# CHAPTER 6

## REFERENCES

1. Nicholls D. R., *The pebble bed nuclear reactor* , Elekron , Nov/Dec 1996,25 – 26.

2. Nicholls D. R.. *The pebble bed modular reactor,* South African Journal of Science, 2000, **96**, 31 - 35.

3. Morgan, D.L., *Personal communication.*

4. Morgan, D.L., *Nuclear Graphite from Refcoal,* CSIR Report 86DC/Ht002, 2000

5. Kirk-Othmer's Encyclopaedia of Chemical technology 4th Ed., Executive editor Kroschwitz, J., Vol.17, pp369 - 594

6. Kirk-Othmer's Encyclopaedia of Chemical Technology 4th Ed., Executive editor Kroschwitz, J., Vol. 6, pp423 - 594

7. Ullman's Encyclopaedia of Industrial Chemistry 5th Ed, Vol. A5 98 – 120 Executive editor W. Gerhartz

8. Kelly, B.T., *Physics of Graphite*, Applied Science Publishers, 1981, London and New Jersey, pp477.

9. Kelly, B.T., *Nuclear Reactor Materials, in Material Science and Technology, Vol. 10 A, Edited by* Cahn, R.W., Haasen, P. and Kramer, E.J.

10. Marsden, *Irradiation damage in graphite due to fast neutrons in fission and fusion systems,* International atomic energy agency, Report IAEA-TECDOC-1154,2000.

11. Kirk-Othmer's Encyclopaedia of Chemical technology 4th Ed., Executive editor Kroschwitz, J., Vol. 4, pp 949 - 1015

12. Stach, E., Mackowsky, H-Th., Teicmuller M., Talor, G. H., Chandra, D., Teichmuller, R., *Stach's Textbook of coal petrology*, 1982 Gebruder Borntraeger, Berlin, Edward Arnold

Stuttgart.

13. Marsh, H., *Introduction to Carbon Science, UK, (1989)*

14. Valkovic', V., *Trace elements in coal, Vol. I,*CRC press, Inc. Boca Raten, Florida 1983.

15. Hayatsu, R., Winans, R.E., Scott, R.G., Moore, L.P. and Studier, M.H., *Trapped organic compounds and aromatic units in coals*, Fuel, 1978, **57**, 541 - 548.

16. Lyons, P. C., Palmer, C. A., Bostick, N. H., Fletcher, J. D., Dulong, F. T., Brown, F. W., Brown, Z. A., Krasnow, M. R. and Romankiw, L. A., *Chemistry and origin of minor and trace elements in vitrinite concentrates from a rank series from the eastern United States, England, and Australia*, Int. J. Coal Geol., 1989, **13**, 481 – 527

17. Spears, D. A., Manzanares-Papayanopoulos, L. I. and Booth, C. A., *The distribution and origin of trace elements in UK coals: the importance of pyrite*, Fuel, 1999, **78**, 1671 - 1677.

18. Ren, D. Y., Zhao, F. H., Wang, Y. Q. and Yang, S. J., *Distribution of minor and trace elements in Chinese coals,* Int. J. Coal Geol., 1999, **40**, 109 - 118.

19. Senior, C. L., Zeng, T., Che, J., Ames, M. R., Sarofim, A. F., Olmez, I., Huggins, F. E., Shah, N., Huffman, G. P., Kolker, A., Mroczkowski, S., Palmer, C. and Finkelman, R., *Distribution of trace elements in selected pulverized coals as a function of particle size and density,* Fuel Processing Technology, 2000, **63**, 215 - 241.

20. Huggins, F. E. and Huffman, G. P., *Modes of occurrence of trace elements in coal from XAFS spectroscopy,* Int. J. Coal Geol., 1996, **32**, 31 - 53.

21. Finkelman, R. B., *Modes of occurrence of potentially hazardous elements in coal: levels of confidence*, Fuel Processing Technology, 1994, **39**, 21 - 34.

22. Kolker, A., Huggins, F. E., Palmer, C. A., Shah, N., Crowley, S. S., Huffman, G. P. and Finkelman, R. B., *Mode of occurrence of arsenic in four US coals*, Fuel Processing Technology, 2000, **63**, 167 - 178.

