906	82.458	69.115	69.319	55.253	74.457	1017.2
30	77.476	86.368	72.452	72.386	57.860	78.900	1018.1
40	79.416	88.541	75.292	75.619	60.447	82.427	1019.9
50	82.764	90.697	78.343	77.506	62.372	85.052	1020.6
60	84.093	91.919	79.974	79.192	64.282	86.789	1021.6
70	84.917	92.980	81.592	80.306	65.545	88.511	1022.2
80	87.205	94.785	82.967	81.412	66.798	90.221	1023.5
90	87.813	95.233	83.877	82.509	67.420	91.068	1023.2
100	88.216	96.269	85.005	83.235	69.270	91.909	1024.3
110	89.692	97.223	85.900	84.134	69.882	92.743	1025.1
120	90.562	98.169	86.788	85.027	71.095	93.571	1026.6
150	92.445	99.252	88.109	86.088	72.298	94.391	1025.9
180	94.158	99.825	89.418	87.141	73.492	95.205	1026.4
210	95.161	100.04	90.501	88.185	74.083	96.011	1027.6
240	96.538	100.32	91.145	88.703	74.670	96.811	1028.4
270	97.183	100.67	91.996	89.045	75.252	97.605	1029.1
300	98.349	100.88	92.840	89.554	75.828	98.391	1030.1
330	99.281	101.01	93.467	89.890	76.400	99.171	1030.6
360	99.466	101.15	94.296	90.557	76.967	99.943	1030.5

RUN 26

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Reactor pressure	= 690 KPa
Total leaching period	= 6.00 hours

Table C26.1: Raw Data for the Leaching Experiment 26.

Time (min)	Sample Vol (ml)	Sample Analysis results in ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1687	994	256	336	78	82
15	15	1800	1065	304	368	87	89
20	15	1872	1112	318	384	92	93
30	15	1950	1128	332	399	96	96
40	15	2008	1173	342	408	99	99
50	15	2050	1214	350	418	102	101
60	15	2095	1226	356	424	105	103
70	15	2120	1233	364	431	107	105
80	15	2148	1244	368	436	109	106
90	15	2180	1252	371	440	111	107
100	15	2186	1258	375	443	113	108
110	15	2194	1260	380	446	114	109
120	15	2210	1264	382	449	115	110
150	15	2240	1270	387	455	118	111
180	15	2275	1272	390	458	120	112
210	15	2290	1278	392	462	122	112
240	15	2300	1280	395	465	124	113
270	15	2321	1282	398	468	125	114
300	15	2332	1284	402	471	126	115
330	15	2341	1286	406	474	127	116
360	15	2350	1288	409	476	128	117
Pregn.		2350	1288	409	476	128	117
Wash A	in (ppm)	37	54	21	18	12	8
Wash B	in (ppm)	1	1	1	1	<1	<1
Residue	in (%)	0.02	0.01	0.69	3.45	2.08	0.01

Liquids:

Volume of liq. (HCl) into Leach = 2.000 L
Volume of liq. (HCl) ex-leach = 1.885 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C26.2: Assay values for each 26 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	0.02	0.01	0.69	3.45	2.08	0.01
Solids in sample	0.01	0.01	0.18	1.74	1.59	0.01

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 2.45 g
Solids in sample = 0.30 g

Solids dissolved in solution = 17.25 g

Table C26.3: Mass Balance for Leach 26

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach,						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach,						
Residue	0.0005	0.0003	0.0169	0.0845	0.0510	0.0003
Solids in sample	0.0000	0.0000	0.0005	0.0052	0.0048	0.0000
Pregn. Solution	4.4298	2.4279	0.7710	0.8973	0.2413	0.2206
Wash A Liquor	0.0185	0.0270	0.0105	0.0090	0.0060	0.0040
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.6390	0.3656	0.1090	0.1295	0.0329	0.0315
Total Out	5.0893	2.8223	0.9094	1.1270	0.3374	0.2578
Mass Balance % (Out/In)	110.64	112.89	110.91	110.49	112.45	117.20
% Extraction	99.99	99.99	98.08	92.04	83.48	99.89

Table C26.4: Extraction vs time data for Leach 26.

Time (min)	% Extraction						RedoxPot (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	1027.2
5	73.348	79.520	62.44	65.882	52.000	74.546	1026.0
15	78.224	85.157	74.059	72.110	57.955	80.861	1026.8
20	81.308	88.861	77.422	75.200	61.238	84.443	1026.7
30	84.623	90.112	80.760	78.075	63.845	87.109	1027.3
40	87.069	93.604	83.126	79.787	65.785	89.755	1027.4
50	88.826	96.761	85.004	81.674	67.710	91.505	1027.9
60	90.695	97.678	86.401	82.798	69.620	93.241	1027.8
70	91.725	98.209	88.250	84.098	70.883	94.964	1028.1
80	92.869	99.036	89.167	85.020	72.137	95.818	1028.9
90	94.166	99.633	89.849	85.751	73.380	96.666	1028.8
100	94.408	100.08	90.752	86.295	74.613	97.507	1029.4
110	94.727	100.22	91.871	86.835	75.225	98.341	1030.2
120	95.360	100.52	92.315	87.370	75.832	99.168	1030.6
150	96.537	100.95	93.415	88.432	77.637	99.989	1031.2
180	97.899	101.09	94.070	88.958	78.830	100.80	1031.6
210	98.478	101.52	94.503	89.654	80.013	100.80	1031.8
240	98.860	101.66	95.147	90.172	81.187	101.60	1031.8
270	99.657	101.80	95.785	90.685	81.768	102.40	1032.4
300	100.07	101.94	96.629	91.194	82.345	103.18	1032.8
330	100.41	102.07	97.466	91.699	82.917	103.96	1033.1
360	100.74	102.21	98.088	92.032	83.483	104.73	1032.8

RUN 27

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Reactor pressure	= 1034 KPa
Total leaching period	= 6.00 hours

Table C27.1 Raw Data for the Leaching Experiment 27.

