THE DISSOLUTION OF GOLD COLLOIDS IN AQUEOUS THIOSULFATE SOLUTIONS

By

Xinmin Zhang
B. Eng. (Material Sci.) East China University of Technology,
Shanghai, China

This thesis is presented for the degree of Doctor of Philosophy of Murdoch University
Perth, Western Australia

August 2008
I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institute

________________
Xinmin Zhang
August 2008
ABSTRACT

The kinetics of the dissolution of gold and silver colloids in ammoniacal thiosulfate solutions has been studied using oxygen, copper(II) or oxygenated copper(II) as oxidants at pH 9 - 11 and temperature 22ºC to 48ºC. The effects of the concentration of the main reagents such as copper(II), ammonia and thiosulfate as well as various background reagents have been investigated. Gold and silver colloids have characteristic absorption peaks at 530 nm and 620 nm respectively. Thus, the extent of gold or silver dissolution in different lixiviant systems was monitored using an ultraviolet-visible spectrophotometer. A comparison of the behaviour of gold colloids and powders has also been made. The beneficial or detrimental effects of silver colloid, and background reagents such as silver nitrate, and sodium salts of nitrate, carbonate, sulfite, sulfate, trithionate, tetrathionate anions have also been investigated.

Experimental results show that the relative rates and the extent of gold colloid dissolution at 25ºC in different lixiviant systems in a given time interval are in the order: oxygen-cyanide > copper(II)-ammonia-thiosulfate ≈ oxygen-copper(II)-ammonia-thiosulfate > oxygen-ammonia-thiosulfate ≥ oxygen-ammonia > copper(II)-ammonia. The analysis of electrode potentials shows that \( \text{Au(S}_2\text{O}_3\text{)}_2^{3-} \) is the predominant gold(I) species in the lixiviant solutions containing oxygen or copper(II) as oxidant and thiosulfate or mixed ammonia-thiosulfate as ligands. During the reaction of copper(II) with thiosulfate in ammoniacal solution without oxygen, the measured potential using a platinum electrode represent the redox couple \( \text{Cu(NH}_3\text{)}_n^{2+}/\text{Cu(S}_2\text{O}_3\text{)}_m^{1-2m} \) \( (n = 4 \text{ or } 3, m = 3 \text{ or } 2) \) depending on the concentrations of thiosulfate and ammonia.
The initial dissolution rates of gold colloid by oxygen in copper-free solutions show a reaction order of 0.28 with respect to the concentration of dissolved oxygen, but independent of the concentration of ammonia and thiosulfate. The reaction activation energy of 25 kJ/mol in the temperature range 25°C to 48°C indicated a diffusion controlled reaction.

The initial dissolution rates of gold colloid by oxidation with copper(II) in oxygen-free solutions show reaction orders of 0.41, 0.49, 0.60, 0.15 and 0.20 with respect to the concentrations of copper(II), thiosulfate, ammonia, chloride and silver respectively. The presence of silver(I) or chloride ions enhances the rate of gold dissolution, indicating their involvement in the surface reaction, possibly by interfering with or preventing a passivating sulfur rich film on gold surface. An activation energy of 40-50 kJ/mol for the dissolution of gold by oxidation with copper(II) in the temperature range 22°C to 48°C suggests a mixed chemically/diffusion controlled reaction. The dissolution of gold by oxidation with copper(II) in oxygen-free solutions appears to be a result of the reaction between gold, thiosulfate ions and the mixed complex Cu(NH₃)ₓ(S₂O₃)₀. The half order reactions support electrochemical mechanisms in some cases.

The initial dissolution rates of gold colloid, massive gold and gold-silver alloys by oxygenated copper(II) solutions also suggest a reaction that is first order with respect to copper(II) concentration. High oxygen concentration in solutions has a negative effect on the initial rate of gold dissolution and overall percentage of gold dissolution, indicating that oxygen affects the copper(II), copper(I) or sulfur species which in turn affects the gold dissolution. The surface reaction produces
Au(NH₃)(S₂O₃)⁻ and Cu(NH₃)₂⁺. The mixed complexes Au(NH₃)(S₂O₃)⁻ and Cu(NH₃)₂⁺ re-equilibrate to the more stable complexes Au(S₂O₃)₂³⁻ and Cu(S₂O₃)₃⁵⁻ in solution.

The dissolution of gold powder by oxidation with copper(II) in oxygen-free solutions shows the same trends as that of gold colloid. The presence of silver(I) or chloride ions enhances the initial rate and percentage dissolution of gold colloid and powder. The dissolution kinetics of gold powder and colloid follow a shrinking sphere kinetic model in solutions of relatively low concentrations of thiosulfate and ammonia, with apparent rate constants being inversely proportional to particle radius.

The best system for dissolving gold based on the results of this work is the copper(II)-ammonia-thiosulfate solution in the absence of oxygen or in the presence of oxygen. In the absence of oxygen, copper(II) 1.5-4.5 mM, thiosulfate 20-50 mM, ammonia 120-300 mM and pH 9.3-10 are the best conditions. The presences of carbonate and sulfite have a significant negative effect on the dissolution of gold. The presence of sodium trithionate shows a beneficial effect in the first two hours, while sodium tetrathionate or lead nitrate have a small negative effect and sodium nitrate showed no effect on the dissolution of gold. Silver nitrate and sodium chloride also show beneficial effects. In the presence of oxygen, copper(II) 2.0-3.0 mM, thiosulfate 50 mM, ammonia 240 mM and pH 9.3-9.5 are the best conditions.
ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisors Dr. Gamini Senanayake and Professor Michael J. Nicol of Extractive Metallurgy at Murdoch University for their genuine help, inspiration, guidance, invaluable advice; and especially, thanks to Dr. Gamini Senanayake for his patience and kindness throughout my PhD studies. I would like to thank Mr. Bill Staunton, Manager of the Gold Program of the A. J. Parker Cooperative Research Centre for Hydrometallurgy and Dr. Jim Avraamides, deputy director of the A J Parker Centre for their support.

I acknowledge the financial support from Murdoch University and the A. J. Parker Cooperative Research Centre through the award of post-graduate scholarships.