23. Muhkopadhyay, P. K., Goodarzi, F., Crandlemire, A. L., Gills, K. S., MacNeil, D. J. and Smith, W. D., *Comparison of coal composition and elemental distribution in selected seams of the*

*Sydney and Stellarton Basins, Nova Scotia, Eastern Canada,* Int. J. Coal Geol., 1998, **37**, 113 - 141.

24. Huggins, F. E., Shah, N., Huffman, G. P., Kolker, A., Crowley, S., Palmer, C. A. and Finkelman, R. B., *Mode of occurrence of chromium in four US coals,* Fuel Processing Technology, 2000, **63**, 79 - 92.

25. Palmer, C. A. and Lyons, P. C., *Selected elements in major minerals from bituminous coal as detremined by INAA: implications for removing environmentally sensitive elements from coal,* Int. J. Coal Geol., 1996, **32**, 151 - 166.

26. Hart, R. J. and Leahy, R., *The geochemical characterisation of the seam from the Witbank basin*, Spec. Publ. Geol. Soc. S. Afr., 1983, **7**, 169 – 174.

27. Laban, K. L. and Atkin, B. P., *The determination of minor and trace element associations in coal using a sequential microwave digestion procedure*, Int. J. Coal Geol.,1999, **41**, 351 – 369.

28. Kortenski, J. and Bakardjiev, S., *Rare earth and radioactive elements in some coals from the Sofia, Svoge and Pernik Basis, Bulgaria,* Int. J. Coal Geol., 1993, **22**,237 -246.

29. Spears, D. A. and Zheng, Y., *Geochemistry and origin of elements in some UK coals*, Int. J. Coal Geol., 1999, **38**, 161 - 179.

30. Coleman, W. M., Perfetti, P., Dorn, H. C. and Taylor, L. T., *Trace element distribution in various solvent refined coal fractions as a function of the feed coal,* Fuel, 1978, **57**, 612 - 616.

31. Pearson, C. D. and Green, J. B., *Comparison of processing characteristics of Mayan and Wilmington heavy residues: 2. Characterization of vanadium and nickel complexes in acid-base-neutral fractions,* Fuel, 1989, **88**, 465 - 474.

32. Zeng, Y. and Uden, P. C., *Size exclusion chromatography sample pretreatment for GC-AED analysis of metalloporphyrins in crude oils,* J. High Resoln. Chromatogr. 1994, **17**, 217 - 222.

33. Zeng, Y. and Uden, P. C., *High temperature gas chromatography - Atomic emission detection of metalloporhyrins in crude oils,* J. High Resoln. Chromatogr. 1994, **17**, 223 - 229.

34. Bonnet, R., *Porphyrins in coal*, Int. J. Coal Geol., 1996, **32** 137 - 149.

35. Bonnet, R., Burke, P. J. and Reszka, A., *Metalloporphyrins in coal*, Fuel, 1987 **66**, 515 –520.

36. Fourie, C. J. E. and Engelbrecht, P. C., *Trace Elements in South African Coal and Coal Ashes*, CSIR Report, ENER-C, 1990

37. Howard, A. G. and Statham, P. J., *Inorganic trace analysis: Philosophy and practice*, John Wiley & sons, Chinchester. New York. Brisbane. Toronto. Singapore, 1995, pp182.

38. Vandecasteele, C. and Block, C. B., *Modern methods for trace element determination*, John Wiley & sons, Chinchester. New York. Brisbane. Toronto. Singapore, 1993, pp330.

39. Skoog, D. A. and Leary, J. J., *Principles of Instrumental Analysis 4th Ed.*, Saunders College Publishing, Harcourt Brace College Publishers, Fort Worth, Philadelphia, San Diego, New York, Orlando, Austin, San Antonio, Toronto, Montreal, London, Sydney, Tokyo, 1992, pp700.

40. Smith, F. E. and Arsenault, E. A., *Microwave-assisted sample preparation in analytical chemistry*, Talanta, 1996, **43**, 1207 – 1268.

41. Valkovic, V., *Trace elements in coal*, Vol II, 1983 CRC press, Inc., Boca Raton, Florida, pp281.

42. Mills, J. C. and Belcher, C. B., *Analysis of coal, coke, ash and mineral matter by atomic spectroscopy*, Prog. Analyt. Atom. Spectrosc., 1981, **4**, 49 – 80.