Time (min)	Sample Vol. (ml)	Sample Analysis results in % and ppm					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
5	15	1876	1066	320	369	85	89
15	15	1986	1130	350	400	95	95
20	15	2054	1178	360	417	99	97
30	15	2104	1221	368	429	106	100
40	15	2156	1242	374	435	109	103
50	15	2167	1256	378	442	112	106
60	15	2208	1261	380	447	115	107
70	15	2223	1266	382	449	117	109
80	15	2242	1269	385	453	119	110
90	15	2256	1272	388	455	121	111
100	15	2272	1274	389	460	123	111
110	15	2295	1276	391	462	125	112
120	15	2310	1278	393	464	126	113
150	15	2317	1279	395	468	129	114
180	15	2323	1280	397	472	132	115
210	15	2332	1284	399	478	133	116
240	15	2338	1286	401	482	135	117
270	15	2342	1290	405	486	137	118
300	15	2346	1294	407	490	138	118
330	15	2348	1296	409	493	139	119
360	15	2350	1298	410	496	140	120
Pregn.		2350	1298	410	496	140	120
Wash A	in (ppm)	42	33	25	12	10	8
Wash B	in (ppm)	1	<1	<1	1	<1	<1
Residue	in (%)	0.01	0.01	0.35	1.96	1.17	0.01

Liquids:

Volume of liq. (HCl) into Leach = 2.00 L
Volume of liq. (HCl) ex-leach = 1.885 L
Wash water volume (Wash A) = 500 ml
Wash water volume (Wash B) = 1500 ml.

Table C27.2: Assay values for Leach 27 solids

Solids	Assays, Mass %					
	Pt	Pd	Rh	Ru	Ir	Au
Sample into Leach	23.00	12.50	4.10	5.10	1.50	1.10
Residue	0.01	0.01	0.35	1.96	1.17	0.01
Solids in sample	0.01	0.01	0.25	0.57	1.24	0.01

Masses Recorded :

Sample into Leach = 20.0 g
Residue = 2.24 g
Solids in sample = 0.25 g

Solids dissolved in solution = 17.51 g

Table C27.3: Mass Balance for Leach 27

	Mass (g)					
	Pt	Pd	Rh	Ru	Ir	Au
Into Leach.						
Sample in	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Leaching Solution	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total In	4.6000	2.5000	0.8200	1.0200	0.3000	0.2200
Ex-Leach.						
Residue	0.0002	0.0002	0.0078	0.0439	0.0262	0.0002
Solids in sample	0.0000	0.0000	0.0006	0.0014	0.0031	0.0000
Pregn. Solution	4.4298	2.4467	0.7729	0.9350	0.2639	0.2262
Wash A Liquor	0.0210	0.0165	0.0125	0.0060	0.0050	0.0040
Wash B Liquor	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Samples	0.6674	0.3750	0.1151	0.1358	0.0359	0.0327
Total Out	5.1199	2.8400	0.9104	1.1236	0.3356	0.2647
Mass Balance % (Out/In)	111.30	113.60	111.02	110.15	111.88	120.30
% Extraction	100.00	100.00	99.07	95.97	91.27	99.91

Table C27.4: Extraction vs time data for Leach 27.

Time (min)	% Extraction						RedoxPot. (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	989.6
5	81.565	85.280	78.049	72.353	56.667	80.909	1005.1
15	86.312	90.362	85.311	78.386	63.283	86.323	1006.8
20	89.224	94.144	87.713	81.669	65.910	88.114	1010.2
30	91.349	97.507	89.621	83.969	70.472	90.780	1010.8
40	93.542	99.136	91.040	85.110	72.412	93.425	1011.2
50	94.003	100.21	91.979	86.431	74.337	96.050	1012.6
60	95.705	100.60	92.445	87.368	76.247	96.918	1014.8
70	96.323	100.98	92.907	87.739	77.510	98.641	1016.1
80	97.099	101.20	93.595	88.477	78.763	99.496	1018.6
90	97.667	101.43	94.277	88.842	80.007	100.34	1020.4
100	98.310	101.57	94.503	89.749	81.240	100.34	1022.7
110	99.228	101.72	94.951	90.109	82.463	101.18	1024.7
120	99.821	101.87	95.395	90.466	83.070	102.01	1026.6
150	100.10	101.94	95.835	91.174	84.875	102.83	1031.6
180	100.33	102.01	96.271	91.876	86.665	103.64	1032.2
210	100.68	102.29	96.704	92.920	87.257	104.45	1032.6
240	100.91	102.43	97.134	93.610	88.430	105.25	1032.8
270	101.06	102.71	97.985	94.294	89.593	106.04	1033.8
300	101.21	102.99	98.407	94.973	90.170	106.04	1034.4
330	101.28	103.13	98.825	95.477	90.742	106.82	1034.8
360	101.36	103.26	99.032	95.977	91.308	107.59	1035.6

ACID & CHLORINE SOLUBLE PGMs

Leaching Condition:

Mass of sample	= 20.0 g
Volume of HCl used	= 2.00 L
HCl concentration	= 6.00 M
Temperature	= 50°C
Cl_2 flowrate	= 825 cm^3min^{-1}
Stirrer speed	= 150 rpm
Total leaching period	= 6.00 hours

Table C28.1: **Evaluation of the Chlorine soluble Platinum.**

Platinum [HCl]= 6.00M Stir spd.=150 rpm Temp.=30°C					
Time (min)	Extraction (%)	No Cl_2 %	Cl_2 - No Cl_2 %	X (Cl_2 - No Cl_2)	$1-(1-X)^{1/3}$
0	0.000	0.000	0.000	0.000	0.0000
5	31.304	9.217	22.087	0.366	0.1407
10	43.387	20.825	22.562	0.373	0.1443
20	47.670	24.508	23.161	0.383	0.1488
30	54.045	30.586	23.459	0.388	0.1511
40	58.262	34.255	24.007	0.397	0.1553
50	62.447	37.896	24.551	0.406	0.15995
60	65.353	40.180	25.174	0.417	0.1644
70	67.825	41.827	25.998	0.430	0.1710
80	69.869	43.462	26.406	0.437	0.1743
90	72.301	45.449	26.852	0.444	0.1779
100	74.714	47.339	27.375	0.453	0.1822
110	76.310	48.695	27.615	0.457	0.1842
120	78.288	49.843	28.445	0.471	0.1911
150	81.427	51.608	29.819	0.493	0.2029
180	84.540	53.282	31.259	0.517	0.2156
210	85.698	52.857	32.841	0.543	0.2300
240	87.611	53.852	33.759	0.559	0.2386
270	88.370	52.752	35.618	0.589	0.2568
300	90.250	53.843	36.408	0.602	0.2647
330	91.369	53.246	38.123	0.631	0.2827
360	92.108	40.572	52.536	0.869	0.4926