Many thanks are due to all those in Extractive Metallurgy and the Department of Chemistry, and MPS Store at Murdoch University who provided help during my study. In particular, I am grateful to Mr. Ken Seymour and Stewart Kelly for their technical support; also grateful to Dr. Maria Isabel Lazaro-Baez, Dr. Hongguang Zhang, Dr. Wensheng Zhang, Dr. Daniel Kittelty, Dr. Suchun Zhang, Dr. Zaima Zainol, Professor Keith Gregg, Mr. Vic Clark, Mr. Peter Felon for their time and effort in assisting me in many ways. Also, thanks to Mr. Kleber Claux for his assistance in mechanical work. At last, my most sincere thanks to my parents, my mother in law, my wife and my son for their love, understanding, and encouragement.
PUBLICATIONS


# TABLE OF CONTENTS

Abstract iii  
Acknowledgements vi  
Publications vii  
Table of Contents viii  
List of Figures xiv  
List of Tables xxvii  

## Chapter 1 Introduction 1  
1.1 Gold cyanidation 1  
1.2 Non cyanide lixiviants 2  
1.2.1 Potential lixiviants 2  
1.2.2 Stability constants of gold(I)/(III) complex species 3  
1.3 Thiosulfate as an alternative lixiviant 7  
1.3.1 Advantages 8  
1.3.2 Disadvantages 8  
1.3.3 Complexity of gold leaching process with thiosulfate 9  
1.4 The use of gold colloids for kinetic studies 11  
1.5 Objectives 14  

## Chapter 2 Literature review 15  
2.1 History and recent progress on gold extraction using thiosulfate 15  
2.2 Gold-copper-sulfur species and electrode potentials 17  
2.2.1 Gold-copper species 17  
2.2.2 Sulfur species 23  
2.3 Production, oxidation and stabilization of thiosulfate 25  
2.3.1 Production of thiosulfate 25  
2.3.2 Oxidation of thiosulfate by oxygen 27
2.3.3 Oxidation of thiosulfate by copper(II) 28
2.3.4 Oxidation of thiosulfate by oxygenated copper(II) 30
2.3.5 Stabilization of thiosulfate 33

2.4 Leaching of gold 36
2.4.1 Oxide ore 39
2.4.2 Sulfide ore 40
2.4.3 Carbonaceous ore 41
2.4.4 Refractory ore 44
2.4.5 Pure gold 45

2.5 Factors affecting the leaching of gold 48
2.5.1 Effect of thiosulfate concentration 48
2.5.2 Effect of copper concentration 53
2.5.3 Effect of ammonia concentration 55
2.5.4 Effect of pH 59
2.5.5 Effect of temperature 60
2.5.6 Effect of sulfur containing anions 65
2.5.7 Effect of residence time 68
2.5.8 Effect of foreign ions 70
2.5.9 Effect of oxidants 71

2.6 The mechanism of gold dissolution in a Cu(II)-NH₃-S₂O₃²⁻-system 73

2.7 Aims of present study 77

Chapter 3 Experimental 79

3.1 Materials and reagents 79
3.2 Preparation of gold colloid 80
  3.2.1 Unstabilized gold colloid 80
  3.2.2 Stabilized gold colloid 81
  3.2.3 Silver colloid 82
3.3 Determination of particle size 83
3.4 Reaction vessels and experimental measurements 85
  3.4.1 Reaction vessels 85
  3.4.2 Temperature and pH 88
  3.4.3 Oxygen concentration 88
3.4.4 Redox potentials 88
3.4.5 Nitrogen flow rate 89
3.4.6 Thiosulfate concentration 90
3.4.7 Sampling 91
3.5 UV-visible spectrum of gold, silver and copper 91
3.5.1 Measurement of absorbance 91
3.5.2 Comparison of UV-visible spectrum of Au(c), Au(I), Cu(II) and Cu(I) 92
3.5.3 Comparison between unstabilized and stabilized gold colloid 94
3.5.4 Beer-Lambert Law 97
3.5.5 Correction for background absorbance due to copper(II) 99
3.6 Experimental procedure for rate studies 103
3.6.1 Gold colloid-oxygen-cyanide system 103
3.6.2 Gold colloid-oxygen-thiosulfate-ammonia system 103
3.6.3 Gold colloid-copper(II)-thiosulfate-ammonia system 104
3.6.4 Gold colloid-oxygen-copper(II)-thiosulfate-ammonia system 105
3.6.5 Gold powder-copper(II)-thiosulfate-ammonia system 105
3.7 Summary of experimental conditions 106

Chapter 4 Results 110
4.1 Introduction 110
4.2 Dissolution of gold colloids in cyanide solutions 110
4.3 Dissolution of gold in thiosulfate solutions 112
4.3.1 Effect of oxygen concentration 112
4.3.2 Effect of thiosulfate concentration 114
4.3.3 Effect of ammonia concentration 115
4.3.4 Effect of chloride concentration 116
4.3.5 Effect of temperature 117
4.4 Dissolution of gold by copper(II)-ammonia-thiosulfate under nitrogen 118
4.4.1 Gold and platinum electrode potentials 118
4.4.2 Effect of concentration of gold colloid 119
4.4.3 Effect of particle size of gold colloid 119
4.4.4 Effect of ionic strength 120
4.4.5 Effect of copper(II) concentration 121
4.4.6 Effect of thiosulfate concentration 123
4.4.7 Effect of ammonia concentration 124
4.4.8 Effect of pH 126
4.4.9 Effect of concentrations of sodium nitrate and silver nitrate 127
4.4.10 Effect of silver colloid 128
4.4.11 Effect of lead nitrate 130
4.4.12 Effect of sodium chloride 131
4.4.13 Effect of carbonate, trithionate, tetrathionate, and sulfite 132
4.4.14 Effect of temperature 134
4.5 Dissolution of gold in thiosulfate solutions by oxygenated copper(II) 135
4.5.1 Effect of oxygen concentration 135
4.5.2 Effect of copper(II) concentration 138
4.5.3 Effect of thiosulfate concentration 139
4.6 Dissolution of gold powder in thiosulfate solutions under nitrogen 141
4.6.1 Effect of copper(II) concentration 141
4.6.2 Effect of silver and chloride ions 143
4.6.3 Effect of particle size of gold powder 144

Chapter 5 Electrode potentials and gold-copper speciation 145
5.1 Introduction 145
5.2 Relationship between electrode potentials, rates and speciation 147
5.3 Platinum electrode potentials during reaction 152
5.4 Gold electrode potentials 157
5.4.1 Effect of oxygen and copper(II) 157
5.4.2 Effect of ligand concentrations 159
   (a) Ammoniacal-thiosulfate solution 159
   (b) Thiosulfate-free ammonia solution 160
5.4.3 Effect of background salts 163
5.5 Summary and conclusions 165
Chapter 6 Initial rates of gold dissolution 167