43. Silva, M. M., Goreti, M., Vale, R. and Caramão,B., *Slurry sampling graphite furnace atomic absorption spectrometry: determination of trace metals in mineral coal*, Talanta, 1999, **50**, 1035 – 1043.

44. Kubrakova, I. *Microwave-assisted sample preparation and preconcentration for ETAAS*, Spectrochim. Acta part B, 1997, **52**, 1469 – 1481.

45. Ikävalko, E., Laitinen, T., and Revitzer H., *Optimised method of coal digestion for trace metal determination by atomic absorption spectroscopy*, Fresenius J. Anal. Chem, 1999, **363**, 314 – 316.

46. Bettinelli, M., *Fusion procedure for the trace metal analysis of coal by atomic absorption*, At. Spectrosc., 1983, **4**, 5 – 9.

47. Coleman, W. M., Szabo, P., Wooton, D. L., Dorn, H. C. and Taylor, L. T., *Minor and trace*

*metal analysis of a solvent-refined coal by flameless atomic absorption*, Fuel, 1977, **56**, 195 – 198.

48. Riley, K. W., Schafer, H. N. S. and Orban, H., *Rapid acid extraction of bituminous coal for the determination of phosphorus*, Analyst, 1990, **115**, 1405 – 1406.

49. Alvarado, J., Alvarez, M., Cristiano, A. R. and Marcó, L. M., *Extraction of vanadium from petroleum coke samples by means of microwave wet acid digestion*, Fuel, 1990, **69**, 128 – 130.

50. Alvarado, J., León, L. E., López, F. and Lima, C., *Comparison of conventional and microwave wet acid digestion procedures for the determination of iron, nickel and vanadium in coal by electrothermal atomisation atomic absorption spectrometry*, J. Anal. At. Spectrom., 1988, **3**, 135 – 138.

51. Polkowska-Motrenko, H., Danko, B., Dybczyñski, R., Koster-Ammerlaan, A. and Bode, P., *Effect of acid digestion method on cobalt determination in plant materials*, Anal. Chim. Acta, 2000, **408**, 89 – 95.

52. Que Hee, S. S. and Boyle J. R., *Simultaneous multielemental analysis of some environmental and biological samples by inductively coupled plasma atomic emission spectrometry*, Anal. Chem., 1988, **60**, 1033 – 1042.

53. Nadkari, R. A., *Multitechnique multielement analysis of coal and fly ash*, Anal. Chem.,1980, **52**, 925 - 935.

54. Nadkari, R. A., *Application of microwave oven sample dissolution in analysis*, Anal. Chem.,1984, **56**, 2233 - 2237.

55. Lamothe, P. J., Fries, T. L. and Consul, J. J., *Evaluation of a microwave oven system for the dissolution of geological samples*, Anal. Chem., 1986, **58**, 1881 – 1886.

56. Paudyn, A. M. and Smith, R. G., *Microwave decomposition of dust, ashes, and sediments for the determination of elements* by ICP-AES, Can. J. Appl. Spectros., 1992, **37**, 94 – 99.

57. Munro, S. and Ebdon, L., *Application of inductively coupled plasma mass spectrometry(ICP-MS) for trace metal determination in foods*, , J. Anal. At. Spectrom., 1986, **1**, 211 – 219.

58. Roduskin, I., Axelsson, M. D. and Burman, E., *Multielement analysis of coal by ICP techniques using solution nebulization and laser ablation*, Talanta, 2000, **51**, 743 - 759.

59. Ebdon, L., Foulkes, M. E. and Parry, H. G. M., *Direct atomic spectrometric analysis by slurry atomisation. Part 7: Analysis of coal using inductively coupled plasma mass spectrometry*, J. Anal. At. Spectrom., 1988, **3**, 753 – 761.

60. Fonseca, R. W. and Miller-Ihli, N. J., *Anlyte transport studies of aqueous solutions and slurry samples using electrothermal vaporisation ICP-MS*, Appl. Spectrosc., 1995, **49**, 1403

61. Gregoire, D.N., Miller-Ihli, N. J. and Sturgeon, R. E., *Direct analysis of solids by ultrasonic slurry electrothermal vaporisation inductively coupled plasma mass spectrometry*, J. Anal. At. Spectrom., 1994, **9**, 605

62. Ricaud, R., Lachas, H., Lazaro, M. –J., Clarke, L. J., Jarvis, K. E., Herod, A. A., Gibb, T. C. and Kandiyoti, R., *Trace elements in coal derived liquids: analysis by ICP-MS and Mössbauer spectroscopy*, Fuel, 2000, **79**, 57 – 67.