Table C28.2: **Evaluation of the Chlorine soluble Platinum.**

Platinum [HCl]= 6.00M Stir spd.=150 rpm Temp.=40°C					
Time (min)	Extraction (%)	No Cl_2 %	Cl_2 - No Cl_2 %	X (Cl_2 - No Cl_2)	$1-(1-X)^{1/3}$
0	0.000	0.000	0.000	0.000	0.0000
5	32.087	9.348	22.739	0.379	0.1470
10	46.802	22.811	23.991	0.400	0.1567
20	52.840	27.608	25.233	0.421	0.1665
30	59.003	32.750	26.253	0.438	0.1747
40	62.883	35.239	27.644	0.462	0.1863
50	66.356	37.875	28.481	0.475	0.1934
60	69.263	39.744	29.519	0.492	0.2023
70	71.817	41.474	30.343	0.506	0.2096
80	73.370	42.414	30.956	0.516	0.2151
90	76.086	43.954	32.132	0.536	0.2259
100	77.816	44.759	33.057	0.551	0.2345
110	79.611	45.716	33.895	0.565	0.2426
120	81.312	46.428	34.884	0.582	0.2523
150	84.137	46.781	37.356	0.623	0.2777
180	86.589	46.820	39.769	0.663	0.3044
210	88.402	46.743	41.659	0.695	0.3269
240	90.124	46.399	43.725	0.729	0.3532
270	91.452	45.982	45.470	0.758	0.3773
300	93.031	45.869	47.163	0.787	0.4026
330	93.591	44.862	48.729	0.813	0.4281
360	94.330	40.058	54.272	0.905	0.5444

Table C28.3: **Evaluation of the Chlorine soluble Platinum.**

Platinum [HCl]= 6.00M Stir spd.=150 rpm Temp.=50°C					
Time (min)	Extraction (%)	No Cl_2 %	Cl_2 - No Cl_2 %	X (Cl_2 - No Cl_2)	$1-(1-X)^{1/3}$
0	0.000	0.000	0.000	0.000	0.0000
5	36.391	9.870	26.522	0.444	0.1775
10	53.091	25.706	27.385	0.458	0.1847
20	58.402	28.190	30.211	0.505	0.2091
30	64.097	32.738	31.359	0.524	0.2195
40	66.543	33.497	33.046	0.555	0.2352
50	71.565	36.468	35.096	0.587	0.2553
60	73.516	37.340	36.176	0.605	0.2663
70	75.452	37.958	37.494	0.627	0.2802
80	79.376	39.838	39.538	0.661	0.3029
90	79.822	39.960	39.862	0.667	0.3067
100	81.792	40.040	41.752	0.698	0.3293
110	82.909	40.718	42.191	0.706	0.3348
120	84.175	40.837	43.338	0.725	0.3496
150	86.961	40.798	46.164	0.772	0.3892
180	88.479	40.097	48.382	0.809	0.4243
210	90.717	40.175	50.543	0.845	0.4632
240	92.707	40.213	52.494	0.878	0.5040
270	93.693	40.023	53.670	0.898	0.5322
300	95.536	40.211	55.325	0.925	0.5789
330	96.468	40.025	56.443	0.944	0.6174
360	97.761	40.210	57.552	0.963	0.6655

Appendix D

(i) Raw data for the Heat transfer coefficient for the Impala reactor 2101

(ii) Raw data for the Mass Transfer Coefficient of the Impala plant reactor 2101

(iii) Raw data for the Impala plant leach test

Table D1.1 Raw data for the Heat transfer coefficient of the Impala reactor 2101

Time (min)	Heating			Cooling		
	Temp. (°C)	$\frac{(T_f-T_o}{T_f-T)}$	$\frac{\ln(T_f-T_o}{T_f-T)}$	Temp. (°C)	$\frac{(T_f-T_o}{T_f-T)}$	$\frac{\ln(T_f-T_o}{T_f-T)}$
0	15.4	-	-	92.0	-	-
1	15.4	-	-	91.0	-	-
2	15.5	-	-	89.1	-	-
3	16.0	-	-	86.8	-	-
4	16.9	-	-	84.2	1.03576	0.03514
5	18.3	-	-	81.0	1.08345	0.08015
6	20.2	1.01547	0.01535	78.4	1.12556	0.11828
7	22.6	1.03571	0.03509	75.4	1.17840	0.16416
8	25.5	1.06128	0.05947	72.4	1.23645	0.21225
9	28.8	1.09194	0.08796	69.5	1.29828	0.26104
10	32.3	1.12647	0.11909	66.6	1.36661	0.31233
11	36.1	1.16651	0.15402	63.7	1.44253	0.36640
12	40.1	1.21186	0.19215	60.6	1.53360	0.42762
13	44.2	1.26215	0.23281	58.4	1.60554	0.47346
14	48.4	1.31818	0.27625	56.0	1.69213	0.52599
15	52.6	1.37942	0.32167	53.6	1.78860	0.58143
16	56.9	1.44832	0.37040	51.3	1.89196	0.63761
17	61.1	1.52259	0.42041	49.2	1.99735	0.69182
18	65.2	1.60283	0.47177	47.3	2.10335	0.74353
19	69.2	1.68970	0.52455	44.9	2.25449	0.81292
20	73.2	1.78653	0.58028	42.7	2.41346	0.88106
21	77.0	1.88939	0.63626	40.6	2.58762	0.95074
22	80.6	1.99840	0.69235	38.6	2.77860	1.02195
23	83.0	2.07833	0.73157	37.2	2.92996	1.07499
24	85.4	2.16493	0.77239	35.6	3.12448	1.13927
25	87.8	2.25906	0.81495	34.2	3.31718	1.19912

Table D1.2 Raw data for the Chlorine mass transfer coefficient for the Impala reactor 2101

Chlorine dissolution in HCl solution [HCl] = 6.00 M, Stirrer speed = 140 rpm, Temp. = 50°C			
Time (min)	Titr. Value (ml)	$[Cl_2]$ (M)	$\ln(1-C/C_s)$
0	0.0	0.00000	0.0000
10	9.2	0.02274	-0.5620
20	13.3	0.03288	-0.9716
30	15.8	0.03906	-1.3408
40	17.6	0.04351	-1.7287
50	18.8	0.04648	-2.1083
60	19.4	0.04796	-2.3708
70	19.8	0.04895	-2.5942
80	20.2	0.04994	-2.8821
90	20.4	0.05043	-3.0647
100	20.6	0.05093	-3.2881
110	20.7	0.05117	-3.4219
120	20.9	0.05167	-3.7591
130	21.1	0.05216	-4.2717
140	21.2	0.05241	-4.6794
150	21.3	0.05266	-5.3793
160	21.4	0.05290	-
170	21.4	0.05290	-
180	21.4	0.05290	-

Table D1.3 Raw Data for the Impala plant Leach test.