6.1 Introduction 167
6.2 Gold dissolution in different lixiviant systems 169
6.3 Oxidation of thiosulfate by oxygen or copper(II) 172
6.4 Determination of initial rate 175
  6.4.1 Thiosulfate media 175
  6.4.2 Cyanide media 181
6.5 Initial rates of gold, silver and gold-silver alloys in thiosulfate solutions 183
6.6 Comparison with literature data 187
6.7 Effect of temperature on initial rate 190
6.8 Dissolution of gold in the absence of copper(II) 192
  6.8.1 Effect of oxygen concentration 192
  6.8.2 Effect of ligand concentration 193
  6.8.3 Effect of chloride concentration 197
6.9 Dissolution of gold in anaerobic copper(II) solutions 199
  6.9.1 Effect of reagent concentration and pH 199
  6.9.2 Effects of background salts 202
6.10 Dissolution of gold by oxygenated copper(II) solutions 206
  6.10.1 The role of oxygen 206
  6.10.2 Effect of initial copper(II) concentration 208
  6.10.3 Effect of thiosulfate concentration 209
  6.10.4 Effect of oxygen concentration 210
6.11 Effect of concentration ratio of [NH3] / [Na2S2O3] 214
  6.11.1 Non-oxygenated systems 214
  6.11.2 Oxygenated systems 219
6.12 Summary and conclusions 221

Chapter 7 Kinetic models for gold dissolution 223

7.1 Introduction 223
7.2 Reaction orders based on initial rates 224
7.3 Rate controlling step for the dissolution of gold by copper(II) in oxygenated solution 231
7.4 Electrochemical model for the dissolution of gold by copper(II) in anaerobic solutions 236
7.5 Shrinking particle kinetic models 241
7.6 Shrinking sphere model in copper(II)-ammonia-thiosulfate media 244
  7.6.1 Conditions and limitations 244
  7.6.2 Effect of particle size and copper(II) concentration 246
  7.6.3 Effect of oxygenation 249
  7.6.4 Effect of tetrathionate and trithionate 251
  7.6.5 Effect of lead(II), silver(I), chloride and ammonia 255
7.7 Summary and conclusions 264

Chapter 8 Summary and recommendations 266
  8.1 Summary 266
  8.2 Recommendations for further work 270

Reference 271

Appendix 287
  Appendix A1 Comparison between measured and calculated absorbance for the mixture of gold colloid and copper(II)-ammonia solutions 287
  Appendix A2 Initial dissolution rates of gold colloid (R_i) in difference solutions 288
  Appendix A3 Apparent rate constants for shrinking core or shrinking sphere model in difference solutions 292
  Appendix A4 Graphs of Results 295
  Appendix A5 Reaction order and electrochemistry theory 324
  Appendix A6 Optimum reagent concentrations and conditions to leach gold from this work 326
  Appendix A7 Front page of the three publications with abstract 327
List of Figures

Fig. 1.1 A diagrammatic representation of the composition of gold colloid 12
Fig. 2.1 Potential-pH diagrams at low reagent concentrations for copper-gold-ammonia-thiosulfate systems 21
Fig. 2.2 Effect of ammonia concentration on gold(I) species distribution 22
Fig. 2.3 Effect of pH on copper(I)/(II) species distribution 22
Fig. 2.4 Potential-pH diagram for the metastable S-H_{2}O system at 25°C 24

Fig. 3.1 Transmission electron micrographs of gold colloid particles 83-84
Fig. 3.2 Experimental set up for gold colloid oxidation 86
Fig. 3.3 Experimental set up for gold powder oxidation 87
Fig. 3.4 Effect of nitrogen flow rate on de-oxygenation of reaction solution 90
Fig. 3.5 Comparison between UV-visible spectra of stabilized gold colloid and Na_{3}Au(S_{2}O_{3})_{2} 93
Fig. 3.6 Comparison between UV-visible spectra of copper(II) tetraamine and copper(I)-thiosulfate complex 93
Fig. 3.7 UV-visible spectrum for the Cu(II)-NH_{3}-S_{2}O_{3}^{2-} system 94
Fig. 3.8 Effect of particle size on UV-visible spectrum of unstabilized gold colloids 95
Fig. 3.9 Effect of particle size on UV-visible spectrum of stabilized gold colloids 95
Fig. 3.10 Effect of storage time on UV-visible spectrum of stabilized gold colloids 96
Fig. 3.11 Effect of storage time on UV-visible spectrum of unstabilized gold colloids 96
Fig. 3.12 Effect of ionic strength and air on UV-visible absorption of stabilized gold colloids 97
Fig. 3.13 Verification of the Beer-Lambert Law for gold colloids 98
Fig. 3.14 Verification of the Beer-Lambert Law for copper(II) 98
Fig. 3.15 UV-visible spectra for gold colloid, silver colloid, Cu(NH_{3})_{4}^{2+} and a mixture of colloids and Cu(NH_{3})_{4}^{2+} 100
Fig. 3.16 Variation of UV-visible absorption with time in a typical reaction solution

Fig. 3.17 Effect of copper(II) concentration on initial absorbance of gold colloids

Fig. 4.1 Effect of cyanide on gold dissolution at variable ionic strengths

Fig. 4.2 Effect of cyanide on gold dissolution at ionic strength 0.5

Fig. 4.3 Effect of oxygen on gold dissolution in non-ammoniacal thiosulfate solutions

Fig. 4.4 Effect of oxygen on gold potential in non-ammoniacal thiosulfate solutions

Fig. 4.5 Effect of oxygen on gold dissolution in ammoniacal thiosulfate solutions

Fig. 4.6 Effect of oxygen on gold potential in ammoniacal thiosulfate solutions

Fig. 4.7 Effect of main reagents on gold dissolution in copper(II)-ammonia-thiosulfate solutions

Fig. 4.8 Effect of main reagents on gold and platinum electrode potentials in copper(II)-ammonia-thiosulfate solutions

Fig. 4.9 The dissolution of gold and silver colloid in copper(II)-ammonia-thiosulfate solutions

Fig. 4.10 Effect of silver nitrate on gold dissolution in copper(II)-ammonia-thiosulfate solutions

Fig. 4.11 Effect of oxygen on gold dissolution in copper(II)-ammonia-thiosulfate solution

Fig. 4.12 Effect of oxygen on electrode potential in copper(II)-ammonia-thiosulfate solution

Fig. 4.13 Effect of oxygen on residual copper(II) concentration in copper(II)-ammonia-thiosulfate solutions

Fig. 4.14 Effect of oxygen on platinum electrode potential in copper(II)-ammonia-thiosulfate solutions