63. Feng, S., Wu, S., Wharmby, A. and Wittmeier, A., *Microwave digestion of plant and grain standard reference materials in nitric and hydrofluoric acids for multi-element determination by inductively coupled plasma mass spectrometry*, J. Anal. At. Spectrom., 1999, **14**, 939 - 946.

64. Booth, C. A., Spears, D. A., Krause, P. and Cox, A. G., *The determination of low level trace elements in coals by laser ablation-inductively coupled plasma-mass spectrometry*, Fuel, 1999, **78**, 1665 – 1670.

65. Jenkins, R., *X-ray fluorescence analysis*, Anal. Chem., 1994, **56**, 1099A - 1106A

66. Malmqvist, J., *Semi-low-dilution fusion technique for analysis of geological, environmental and production plant samples in ferrous and non-ferrous industries*, X-ray spectrom., 1998, **27**, 183 - 197.

67. Pearce, B. C., Hill, J. W. F. and Kerry, I., *Use of X-ray fluorescence spectrometry for the direct multi-element analysis of coal powders*, Analyst, 1990, **115**, 1397 – 11403.

68. White, R. N., Smith, J. V., Spears, D. A., Rivers, M. L. and Sutton, S. R., *Analysis of iron*

*sulphides from UK coal by synchrotron X-ray fluorescence*, Fuel, 1989, **68**, 1480 – 1486.

69. Suarez-Fernandez, G. P., Vega, J. M. G., Fuertes, A. B., Gracia, A. B. and Martinez-Tarazoma, M. R., *Analysis of major, minor and trace elements in coal by radioisotope X-ray fluorescence spectrometry*, Fuel, 2001, **80**, 255 - 261.

70. Garbauskas, M. F. and Wong, J., *XRF analysis of trace titanium in coal using fundamental parameters*, X-ray Spectrom., 1983, **12**, 118 – 120.

71. Rowe, J. J. and Steinnes, E., *Determination of 30 elements in coal and fly ash by thermal and epithermal neutron activation analysis*, Talanta, 1977, **24**, 433 - 439.

72. Erasmus, C. S., Fesq, H. W., Kable, E. J. D., Rasmussen, S. E. and Sellschop, J. P. F., *The Nimroc samples as reference materials for neutron activation*, J. Radioanal. Chem., 1977, **39**, 323 – 329.

73. Nadkarni, R. A. and Morrison, G. H., *Multielement instrumental neutron activation analysis of biological materials*, Anal. Chem., 1973, **45**, 1957 – 1960.

74. Chattopadhay and Jervis, R. E., *Multielement determination in Market-Garden soils by instrumental photon activation analysis*, Anal. Chem. 1974, **46**, 1630 - 1639.

75. Block, C. and Dams, R., *Determination of trace elements in coal by instrumental neutron activation analysis,* Anal. Chim. Acta, 1973, **68**, 11 - 24.

76. Damarupurshad, A., Hart, R. J., Sellschop, J. P. F. and Meyer, H. O., *The application of INAA to the geochemical analysis of single diamonds*, , J. Radioanal. Nucl. Chem., 1997, **219**, 33 – 39.

77. Somer, G., Çakir, O. and Solak, A. O., *Differential-pulse polarographic determination of trace heavy elements in coal samples*, Analyst, 1984, **109**, 135 - 137.

78. Husain, S., Prasad, P. R. and Hasan, S. J., *Quantitative determination of trace elements in Indian coals by differential pulse polarography*, Fuel, 1990, **69**, 130 – 131.

79. Ondov, J. M., Zoller, W. H., Olmez, I., Aras, N. K., Gordon, G. E., Rancitelli, L. A., Abel, K. H., Filby, R. H., Shah, K. R. and Ragaini, R. C., *Elemental concentrations in the National*

*Bureau of Standards' environmental coal and fly ash standard reference materials*, Anal. Chem., 1975, **47**, 1102 - 1109.

80. Von Lehmden, D. J., Jungers, R. H. and Lee, R. E., Jr., *Determination of trace elements in coal, fly ash, fuel oil and gasoline – A preliminary comparison of selected analytical techniques*, Anal. Chem., 1974, **46**, 239 – 245.