Time (min)	Sample Vol. (l)	Sample Analysis results in gl^{-1}					
		Pt	Pd	Rh	Ru	Ir	Au
0	-	-	-	-	-	-	-
10	0.50	15.60	11.20	2.10	3.20	0.70	0.80
20	0.50	26.70	17.50	3.60	4.50	1.20	1.30
30	0.50	35.80	20.80	4.40	5.80	1.50	1.50
40	0.50	41.10	22.30	5.10	7.20	1.75	1.60
60	0.50	47.20	24.60	5.92	7.62	2.04	1.92
80	0.50	50.80	26.50	6.32	8.20	2.23	1.98
100	0.50	53.40	27.80	6.70	8.82	2.38	2.15
120	0.50	55.20	28.70	6.94	9.10	2.48	2.17
150	0.50	56.80	29.50	7.24	9.42	2.60	2.29
180	0.50	58.00	30.00	7.41	9.70	2.67	2.36
210	0.50	58.90	30.50	7.56	9.90	2.72	2.40
240	0.50	59.70	30.80	7.70	10.00	2.75	2.43
270	0.50	60.60	31.10	7.84	10.10	2.79	2.48
300	0.50	61.10	31.40	7.90	10.20	2.81	2.53
330	0.50	61.80	31.60	8.06	10.30	2.83	2.56
360	0.50	62.50	31.85	8.12	10.40	2.85	2.59

Liquids:

Volume of liq. (HCl) into Leach =1400.0 L

Volume of liq. (HCl) ex-leach = 1392.5 L

Table D1.4: Extraction vs time data for the Impala plant Leach test.

Time (min)	% Extraction						RedoxPot (mV)
	Pt	Pd	Rh	Ru	Ir	Au	
0	0.000	0.000	0.000	0.000	0.000	0.000	930
10	23.294	33.840	22.912	25.641	19.758	28.226	914
20	39.862	52.868	39.271	36.054	33.866	45.861	905
30	53.440	62.831	47.993	46.463	42.328	52.912	900
40	61.345	67.359	55.622	57.669	49.377	56.437	928
60	70.441	74.298	64.556	61.030	57.550	67.711	1063
80	75.807	80.028	68.912	65.669	62.904	69.824	1096
100	79.681	83.948	73.049	70.626	67.128	75.809	1100
120	82.362	86.660	75.661	72.864	69.944	76.513	1102
150	84.744	89.071	78.924	75.421	73.321	80.735	1104
180	86.530	90.576	80.773	77.657	75.291	83.196	1110
210	87.869	92.082	82.404	79.254	76.697	84.603	1118
240	89.059	92.985	83.925	80.052	77.541	85.657	1121
270	90.397	93.887	85.446	80.850	78.665	87.414	1126
300	91.140	94.789	86.098	81.648	79.227	89.170	1130
330	92.180	95.391	87.835	82.445	79.788	90.223	1131
360	93.220	96.142	88.486	83.242	80.350	91.276	1131

Appendix E

(i) **Derivation and calculation of the Heat transfer coefficient for the Impala reactor 2101**

(ii) **Derivation of the equation of Mass Transfer Coefficient**

Appendix E1

Derivation and Calculation of the Overall Heat Transfer Coefficient for the Impala PMR Reactor 2101.

Heat transfer in an agitated vessel having an external jacket like the Impala PMR reactor 2101 follows the relationship:

$$Q = U_{ht} A \Delta T \qquad \text{E1.1}$$

where,

U_{ht} = heat transfer coefficient

A = heat transfer area

Energy balance equation for cooling curves is of the form:

$$\frac{du}{dt} = \dot{q} = -U_{ht} A\left(T - T_w\right) \qquad \text{E1.2}$$

where,

$$u = \sum_{i=0} N_i \dot{U}_i = \sum_{i=0} N_i \left(\dot{H}_i - \rho \dot{\upsilon}\right) \qquad \text{E1.3}$$

For a Liquid system, $\frac{dV_l}{dt} \approx 0$

$$\frac{d\sum_{i=0} N_i H_i}{dt} = -U_{ht} A\left(T - T_w\right) \qquad \text{E1.4}$$

Now,

$$\sum_{i=0} N_i \frac{d\dot{H}_i}{dt} + \sum_{i=0} \dot{H}_i \frac{dN_i}{dt} = -U_{ht} A\left(T - T_w\right) \qquad \text{E1.5}$$

Since there is no reaction in the reactor, $\frac{dN_i}{dt} = 0$

$$\dot{H}_i = \dot{H}_{fi}^0\Big|_{T_{ref}} + \int_{T_{ref}}^{T} \dot{C}_{p_i}\, dt \qquad \text{E1.6}$$

$$\sum_{i=0} N_i \frac{d\int_{T_{ref}}^{T} \dot{C}_{p_i}\, dT}{dt} = -U_{ht} A\left(T - T_w\right) \qquad \text{E1.7}$$

Integrating using Liebnitz's rule for differentiating definite i .als gives:

$$\sum_{i=0} N_i \dot{C}_{p_i} \frac{dT}{dt} = -U_{ht} A\left(T - T_w\right) \qquad \text{E1.8}$$

Integrate

$$\int_{T_o}^{T} \frac{dT}{T - T_w} = -\frac{U_{ht} A}{\sum_{i=0} N_i \dot{C}_{p_i}} \int_0^t dt \qquad \text{E1.9}$$

$$\ln\left(T - T_w\right)\Big|_{T_o}^{T} = \frac{U_{ht} A}{\sum_{i=0} N_i \dot{C}_{p_i}} t \qquad \text{E1.10}$$

From the energy balance equation,

$$\boxed{\ln\left(\frac{T - T_w}{T_o - T_w}\right) = \frac{U_{ht} A}{\sum_{i=0} N_i \dot{C}_{p_i}} t} \qquad \text{E1.11}$$

$$N_{Water} = \frac{550l \times 1000g/l}{18g/l} = 30{,}555.56mol \quad \text{E1.12}$$