Fig. 4.15 Comparison of gold and platinum electrode potentials in copper(II)-ammonia-thiosulfate solutions
Fig. 4.16  Comparison of gold and platinum electrode potentials in oxygenated copper(II)-ammonia-thiosulfate solutions
Fig. 4.17  Effect of copper(II) on the dissolution of gold powder in copper(II)-ammonia-thiosulfate solution
Fig. 4.18  Effect of copper(II) on gold electrode potential in copper(II)-ammonia-thiosulfate solution
Fig. 4.19  Change in residual copper(II) concentration during gold powder dissolution

Fig. 5.1  Schematic representation of current-potential curves for gold oxidation and copper(II) reduction
Fig. 5.2  Measured and calculated potentials of platinum electrode in copper(II)-ammonia-thiosulfate solution under nitrogen atmosphere
Fig. 5.3  Measured potentials of platinum electrode in copper(II)-ammonia-thiosulfate solutions under nitrogen or oxygen atmosphere
Fig. 5.4  Measured and calculated potentials of platinum in copper(II)-ammonia-thiosulfate solution under nitrogen atmosphere
Fig. 5.5  Measured and calculated potentials of gold electrode in oxygenated ammonia-thiosulfate solutions
Fig. 5.6  Measured and calculated potentials of gold electrode in copper(II)-ammonia-thiosulfate solutions under nitrogen
Fig. 5.7  Comparison between measured and calculated potentials of gold electrode during gold dissolution
Fig. 5.8  Measured and calculated potentials of gold electrode in ammonia solutions without thiosulfate
Fig. 5.9  Measured and calculated potentials of gold electrode in copper(II)-ammonia-thiosulfate-silver(I) or chloride solution
Fig. 5.10  Measured and calculated potentials of gold electrode in copper(II)-ammonia-thiosulfate-carbonate solution
Fig. 5.11  Measured and calculated potentials of gold electrode in copper(II)-ammonia-thiosulfate-sulfite or trithionate solutions

Fig. 6.1  Dissolution of gold colloid in different solution systems at 25°C
| Fig. 6.2 | Effect of sparging nitrogen, air or oxygen on gold dissolution in copper(II)-ammonia-thiosulfate solutions |
| Fig. 6.3 | Effect of ammonia, thiosulfate, and dissolved oxygen on gold dissolution in non-copper(II) solutions |
| Fig. 6.4 | Effect of oxygen and/or copper(II) on gold dissolution in ammonia-thiosulfate solutions |
| Fig. 6.5 | Comparison of gold dissolution in cyanide and thiosulfate solutions |
| Fig. 6.6a | A plot of ln(A₀/ₐₚ) versus time in gold-copper(II)-ammonia-thiosulfate solution |
| Fig. 6.6b | Initial gold dissolution in copper(II)-ammonia-thiosulfate solution |
| Fig. 6.7 | Logarithmic plot of initial rates (Rᵢ) as a function of particle size of colloids in copper(II)-ammonia-thiosulfate solutions |
| Fig. 6.8 | Effect of cyanide concentration on rates of cyanidation of colloidal gold and massive impurity-free gold at 25°C |
| Fig. 6.9 | Effect of copper(II) concentration or rotation speed on the rate of dissolution of silver and gold-silver (5%) alloy |
| Fig. 6.10 | Effect of temperature on initial rate and final gold dissolution |
| Fig. 6.11 | Arrhenius plots based on initial rates |
| Fig. 6.12 | Arrhenius plots based on initial rates at a residual copper(II) concentration of 1.75 mM |
| Fig. 6.13 | Effect of ammonia and thiosulfate on initial rates of gold dissolution by oxygen |
| Fig. 6.14 | Comparison between initial rates and final gold dissolution |
| Fig. 6.15 | Effect of chloride on initial rates and final gold dissolution by oxygen |
| Fig. 6.16 | Comparison between initial rates and final gold dissolution by oxygen |
| Fig. 6.17 | Effect of copper(II) on initial rate of gold dissolution |
| Fig. 6.18 | Effect of ammonia, thiosulfate and pH on initial rates of gold dissolution in copper(II) solutions |
| Fig. 6.19 | Effect of pH on initial rates of gold dissolution in copper-ammonia-thiosulfate solutions |
| Fig. 6.20 | Effect of sulfate on initial rate of gold dissolution and residual copper(II) in ammonia-thiosulfate solutions |
Fig. 6.21 Effect of chloride on initial rate of gold dissolution and residual copper(II) in ammonia solutions 203
Fig. 6.22 Effect of sulfite or carbonate on residual copper(II) in ammonia-thiosulfate solution 204
Fig. 6.23 Effect of sulfite or carbonate on potential of platinum electrode 204
Fig. 6.24 Effect of sulfite or carbonate on gold dissolution in copper(II)-ammonia-thiosulfate solutions 204
Fig. 6.25 Effect of nitrate, chloride or silver(I) ions on initial rate of gold dissolution 205
Fig. 6.26 Comparison between initial rates and final gold dissolution In the present of chloride, nitrate or silver(I) 205
Fig. 6.27 Effect of initial copper(II) on initial rate of gold dissolution and residual copper(II) concentration 208
Fig. 6.28 Effect of initial copper(II) on final gold dissolution 208
Fig. 6.29 Effect of thiosulfate on initial rate of gold dissolution and residual copper(II) concentration 209
Fig. 6.30 Effect of thiosulfate on final gold dissolution 209
Fig. 6.31 Effect of oxygen and copper(II) on initial rate of gold dissolution 211
Fig. 6.32 Effect of oxygen and copper(II) on final gold dissolution 211
Fig. 6.33 Effect of oxygen on the rate of gold oxidation by copper(II) 211
Fig. 6.34 Reaction model for the oxidation of thiosulfate and gold by copper(II) 216
Fig. 6.35 Effect of ammonia/thiosulfate concentration ratio on initial rate of copper(II) reduction 217
Fig. 6.36 Effect of ammonia/thiosulfate concentration ratio on initial rate of gold oxidation 217
Fig. 6.37 Effect of decreasing thiosulfate concentration on initial rate of gold oxidation 218
Fig. 6.38 Effect of increasing ammonia concentration or pH on initial rate of gold oxidation 218
Fig. 6.39 Effect of increasing thiosulfate concentration on initial rate of gold oxidation 220
Fig. 6.40 Effect of increasing ammonia concentration or pH on initial rate of gold oxidation 220
Fig. 7.1  Logarithmic plot of initial rate of gold oxidation as a function of oxygen or ammonia concentration in non-copper solutions 227

Fig. 7.2  Logarithmic plot of initial rate of gold oxidation by copper(II) as a function of reagent concentration 227