550 l of 33% w/v Hcl $= 550\ l\ (0.33)$ HCl E1.13

$= 550\ l\ (1 - 0.33)$ H_2O E1.14

$$N_{Water} = \frac{550kg + 550(1-0.33)kg}{18g/mol} \times 1000g/kg \quad \text{E1.15}$$

$$= 51{,}027.78\,mol \quad H_2O$$

$$N_{HCl} = \frac{550l \times 0.33kg/l}{36.5g/mol} \times 1000g/kg \quad \text{E1.16}$$

$$= 4{,}972.6\,mol \quad HCl$$

$C_{P(HCl)} = 28.1$ cal/mol K E1.17

$= 28.1$ cal/mol K $\times$ 4.186 J/cal E1.18

$= 117.63$ Jmol^{-1} K^{-1} E1.19

$C_{P(Water)} = 18$ cal/mol K $\times$ 4.186 J/cal E1.20

$= 75.35$ Jmol^{-1} K^{-1} E1.21

Now,

$$\sum_{i=0} N_i C_{P_i} = (51{,}027.78 \times 75.35) + (4{,}972.6 \times 117.63)J/K \quad \text{E1.22}$$

$$= 3{,}844{,}943.223 + 584{,}926.938$$

$$= 4.4298 \times 10^6\,JK^{-1}$$

$$\frac{U_{ht}A}{\sum_{i=0} N_i C_{P_i}} = gradient \quad \text{E1.23}$$

$$U_{ht}A = grad \times \sum_{i=0} N_i C_{p_i} \qquad \text{E1.24}$$

$$U_{ht}A = \frac{\left(0.05526\,{}^{1}/_{\min}\right) \times \left(4.4298 \times 10^{6}\right) J/K}{60\,{}^{s}/_{\min}} \qquad \text{E1.25}$$

$$= 4{,}079.85\ WK^{-1} \quad for \quad Cooling$$

$$U_{ht}A = \frac{\left(0.04331\,{}^{1}/_{\min}\right) \times \left(4.4298 \times 10^{6}\right) J/K}{60\,{}^{s}/_{\min}} \qquad \text{E1.26}$$

$$= 3{,}197.58\ WK^{-1} \quad for \quad Heating$$

Now,

$A = 6.3\ m^2$

Cooling $U_{ht} = 647.6\ Wm^{-2}K^{-1}$

Heating $U_{ht} = 507.55\ Wm^{-2}K^{-1}$

Appendix E2

Derivation of the equation of Mass Transfer Coefficient

From the mass transport rate equation

$$\frac{dC}{dt} = -k_m(C - C_s) \qquad \text{E2.1}$$

where,

C = Chlorine concentration at time t

C_s = Saturated chlorine concentration

$$\frac{dC}{C_s - C} = k_m dt \qquad \text{E2.2}$$

$$\int_0^C \frac{dC}{C_s - C} = k_m \int_0^t dt \qquad \text{E2.3}$$

$$-\ln(C_s - C)\Big|_0^C = k_m t \qquad \text{E2.4}$$

$$-\left[\ln(C_s - C) - \ln C_s\right] = k_m t \qquad \text{E2.5}$$

$$-\ln\left(\frac{C_s - C}{C_s}\right) = k_m t \qquad \text{E2.6}$$

$$-\ln\left(1 - \frac{C}{C_s}\right) = k_m t \qquad \text{E2.7}$$

$$\ln\left(1 - \frac{C}{C_s}\right) = -k_m t \qquad \text{E2.8}$$

Appendix F

C++ computer program for solving 14 differential equations for the

(i) Energy balance,

(ii) Chlorine mass balance and

(iii) PGM leaching reactions ,

to calculate the overall PGM dissolution conversion from the Chlorine soluble and Acid soluble PGM fractions for the Impala PMR reactor 2101

```
/* Yaw.cpp                                                              */

/* program yaw - to model the temperature profile in a batch reactor    */
/* to model Yaw's plant results for his MSc - 14/2/98                   */
/* written by FK Crundwell using objects for initial value problems     */
/* (ivp) and for presentation of results (border)                       */
/* Use of this program must acknowledge the author!!!                   */

#include <stdio.h>
#include <iostream.h>
#include <io.h>
#include <conio.h>
#include <stdlib.h>
#include <math.h>
#include "c:\tc\programs\ftoc.h"
#include "c:\tc\programs\ivp_oop.cpp"
#include "c:\tc\programs\border.cpp"

#define MP 3   //number of parameters+1
#define NP 2   //number of parameters
#define FTOL 1.0e-4

static float sqrarg, cubearg;
#define SQR(a) ((sqrarg=(a)) == 0.0 ? 0.0 : sqrarg*sqrarg)
#define CUBE(a) ((cubearg=(a)) == 0.0 ? 0.0 : cubearg*cubearg*cubearg)

/* global parameters                                                    */

float TotalMass,WaterMass,HClMass;
float StartUp Temperature,SteamTemperature,HeatTransferUA;
float CoolingWaterSwitchOnTemp,MassTransferKLA,ChlorineSat,Volume;
float FracChlorineSoluble[20];

/* ++++++++++++++++class batch leach++++++++++++++++*/

class BatchLeach {

private:

public:

float Time[20],Temp[20],Pt[20],Pd[20],Rh[20],Ru[20],Ir[20],Au[20],
            BaseMetals[20],Chlorine[20];

/* Member functions of class BatchLeach                                 */
```

```
BatchLeach();
void leach (void);
void BatchLeachParameters(void);
void BatchLeachResults(void);

// this function is use by class ivp (de's that are initial-value problems)
// and derivative evaluates dx/dt

friend int PrimaryLeach(float,float [], float []);
};

/*++++++++++++Members of class BatchLeach++++++++++++++*/

/*==========================================*/
BatchLeach::BatchLeach()
{
 // constructor function
 // create an input and out environment for  data

 char s[80];
 wintype w2(0,0,80,25,1," YAW ASAMOAH-BEKOE ");       // declare object w1
 w2.winput();
 w2.setcolor(yellow);
 w2.setbkcolor(blue);
 w2.wincls();
 //
 w2.winxy(1,1);
 w2.winxy(29,2);
 cout<<"* PGM Chlorine Leach *";
 w2.winxy(31,5);cout<<"by F. K. Crundwell";
 w2.winxy(19,7);cout<<"University of the Witwatersrand, Johannesburg";
 w2.winxy(6,11);cout<<"Program solves 14 differential equations for the leaching
                       reactions,";
 w2.winxy(14,13);cout<<"the energy balance and the chlorine mass balance.";
 w2.winxy(2,22);cout<<"Press the ENTER key";
 w2.winxy(16,22);
 w2>>s;w2.winremove();

}
/*==========================================*/
void BatchLeach::leach (void)

{
 float a,b,xl[14],tout,tin,u,v;
 float abserr,relerr,work[1000];
 int i,j,iwork[500],ibug,neq,iter,ans;
```

```
// create an input and out environment for  data

char s[80];
wintype w1(0,0,80,25,1," OUTPUT ");       // declare object w1
w1.winput(); w1.setcolor(white);w1.setbkcolor(blue); w1.wincls();
// w1>>s;//w1.winremove();

/* declare rkf object                                                    */

ivp de;

/* initial values for the integration                                    */

tin=0.;
for (i=0;i<=14;i++) {x[i]=0.0;}
x[12]=StartUpTemperature;                    //temperature Celcius

/* runge-kutta parameters                                                */

ibug=1;
neq=14;                                  // number of differential equations
abserr=0.1;relerr=0.01;

Time[0]=0.0;
Pt[0]=x[0];
Pd[0]=x[1];
Rh[0]=x[2];
Ru[0]=x[3];
Ir[0]=x[4];
Au[0]=x[5];
BaseMetals[0]=x[6];
Chlorine[0]=x[13];
Temp[0]=x[12];
w1.winxy(1,2);
cout<<" Hours"<<"\tTemp"<<"\tPt"<<"\tPd"<<"\tRh"<<"\tRu"
                <<"\tIr"<<"\tAu"<<"\tBase"<<"\t Cl2\n";
w1.winxy(2,4);
cout<<Time[0]<<"\t"<<Temp[0]<<"\t"<<Pt[0]<<"\t"<<Pd[0]<<"\t"
      <<Rh[0]<<"\t"<<Ru[0]<<"\t"<<Ir[0]<<"\t"<<Au[0]<<"\t"
      <<BaseMetals[0]<<"\t"<<Chlorine[0]<<"\n";
tin=0.0;
tout=0.5*3600.;
for(j=1;j<18;j++)
   {
   if(tout>0.0)
    {
```

```
      de.rkf(neq,x,&tin,&tout,relerr,abserr,&ibug,work,iwork,PrimaryLeach);
      if (ibug>2) {printf ("ibug= %d\n",ibug); getch();return;}
      }
      Time[j]=tout;
      Pt[j]=FracChlorineSoluble[0]*x[0]+(1.-FracChlorineSoluble[0])*x[7];
      Pd[j]=FracChlorineSoluble[1]*x[1]+(1.-FracChlorineSoluble[1])*x[8];
      Rh[j]=FracChlorineSoluble[2]*x[2]+(1.-FracChlorineSoluble[2])*x[9];
      Ru[j]=FracChlorineSoluble[3]*x[3]+(1.-FracChlorineSoluble[3])*x[10];
      Ir[j]=FracChlorineSoluble[4]*x[4]+(1.-FracChlorineSoluble[4])*x[11];
      Au[j]=FracChlorineSoluble[5]*x[5]+(1.-FracChlorineSoluble[5])*0.0;
      BaseMetals[j]=x[6];
      Chlorine[j]=x[13];
      Temp[j]=x[12];
      w1.winxy(2,4+j);
cout<<Time[j]/3600.<<"\t"<<Temp[j]<<"\t"<<Pt[j]<<"\t"
        <<Pd[j]<<"\t"<<Rh[j]<<"\t"<<Ru[j]<<"\t"<<Ir[j]<<"\t"
        <<Au[j]<<"\t"<<BaseMetals[j]<<"\t"<<Chlorine[j]<<"\n";
      tout=tout+0.5*3600.;
     }

  w1.winxy(2,22);cout<<"Press the ENTER key";
  w1.winxy(23,22);
  w1>>s; w1.winremove();
 return;
}

/*==========================================================*/

void BatchLeach::BatchLeachParameters(void)
{

 TotalMass=320.;
 WaterMass=0.8*1200.;
 HClMass=0.2*1200.;
 StartUpTemperature=30.;
 SteamTemperature=116.8;
 HeatTransferUA=5.07e2*6.3;
 MassTransferKLA=0.0312/30.;
 CoolingWaterSwitchOnTemp=78.;
 ChlorineSat=0.0527;

 char s[80];
 wintype w3(0,0,80,25,1," INPUT PARAMETERS ");      // declare object w1