Fig. 7.3  Logarithmic plot of initial rate of gold oxidation as a function of chloride, nitrate, or silver(I) concentration in anaerobic solutions 228

Fig. 7.4  Logarithmic plot of initial rate of gold oxidation as a function of copper(II) concentration in anaerobic solutions 229

Fig. 7.5  Logarithmic plot of initial rate of gold oxidation as a function of copper(II) and thiosulfate concentration in oxygenated solutions 230

Fig. 7.6  Reaction equilibria involved in the oxidation of thiosulfate by copper(II) 234

Fig. 7.7  Initial rate of gold oxidation as a function of $\{[\text{Cu(II)}]^{n}\times[\text{X}]\}^{0.5}$ at variable copper(II) concentrations in ammonia-thiosulfate solutions under nitrogen. 240

Fig. 7.8  Initial rate of gold dissolution as a function of $\{[\text{Cu(II)}]^{n}\times[\text{S}_2\text{O}_3^{2-}]\}^{0.5}$ at variable thiosulfate concentrations in copper(II)-ammonia solutions under nitrogen 240

Fig. 7.9  Initial rate of gold oxidation as a function of $\{[\text{Cu(II)}]^{n}\times[\text{NH}_3]\}^{0.5}$ at variable ammonia concentrations in copper(II)-ammonia solution under nitrogen 241

Fig. 7.10  Validity of shrinking sphere model for gold colloids in copper(II)-ammonia-thiosulfate solutions under nitrogen 245

Fig. 7.11  Validity of shrinking sphere model for gold powder in copper(II)-ammonia-thiosulfate solutions under nitrogen 245

Fig. 7.12  Validity of shrinking sphere/core model for gold colloid in copper-ammonia (low)-thiosulfate solutions under nitrogen 245

Fig. 7.13  Validity of shrinking sphere/core model for gold colloid in copper(II)-ammonia (high)-thiosulfate solutions under nitrogen 245

Fig. 7.14  Shrinking sphere model for the dissolution of stabilized gold colloids of different particle size in copper(II)-ammonia-thiosulfate solutions under nitrogen 246
Fig. 7.15 Shrinking sphere model for the dissolution of unstabilized gold colloids in copper(II)-ammonia-thiosulfate solutions under nitrogen  
246

Fig. 7.16 Logarithmic plot of $k_{ss}$ as a function of $(bC/rp)$ for colloidal gold of difference particle sizes  
247

Fig. 7.17 Shrinking sphere model for the dissolution of gold powder of different particle sizes in copper(II)-ammonia-thiosulfate solutions under nitrogen  
248

Fig. 7.18 Shrinking sphere model for the dissolution of gold powder at different copper(II) concentrations in ammonia-thiosulfate solutions under nitrogen  
248

Fig. 7.19 Shrinking sphere model for the dissolution of gold colloid at different thiosulfate concentrations in oxygenated copper(II)-ammonia solutions  
250

Fig. 7.20 Effect of tetrathionate or trithionate on residual copper(II) during reaction with thiosulfate.  
251

Fig. 7.21 Effect of tetrathionate or trithionate on residual thiosulfate during reaction of copper(II) with thiosulfate.  
252

Fig. 7.22 Effect of tetrathionate or trithionate on the dissolution of gold foil in copper(II)-ammonia-thiosulfate solutions  
252

Fig. 7.23 Shrinking sphere model for the dissolution of gold colloids by copper(II)-ammonia-thiosulfate solutions in the presence of trithionate or tetrathionate under nitrogen.  
253

Fig. 7.24 Formation of tetrathionate and trithionate during the dissolution of gold foil by copper(II)-ammonia-thiosulfate solutions under nitrogen  
254

Fig. 7.25 Effect of oxygenation on dissolution of gold foil  
255

Fig. 7.26 Shrinking sphere model for the dissolution of gold colloids by copper(II)-ammonia-thiosulfate solutions in the presence of silver(I) under nitrogen  
256

Fig. 7.27 Shrinking sphere model for the dissolution of gold colloids by copper(II)-ammonia-thiosulfate solutions in the presence of sodium chloride under nitrogen  
256
Fig. 7.28  Shrinking sphere model for the dissolution of gold colloids by copper(II)-thiosulfate solutions at different ammonia concentrations under nitrogen  256

Fig. 7.29  Logarithmic plot of apparent rate constant as a function of silver(I), chloride, or ammonia concentration in copper(II)-ammonia-thiosulfate solutions under nitrogen  257

Fig. 7.30  Effect of silver(I) concentration on silver(I) speciation at 25°C  260

Fig. 7.31  Comparison between calculated silver(I)/silver(0) and gold(I)/gold(0) potentials at different silver(I) and gold(I) concentrations  261

Fig. 7.32  Logarithmic plot of apparent rate constants as a function of reagent concentration  263

Fig. A4.1a  Effect of thiosulfate on gold dissolution in the absence of ammonia  295
Fig. A4.1b  Effect of thiosulfate on gold electrode potential in the absence of ammonia  295
Fig. A4.1c  Effect of thiosulfate on gold dissolution in the presence of ammonia  295
Fig. A4.1d  Effect of thiosulfate on gold electrode potential in the presence of ammonia  295

Fig. A4.2a  Effect of ammonia on gold dissolution in the absence of thiosulfate  296
Fig. A4.2b  Effect of ammonia on gold electrode potential in the absence of thiosulfate  296
Fig. A4.2c  Effect of ammonia on gold dissolution in the presence of thiosulfate  296
Fig. A4.2d  Effect of ammonia on gold electrode potential in the presence of thiosulfate  296

Fig. A4.3a  Effect of chloride on gold dissolution in the absence of ammonia  297
Fig. A4.3b  Effect of chloride on gold electrode potential in the absence of ammonia  297
Fig. A4.4a  Effect of chloride on gold dissolution in the absence of thiosulfate  298
Fig. A4.4b  Effect of chloride on gold electrode potential in the absence of thiosulfate  298
Fig. A4.5a  Effect of chloride on gold dissolution in the presence of both ammonia and thiosulfate
Fig. A4.5b  Effect of chloride on gold electrode potential in the presence of both ammonia and thiosulfate
Fig. A4.6a  Effect of temperature on gold dissolution in oxygenated-ammonia-thiosulfate solution
Fig. A4.6b  Effect of temperature on gold electrode potential in copper(II)-ammonia-thiosulfate solution
Fig. A4.7a  Effect of concentration of gold colloid on gold dissolution in copper(II)-ammonia-thiosulfate solution
Fig. A4.7b  Effect of concentration of gold colloid on gold electrode potential in copper(II)-ammonia-thiosulfate solution
Fig. A4.7c  Change in residual concentration of copper(II) in copper(II)-ammonia-thiosulfate solution
Fig. A4.8a  Effect of particle size of stabilized gold colloid on gold dissolution in copper(II)-ammonia-thiosulfate solution
Fig. A4.8b  Effect of particle size of stabilized gold colloid on gold electrode potential in copper(II)-ammonia-thiosulfate solution
Fig. A4.9a  Effect of particle size of unstabilized gold colloid on gold dissolution in copper(II)-ammonia-thiosulfate solution
Fig. A4.9b  Effect of particle size of unstabilized gold colloid on gold electrode potential in copper(II)-ammonia-thiosulfate solution
Fig. A4.10a  Copper(II) concentration during reaction of copper(II) and thiosulfate in copper(II)-ammonia-thiosulfate solution in the absence of gold colloids
Fig. A4.10b  Platinum electrode potential during reaction of copper(II) and thiosulfate in copper(II)-ammonia-thiosulfate solution in the absence of gold colloids
Fig. A4.11a  Effect of ionic strength on gold dissolution in copper(II)-ammonia-thiosulfate solution
Fig. A4.11b  Effect of ionic strength on gold electrode potential in copper(II)-ammonia-thiosulfate solution
Fig. A4.11c Effect of ionic strength on copper(II) concentration in copper(II)-ammonia-thiosulfate solution 305
Fig. A4.11d Effect of ionic strength on platinum electrode potential in copper(II)-ammonia-thiosulfate solution 305
Fig. A4.12a Effect of copper(II) on gold dissolution in the absence of thiosulfate 306
Fig. A4.12b Effect of copper(II) on gold electrode potential in the absence of thiosulfate 306
Fig. A4.13a Effect of copper(II) on gold dissolution in copper(II)-ammonia-thiosulfate solution 307
Fig. A4.13b Effect of copper(II) on gold electrode potential in copper(II)-ammonia-thiosulfate solution 307
Fig. A4.13c Effect of initial copper(II) concentration on residual copper(II) in copper(II)-ammonia-thiosulfate solution 307
Fig. A4.13d Effect of copper(II) on platinum electrode potential in copper(II)-ammonia-thiosulfate solution 307
Fig. A4.14a Effect of thiosulfate on gold dissolution in copper(II)-ammonia-thiosulfate solution 308
Fig. A4.14b Effect of thiosulfate on gold electrode potential in copper(II)-ammonia-thiosulfate solution 308
Fig. A4.14c Effect of thiosulfate on copper(II) concentration in copper(II)-ammonia-thiosulfate solution 308
Fig. A4.14d Effect of thiosulfate on platinum electrode potential in copper(II)-ammonia-thiosulfate solution 308
Fig. A4.15a Effect of ammonia on gold dissolution in the absence of thiosulfate 309
Fig. A4.15b Effect of ammonia on gold electrode potential in the absence of thiosulfate 309
Fig. A4.16a Effect of ammonia on gold dissolution in copper(II)-ammonia-thiosulfate solution 310
Fig. A4.16b Effect of ammonia on gold electrode potential in copper(II)-ammonia-thiosulfate solution 310
Fig. A4.16c Effect of ammonia on copper(II) concentration in copper(II)-ammonia-thiosulfate solution 310
Fig. A4.16d Effect of ammonia on platinum electrode potential in copper(II)-ammonia-thiosulfate solution

Fig. A4.17a Effect of pH on gold dissolution in copper(II)-ammonia-thiosulfate solution

Fig. A4.17b Effect of pH on gold electrode potential in copper(II)-ammonia-thiosulfate solution

Fig. A4.17c Effect of pH on copper(II) concentration in copper(II)-ammonia-thiosulfate solution

Fig. A4.17d Effect of pH on platinum electrode potential in copper(II)-ammonia-thiosulfate solution

Fig. A4.18a Effect of nitrate on gold dissolution in copper(II)-ammonia-thiosulfate solution

Fig. A4.18b Effect of nitrate on gold electrode potential in copper(II)-ammonia-thiosulfate solution

Fig. A4.18c Effect of nitrate on copper(II) concentration in copper(II)-ammonia-thiosulfate solution

Fig. A4.18d Effect of nitrate on platinum electrode potential in copper(II)-ammonia-thiosulfate solution

Fig. A4.19a Effect of silver(I) on gold dissolution in copper(II)-ammonia-thiosulfate solution

Fig. A4.19b Effect of silver(I) on gold electrode potential in copper(II)-ammonia-thiosulfate solution

Fig. A4.19c Effect of silver(I) on copper(II) concentration in copper(II)-ammonia-thiosulfate solution

Fig. A4.19d Effect of silver(I) on platinum electrode potential in copper(II)-ammonia-thiosulfate solution

Fig. A4.20a Comparison of gold electrode potentials in the present of silver colloid or silver nitrate

Fig. A4.20b Copper(II) concentrations in the present of silver colloid or silver nitrate