 w3.winput()·
 w3.setcolor(yellow);
 w3.setbkcolor(blue);
```

```
w3.wincls();
//
w3.winxy(1,1);
w3.winxy(19,2);
cout<<"* Enter values of parameters and press ENTER *";
w3.winxy(10,4);
cout<<"Mass concentrate (kg) "<<TotalMass;
w3.winxy(10,5); cin>>TotalMass;
w3.winxy(10,6);
cout<<"Mass water (kg) "<<WaterMass;
w3.winxy(10,7);
cin>>WaterMass;
w3.winxy(10,8);
cout<<"Mass HCl (kg) "<<HClMass;
w3.winxy(10,9);
cin>>HClMass;
w3.winxy(10,10);
cout<<"Start up temperature (C) "<<StartUpTemperature;
w3.winxy(10,11);
cin>>StartUpTemperature;
w3.winxy(10,12);
cout<<"Temperature at which cooling water is switched on (C) "
    <<CoolingWaterSwitchOnTemp;
w3.winxy(10,13);
cin>>CoolingWaterSwitchOnTemp;
w3.winxy(10,14);
cout<<"Steam temperature (C) "<<SteamTemperature;
w3.winxy(10,15);
cin>>SteamTemperature;
w3.winxy(10,16);
cout<<"Heat transfer coefficient (W/m2C) times area "<<HeatTransferUA;
w3.winxy(10,17);
cin>>HeatTransferUA;
w3.winxy(10,18);cout.precision(5);
cout<<"Mass transfer coefficient "<<MassTransferKLA;
w3.winxy(10,19);
cin>>MassTransferKLA;cout.precision(3);
w3.winxy(10,20);cout.precision(5);
cout<<"Sat. Chlorine concentration "<<ChlorineSat;
w3.winxy(10,21);
cin>>ChlorineSat;cout.precision(3);

Volume=WaterMass+1.169*HClMass;
w3.winxy(10,22);
cout<<"Press the ENTER key again";
w3.winxy(32,23);
```

```
/* Chlorine soluble fractions at 70 deg C                                  */

FracChlorineSoluble[0]=1.-0.4091;                                          //Pt
FracChlorineSoluble[1]=1.-0.5752;                                          //Pd
FracChlorineSoluble[2]=1.-0.2498;                                          //Rh
FracChlorineSoluble[3]=1.-0.2714;                                          //Ru
FracChlorineSoluble[4]=1.-0.2103;                                          //Ir
FracChlorineSoluble[5]=1.-0.0;                                             //Au
FracChlorineSoluble[6]=1.-0.0;                                             //Ag
FracChlorineSoluble[7]=1.-0.0;                                             //Ni
FracChlorineSoluble[8]=1.-0.0;                                             //Cu
FracChlorineSoluble[9]=1.-0.0;                                             //Fe
w3>>s;w3.winremove();

return;
}

/*==========================================================*/

void BatchLeach::BatchLeachResults (void)
{
 int i,j;
 float y1,y2,y3,y4,y5,y6,y7,y8,y9,t;
 FILE *fp;
 if ((fp=fopen("YAW5.OUT", "w"))==. ·)LL)
   {
   printf("Cannot open file - Exit to system\n");
   exit(1);
   }
 for(j=0;j<18;j++)
   {
   t=Time[j]/3600.;
   y1=Temp[j];
   y2=Pt[j];
   y3=Pd[j];
   y4=Rh[j];
   y5=Ru[j];
   y6=Ir[j];
   y7=Au[j];
   y8=BaseMetals[j];
   y9=Chlorine[j];
   fprintf(fp,"%12.6f\t%12.6f\t%12.6f\t%12.6f\t%12.6f\t%12.6f\t%12.6f\t%12.6f\t
        %12.6f\t%12.6f\n",t,y1,y2,y3,y4,y5,y6,y7,y8,y9);
   }
 fclose(fp);
 return;
```

```
}

/*++++++++End of member functions of BatchLeach++++++++++++*/

/*==========================================*/
int PrimaryLeach(float t,float x[],float xdot[])

{
 int i;
 float u1,sum;
 float temp,cl2,InitialMoles[23],Moles[23],Conversion[23],cp[23];
 float rate[23],sumCp,sumHeat,HeatTransfer,HeatReaction[23],tau[23],Stoich[23];
 float sumChlorine;

 temp=x[12];                                          //temperature
 cl2=x[13];                                           //chlorine

 /* Initial number of moles of each component                    */

 InitialMoles[0]=0.246*TotalMass*1000./195.09;        //Pt
 InitialMoles[1]=0.133*TotalMass*1000./106.4;         //Pd
 InitialMoles[2]=0.0412*TotalMass*1000./102.9;        //Rh
 InitialMoles[3]=0.0503*TotalMass*1000./101.07;       //Ru
 InitialMoles[4]=0.0149*TotalMass*1000./192.22;       //Ir
 InitialMoles[5]=0.0112*TotalMass*1000./196.9;        //Au
 InitialMoles[6]=0.022*TotalMass*1000./107.87;        //Ag
 InitialMoles[7]=0.012*TotalMass*1000./58.7;          //Ni
 InitialMoles[8]=0.03*TotalMass*1000./63.546;         //Cu
 InitialMoles[9]=0.026*TotalMass*1000./55.847;        //Fe
 InitialMoles[10]=0.129*TotalMass*1000./60.086;       //SiO2
 InitialMoles[11]=HClMass*1000./36.45;                //HCl
 InitialMoles[12]=WaterMass*1000./18.;                //H2O

 /* Specific Heats in cal/deg mol                                */

 cp[0]=5.92+0.00116*(temp+273.);                      //Pt
 cp[1]=5.41+0.00184*(temp+273.);                      //Pd
 cp[2]=5.40+0.00219*(temp+273.);                      //Rh
 cp[3]=5.61+0.00144*(temp+273.);                      //Ru
 cp[4]=5.50+0.00148*(temp+273.);                      //Ir
 cp[5]=5.61+0.00144*(temp+273.);                      //Au
 cp[6]=5.60+0.00150*(temp+273.);                      //Ag
 cp[7]=4.26+0.00640*(temp+273.);                      //Ni
 cp[8]=5.44+0.00146*(temp+273.);                      //Cu
 cp[9]=4.13+0.00638*(temp+273.);                      //Fe
 cp[10]=10.87+0.0087*(temp+273.)-241200./SQR(temp+273.);  //SiO2
```

```
cp[11]=28.1;                                                    //HCl
cp[12]=18.0;                                                    //H2O

/*==========Chlorine-soluble fraction==========*/

/* Calculate conversion for the chlorine soluble fraction                */

/* Heats of reaction for the reactions that are believed to occur        */
/* in kcal/mol                                                           */

HeatReaction[0]=-75.35;                                         //Pt
HeatReaction[1]=-64.65;                                         //Pd
HeatReaction[2]=-69.73;                                         //Rh
HeatReaction[3]=-62.95;                                         //Ru
HeatReaction[4]=-62.95;                                         //Ir
HeatReaction[5]=-28.77;                                         //Au
HeatReaction[6]=-27.36;                                         //Ag
HeatReaction[7]=-89.35;                                         //Ni
HeatReaction[8]=-58.66;                                         //Cu
HeatReaction[9]=-118.9;                                         //Fe

/* Calculate rates                                                       */

tau[0]=3.2e6/60./300.*pow(6.,.94)*pow(fabs(cl2),0.78)*exp(-42360./8.314/(temp+273.));
tau[1]=4.15e6/60./300.*pow(6.,.94)*pow(fabs(cl2),0.78)*exp(-40190./8.314/(temp+273.));
tau[2]=1.3e7/60./300.*pow(6.,.81)*pow(fabs(cl2),0.77)*exp(-44560./8.314/(temp+273.));
tau[3]=2.9e7/60./300.*pow(6.,.68)*pow(fabs(cl2),0.79)*exp(-46620./8.314/(temp+273.));
tau[4]=2.3e7/60./300.*pow(6.,.75)*pow(fabs(cl2),0.71)*exp(-47600./8.314/(temp+273.));