Fig. A4.20c Platinum electrode potential in the present of silver colloid or silver nitrate
Fig. A4.21a Comparison of gold dissolution in the presence of lead(II) or silver nitrate 315
Fig. A4.21b Gold electrode potential in the present of lead(II) 315
Fig. A4.21c Copper(II) concentration in the present of lead(II) 315
Fig. A4.21d Platinum electrode potential in the present of lead(II) 315
Fig. A4.22a Effect of chloride on gold dissolution in the absence of thiosulfate 316
Fig. A4.22b Effect of chloride on gold electrode potential in the absence of thiosulfate 316
Fig. A4.22c Effect of chloride on copper(II) concentration in the absence of thiosulfate 316
Fig. A4.23a Effect of chloride on gold dissolution in copper(II)-ammonia-thiosulfate solution 317
Fig. A4.23b Effect of chloride on gold electrode potential in copper(II)-ammonia-thiosulfate solution 317
Fig. A4.23c Effect of chloride on copper(II) concentration in copper(II)-ammonia-thiosulfate solution 317
Fig. A4.24a Effect of $S_3O_6^{2-}$, $S_4O_6^{2-}$, $CO_3^{2-}$ and $SO_3^{2-}$ on gold dissolution in copper(II)-ammonia-thiosulfate solution 318
Fig. A4.24b Effect of $S_3O_6^{2-}$, $S_4O_6^{2-}$, $CO_3^{2-}$ and $SO_3^{2-}$ on gold electrode potential in copper(II)-ammonia-thiosulfate solution 318
Fig. A4.24c Effect of $S_3O_6^{2-}$, $S_4O_6^{2-}$, $CO_3^{2-}$ and $SO_3^{2-}$ on copper(II) concentration in copper(II)-ammonia-thiosulfate solution 318
Fig. A4.24d Effect of $S_3O_6^{2-}$, $S_4O_6^{2-}$, $CO_3^{2-}$ and $SO_3^{2-}$ on platinum electrode potential in copper(II)-ammonia-thiosulfate solution 318
Fig. A4.25a Effect of temperature on gold dissolution in copper(II)-ammonia-thiosulfate solution 319
Fig. A4.25b Effect of temperature on gold electrode potential in copper(II)-ammonia-thiosulfate solution 319
Fig. A4.25c Effect of temperature on copper(II) concentration in copper(II)-ammonia-thiosulfate solution 319
Fig. A4.25d Effect of temperature on platinum electrode potential in copper(II)-ammonia-thiosulfate solution 319
Fig. A4.26a Effect of copper(II) on gold dissolution in oxygenated copper(II)-ammonia-thiosulfate solution 320
Fig. A4.26b Effect of copper(II) on gold electrode potential in oxygenated copper(II)-ammonia-thiosulfate solution 320
Fig. A4.26c Variation of copper(II) concentration in oxygenated copper(II)-ammonia-thiosulfate solution 320
Fig. A4.26d Effect of copper(II) on platinum electrode potential in oxygenated copper(II)-ammonia-thiosulfate solution 320
Fig. A4.27a Effect of thiosulfate on gold dissolution in oxygenated copper(II)-ammonia-thiosulfate solution 321
Fig. A4.27b Effect of thiosulfate on gold electrode potential in oxygenated copper(II)-ammonia-thiosulfate solution 321
Fig. A4.27c Effect of thiosulfate on copper(II) concentration in oxygenated copper(II)-ammonia-thiosulfate solution 321
Fig. A4.27d Effect of thiosulfate on platinum electrode potential in oxygenated copper(II)-ammonia-thiosulfate solution 321
Fig. A4.28a Effect of silver(I) and chloride ions on the dissolution of gold powder in copper(II)-ammonia-thiosulfate solution 322
Fig. A4.28b Effect of silver(I) and chloride ions on gold electrode potential in copper(II)-ammonia-thiosulfate solution 322
Fig. A4.28c Effect of silver(I) and chloride ions on copper(II) concentration in copper(II)-ammonia-thiosulfate solution 322
Fig. A4.29a Dissolution of gold powder with difference particle size in copper(II)-ammonia-thiosulfate solution 323
Fig. A4.29b Effect of particle size of gold powder on gold electrode potential in copper(II)-ammonia-thiosulfate solution 323
Fig. A4.29c Effect of particle size of gold powder on copper(II) concentration in copper(II)-ammonia-thiosulfate solution 323
### List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1.1</td>
<td>Gold lixivants, conditions and references</td>
<td>5</td>
</tr>
<tr>
<td>Table 1.2</td>
<td>Stability constants of selected Au(I) and Au(III) complexes and corresponding standard reduction potentials at 25°C</td>
<td>6</td>
</tr>
<tr>
<td>Table 1.3</td>
<td>Relevant properties of lixiviants</td>
<td>7</td>
</tr>
<tr>
<td>Table 1.4</td>
<td>Factors investigated in this study</td>
<td>14</td>
</tr>
<tr>
<td>Table 2.1</td>
<td>Sulfur-oxygen species and oxidation states</td>
<td>24</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Summary of reactions and conditions for thiosulfate regeneration</td>
<td>25</td>
</tr>
<tr>
<td>Table 2.3</td>
<td>Stochiometry of oxidation and reductive decomposition of thiosulfate</td>
<td>32</td>
</tr>
<tr>
<td>Table 2.4</td>
<td>Stochiometry of the stabilization reaction of thiosulfate</td>
<td>35</td>
</tr>
<tr>
<td>Table 2.5</td>
<td>Different types of ores/concentrates used in thiosulfate leaching</td>
<td>36</td>
</tr>
<tr>
<td>Table 2.6</td>
<td>Chemical composition of different types of starting material used in thiosulfate leaching</td>
<td>37</td>
</tr>
<tr>
<td>Table 2.7</td>
<td>Maximum gold leaching under optimum conditions</td>
<td>38</td>
</tr>
<tr>
<td>Table 2.8</td>
<td>Dissolution rates of gold under optimum conditions</td>
<td>46</td>
</tr>
<tr>
<td>Table 2.9a</td>
<td>Effect of thiosulfate concentration on gold dissolution rates</td>
<td>49</td>
</tr>
<tr>
<td>Table 2.9b,c</td>
<td>Effect of thiosulfate concentration on gold leaching</td>
<td>51-52</td>
</tr>
<tr>
<td>Table 2.10</td>
<td>Effect of copper concentration on gold leaching</td>
<td>54</td>
</tr>
<tr>
<td>Table 2.11</td>
<td>Effect of ammonia concentration on gold leaching</td>
<td>58</td>
</tr>
<tr>
<td>Table 2.12</td>
<td>Effect of pH on gold leaching</td>
<td>60</td>
</tr>
<tr>
<td>Table 2.13</td>
<td>Effect of temperature on gold leaching</td>
<td>64</td>
</tr>
<tr>
<td>Table 2.14</td>
<td>Effect of sulfur-oxy species on gold dissolution rates</td>
<td>65</td>
</tr>
<tr>
<td>Table 2.15</td>
<td>Effect of retention time on gold leaching</td>
<td>69</td>
</tr>
<tr>
<td>Table 2.16</td>
<td>Effect of oxidants on gold leaching</td>
<td>71</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>List of materials and reagents</td>
<td>79</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Effect of amount of sodium citrate on the particle size and colour of gold colloids</td>
<td>81</td>
</tr>
<tr>
<td>Table 3.3</td>
<td>Stability of gold colloid upon storage</td>
<td>96</td>
</tr>
<tr>
<td>Table 3.4</td>
<td>Experimental conditions used in Au(c)-oxygen-cyanide systems</td>
<td>106</td>
</tr>
</tbody>
</table>
Table 3.5 Experimental conditions used in Au(c)-oxygen-thiosulfate-ammonia systems

Table 3.6 Experimental conditions used in Au(c)-copper(II)-thiosulfate-ammonia-nitrogen systems

Table 3.7 Experimental conditions used in Au(c)-copper(II)-oxygen-thiosulfate-ammonia systems

Table 3.8 Experimental conditions used in Gold powder-copper(II)-thiosulfate-ammonia systems