tau[5]=1.8e6/60./300.*pow(6.,.67)*pow(fabs(cl2),0.5)*exp(-40440./8.314/(temp+273.));
tau[6]=1.3e6/60./300.*pow(6.,.7)*pow(fabs(cl2),0.49)*exp(-42360./8.314/(temp+273.));

for (i=0;i<7;i++)
  {
  xdot[i]=3.*tau[i]*pow(fabs(1.-x[i]),2./3.);
  if(x[i]>1.0)xdot[i]=0.0;
  }

rate[0]=-FracChlorineSoluble[0]*InitialMoles[0]*xdot[0];        //Pt
rate[1]=-FracChlorineSoluble[1]*InitialMoles[1]*xdot[1];        //Pd
rate[2]=-FracChlorineSoluble[2]*InitialMoles[2]*xdot[2];        //Au
rate[3]=-FracChlorineSoluble[3]*InitialMoles[3]*xdot[3];        //Ru
rate[4]=-FracChlorineSoluble[4]*InitialMoles[4]*xdot[4];        //Rh
rate[5]=-FracChlorineSoluble[5]*InitialMoles[5]*xdot[5];        //Ir
rate[6]=-FracChlorineSoluble[6]*InitialMoles[6]*xdot[6];        //Ag
rate[7]=-FracChlorineSoluble[7]*InitialMoles[7]*xdot[6];        //Ni
rate[8]=-FracChlorineSoluble[8]*InitialMoles[8]*xdot[6];        //Cu
```

```
rate[9]=-FracChlorineSoluble[9]*InitialMoles[9]*xdot[6];          //Fe

/* Calculate conversion                                          */

Conversion[0]=x[0];                                               //Pt
Conversion[1]=x[1];                                               //Pd
Conversion[2]=x[2];                                               //Rh
Conversion[3]=x[3];                                               //Ru
Conversion[4]=x[4];                                               //Ir
Conversion[5]=x[5];                                               //Au
Conversion[6]=x[6];                                               //Ag
Conversion[7]=x[6];                                               //Ni
Conversion[8]=x[6];                                               //Cu
Conversion[9]=x[6];                                               //Fe

/*==========Acid-soluble fraction==========*/

/* Now calculate the conversion for the acid-soluble fraction    */
/* Heats of reaction for the reactions that are believed to occur */
/* in kcal/mol                                                   */

HeatReaction[10]=23.28;                                           //Pt
HeatReaction[11]=38.88;                                           //Pd
HeatReaction[12]=-72.02;                                          //Rh
HeatReaction[13]=-11.42;                                          //Ru
HeatReaction[14]=-11.42;                                          //Ir

/* Calculate rates                                               */

tau[7]=2.96e3/60./300.*pow(6.,.56)*exp(-23050./8.314/(temp+273.));
tau[8]=7.2e2/60./300.*pow(6.,.58)*exp(-19590./8.314/(temp+273.));
tau[9]=3.73e2/60./300.*pow(6.,.66)*exp(-23820./8.314/(temp+273.));
tau[10]=5.65e2/60./300.*pow(6.,.6)*exp(-18760./8.314/(temp+273.));
tau[11]=5.65e2/60./300.*pow(6.,.56)*exp(-18220./8.314/(temp+273.));

for (i=7;i<12;i++)
 {
 xdot[i]=3.*tau[i]*pow(fabs(1.-x[i]),2./3.);
 if(x[i]>1.0)xdot[i]=0.0;
 }

rate[10]=-(1.-FracChlorineSoluble[0])*InitialMoles[0]*xdot[7];    //Pt
rate[11]=-(1.-FracChlorineSoluble[1])*InitialMoles[1]*xdot[8];    //Pd
rate[12]=-(1.-FracChlorineSoluble[2])*InitialMoles[2]*xdot[9];    //Rh
rate[13]=-(1.-FracChlorineSoluble[3])*InitialMoles[3]*xdot[10];   //Ru
rate[14]=-(1.-FracChlorineSoluble[4])*InitialMoles[4]*xdot[11];   //Ir
```

```
/* Calculate conversion                                                    */

Conversion[10]=x[7];                                                  //Pt
Conversion[11]=x[8];                                                  //Pd
Conversion[12]=x[9];                                                  //Rh
Conversion[13]=x[10];                                                 //Ru
Conversion[14]=x[11];                                                 //Ir
Conversion[15]=0.0;                                                   //Au

/* Calculate Number of moles                                               */

for (i=0;i<10;i++)
  {
  Moles[i]=InitialMoles[i]*FracChlorineSoluble[i]*(1.0-Conversion[i]);//     */
  }

for (i=0;i<6;i++)
  {
  Moles[i]=Moles[i]+InitialMoles[i]*(1.0-FracChlorineSoluble[i])*(1.0-Conversion[i+10]);
  }

Moles[10]=InitialMoles[10];
Moles[11]=InitialMoles[11];
Moles[12]=InitialMoles[12];

/* Calculate Sigma NiCpi                                                   */

sumCp=0.0;
for (i=0;i<13;i++)
  {
  sumCp=sumCp+Moles[i]*4.18*cp[i];
  }

/*Calculate Sigma (Heat of reaction * rate)                                */

sumHeat=0.0;
for (i=0;i<15;i++)
  {
  sumHeat=sumHeat+4.18*1000.*HeatReaction[i]*rate[i];
  }

/* Calculate Heat transfer term                                            */

HeatTransfer=HeatTransferUA*(SteamTemperature-temp);
if(temp>CoolingWaterSwitchOnTemp)HeatTransfer=647.6*(11.8-temp);
```

```
/* calculation of temperature from the energy balance                    */

xdot[12]=(HeatTransfer+sumHeat)/sumCp;

/* calculation of chlorine equation                                      */

Stoich[0]=2.0;
Stoich[1]=2.0;
Stoich[2]=1.5;
Stoich[3]=2.0;
Stoich[4]=1.5;
Stoich[5]=2.0;
Stoich[6]=0.5;
Stoich[7]=1.0;
Stoich[8]=1.0;
Stoich[9]=1.5;

sumChlorine=0.0;
for(i=0;i<10;i++)
  {
  sumChlorine=sumChlorine+Stoich[i]*rate[i];
  }
xdot[13]=MassTransferKLA*(ChlorineSat-cl2)+sumChlorine/Volume;

return (0);
}
/*=============================================================*/

void main (void)
{
  cout.precision(3);
  set_v_ptr();

  BatchLeach ob;
  ob.BatchLeachParameters();
  ob.leach();
  ob.BatchLeachResults();
  //write_data();

  /* end of program                                                      */

  return;
}

/*=============================================================*/
```

Author: Asamoah-Bekoe, Yaw.
Name of thesis: Investigation of the leaching of the platinum-group metal concentrate in hydrochloric acid solution by chlorine.

PUBLISHER:
University of the Witwatersrand, Johannesburg
©2015

LEGALNOTICES:

Copyright Notice: All materials on the University of the Witwatersrand, Johannesburg Library website are protected by South African copyright law and may not be distributed, transmitted, displayed or otherwise published in any format, without the prior written permission of the copyright owner.

Disclaimer and Terms of Use: Provided that you maintain all copyright and other notices contained therein, you may download material (one machine readable copy and one print copy per page)for your personal and/or educational non-commercial use only.

The University of the Witwatersrand, Johannesburg, is not responsible for any errors or omissions and excludes any and all liability for any errors in or omissions from the information on the Library website.