Table 4.1 Effect of thiosulfate on the dissolution and potentials of gold

Table 4.2 Effect of ammonia on the dissolution and potentials of gold

Table 4.3 Effect of chloride on the dissolution and potentials of gold

Table 4.4 Effect of temperature on the dissolution and potentials of gold

Table 4.5 Effect of colloid strength on the dissolution and potentials of gold

Table 4.6 Effect of colloid particle size on the dissolution and potentials of gold

Table 4.7 Effect of ionic strength on the dissolution and potentials of gold

Table 4.8 Effect of copper(II) on the dissolution and potentials of gold

Table 4.9 Effect of thiosulfate on the dissolution and potentials of gold

Table 4.10 Effect of ammonia on the dissolution and potentials of gold

Table 4.11 Effect of ammonia on the residual copper(II) and potentials of platinum electrode

Table 4.12 Effect of pH on the dissolution and potentials of gold

Table 4.13 Effect of pH on residual copper(II) concentration and platinum electrode potentials

Table 4.14 Effect of nitrate on the dissolution and potentials of gold

Table 4.15 Effect of silver(I) on the dissolution and potentials of gold

Table 4.16 The dissolution of gold and silver colloids in copper(II)-ammonia-thiosulfate solutions

Table 4.17 Effects of lead(II) and silver(I) on the dissolution and potentials of gold

Table 4.18 Effect of chloride on the dissolution and potentials of gold in the absence of thiosulfate
Table 4.19 Effect of chloride on the dissolution and potentials of gold in the presence of thiosulfate

Table 4.20 Effect of different anions on the dissolution and potentials of gold and residual copper(II)

Table 4.21 Effect of temperature on the dissolution and potentials of gold and residual copper(II)

Table 4.22 Effect of oxygen on gold dissolution in oxygenated copper(II)-ammonia-thiosulfate solution

Table 4.23 Effect of copper(II) concentration on gold dissolution in oxygenated copper(II)-ammonia-thiosulfate solution

Table 4.24 Effect of thiosulfate on gold dissolution in oxygenated copper(II)-ammonia-thiosulfate solution

Table 4.25 Effect of initial copper(II) on the dissolution of gold colloid, gold powder and gold electrode potentials

Table 4.26 Effect of silver(I) and chloride ions on the dissolution of gold powder and gold electrode potentials

Table 4.27 A comparison of gold dissolution with different particle size

Table 5.1 Possible chemical reactions involved in gold oxidation

Table 5.2 Effect of complex-formation on standard reduction potentials at 25°C

Table 5.3 Comparison between measured and predicted $E^o\{\text{Cu(NH}_3\text{)}_n^{2+}/\text{Cu(S}_2\text{O}_3\text{)}_m^{1-2m}\}$ for different redox couples

Table 5.4 Effect of initial reagent concentration on measured equilibrium potential (E, SHE) and $E^o$ for gold(I)/(0) redox couple

Table 5.5 Effect of initial reagent concentrations on measured equilibrium potential (E, SHE) and $E^o$ for gold(I)/(0) redox couple

Table 6.1 Decrease in thiosulfate concentration with time

Table 6.2 Effect of gold concentration on initial rate ($R_i$)

Table 6.3 Effect of particle size of gold on initial rate ($R_i$)

Table 6.4 Initial rates for cyanidation
Table 6.5  Effect of the type of gold and additives on the initial rate of dissolution 188
Table 6.6  Comparison of rate data for massive gold and colloidal gold at 25 °C 189
Table 6.7  Effect of oxygen on the initial rate of gold dissolution 193
Table 6.8  Effect of ammonia and thiosulfate on dissolution rate of massive gold 196
Table 6.9  Comparison between oxidation rate of gold and thiosulfate 212
Table 6.10  Comparison of residual copper(II) concentration after aeration/oxygenation of ammoniacal-thiosulfate solutions 213
Table 6.11  Experimental conditions representing copper(II) reduction and massive gold oxidation 218
Table 6.12  Experimental conditions representing gold colloid oxidation 219

Table 7.1  Reaction orders based on initial rate with respect to each reagent at 25°C 225
Table 7.2  Effect of copper(II) on initial rate of gold colloid and powder oxidation 229
Table 7.3  Calculation of mass transfer coefficient of copper(II) to gold surface 232
Table 7.4  Comparison of initial rates of gold dissolution at 25 °C 236
Table 7.5  Effect of Cu(NH₃)₄²⁺ concentrations on the dissolution rate of gold 237
Table 7.6  Rate constant for the dissolution of gold powder based on a shrinking sphere model 249
Table 7.7  Reaction orders for the dissolution of gold colloid by copper(II) based on apparent rate constants 257
Table 7.8  Stability constants of gold and silver complexes at 25°C 259
Table 7.9  Standard Gibbs free energy values (ΔG°f, 298 K) and equilibrium constants for silver and gold dissolution 259
Table 7.10  Effect of sodium and silver nitrates on apparent rate constants and rates 262
Table A1.1 Comparison between measured and calculated absorbance for the mixture of gold colloid in copper(II)-ammonia solution

Table A2.1 Initial dissolution rates of gold colloid \((R_i)\) and reaction orders in oxygenated ammonia-thiosulfate solution: effect of reagent concentration

Table A2.2 Initial dissolution rates of gold colloid \((R_i)\) and reaction orders in copper(II)-ammonia-thiosulfate solution: effect of reagent concentration

Table A2.3 Initial dissolution rates of gold colloid \((R_i)\) and reaction orders in copper(II)-ammonia-thiosulfate solution: effect of reagent concentration

Table A2.4 Initial dissolution rates of gold colloid \((R_i)\) and reaction orders in oxygenated copper(II)-ammonia-thiosulfate solution: effect of reagent concentration

Table A2.5 Effect of temperature on initial dissolution rates of gold colloid \((R_i)\)

Table A3.1 Apparent rate constants for shrinking core and shrinking sphere models in copper(II)-ammonia-thiosulfate solutions

Table A3.2 Apparent rate constants for shrinking sphere model in copper(II)-ammonia-thiosulfate solutions

Table A3.3 Apparent rate constants for shrinking sphere model in oxygenated copper(II)-ammonia-thiosulfate solutions

Table A3.4 Apparent rate constants for shrinking sphere model in copper(II)-ammonia-thiosulfate solutions: effect of particle size of gold colloid and gold powder

Table A6.1 Copper(II)-ammonia-thiosulfate system without oxygen

Table A6.2 Oxygenated copper(II)-ammonia-thiosulfate system