81. Dulka, J. J. and Risby, T. H., *Ultratace metals in some environmental and biological systems*, Anal. Chem., 1976, **48**, 640 A – 653 A.

82. Stambaugh, E. P., *Treating carbonaceous material*, U.S. Pat. No. 4.121,910, 1978.

83. Waugh, A. B. and Bowling, K. McG., *Demineralization of coal*, U.S. Pat. No. 4,936,045, 1990.

84. Waugh, A. B. and Bowling, K. McG., *Removal of mineral matter from bituminous coals by aqueous chemical leaching*, Fuel Processing Technology, 1984, **9**, 217 – 233.

85. Reggel, L., Raymond, R. and Blaustein, B. D., *Removal of mineral matter including pyrite from coal*, U.S. Pat. No. 3,993,455, 1976.

86. Yang, R. T, *Process for producing high-purity coal*, U.S. Pat. No. 4,134,737, 1979.

87. Yang, R. T, Das, S. L. and Tsai, M. C., *Coal demineralization using sodium hydroxide and acid solutions*, Fuel, 1985, **64**, 735 – 742.

88. Mukherjee, S. and Borthakur, K. C., *Chemical demineralisation/desulphurisation of high sulphur coal using sodium hydroxide and acid solutions*, Fuel, 2001, **80**, 2037 - 2040.

89. Wang, Z. Y., Ohtsuka, Y. and Tomita, A, *Removal of mineral matter from coal by alkali treatment*, Fuel Processing Technology, 1986, **13**, 279 – 289.

90. Çulfaz, M., Ahmed, M. and Gürkan, S., *Removal of mineral matter and sulfur from lignites by alkali treatment*, Fuel Processing Technology, 1996, **47**, 99 – 109.

91. Bolat, E., Saglam, S. and Piskin, S., *Chemical demineralization of a Turkish high ash bituminous coal*, Fuel Processing Technology, 1998, **57**, 93 – 99.

92. Sharma, D. K. and Gihar, S., *Chemical cleaning of low grade coals through alkali- acid leaching employing mild conditions under ambient pressure*, Fuel, 1991, **70**, 663 – 665.

93. Wang, J. and Tomita, A, *Removal of mineral matter from some Australian coals by $Ca(OH)_2$/HCl leaching*, Fuel, 1998, **77**, 1747 – 1753.

94. Steel, K. M. and Patrick, J. W. *The production of ultra clean coal by chemical demineralisation*, Fuel, 2001, **80**, 2019 - 2023.

95. Steel, K. M., Besida, J., O'Donnell, T. A. and Wood, D. G., *Production of ultra clean coal: Part I-Dissolution behaviour of mineral matter in black coal toward hydrochloric and hydrofluoric acids*, Fuel Processing Technology, 2001, **70**, 171 – 192.

96. Steel, K. M., Besida, J., O'Donnell, T. A. and Wood, D. G., *Production of ultra clean coal: Part II-Ionic equilibrium in solution when mineral matter from black coal is treated with aqueous hydrofluoric acid*, Fuel Processing Technology, 2001, **70**, 193 – 219.

97. Steel, K. M., Besida, J., O'Donnell, T. A. and Wood, D. G., *Production of ultra clean coal: Part III. Effect of coal's carbonaceous matrix on the dissolution of mineral matter using hydrofluoric acid*, Fuel Processing Technology, 2002, **76**, 51 – 59.

98. Lloyd, R. and Turner, M. J., *Method for the continuous chemical reduction and removal of mineral matter contained in carbon structures*, U.S. Pat. No. 4,780,112, 1988.

99. Kindig, J. K. and Reynolds, J. E., *Integrated coal cleaning process with mixed acid regeneration*, U.S. Pat. No. 4,695,290, 1987.

100. Dwivedi, S. R., Dasgupta, P. K., Chatterjee, P. K., Bose, A. N., Mukherjee, S. N., Chatterjee, S. S. and Brahmachari, B. B., *Solvent refined coal – studies on the behavior of an iron catalyst*, Fuel Processing Technology, 1995, **42**, 19 –23.

101. Choudhury, S. B, Brahmachari, B. B Dwivedi, S. R., Roy, A. K., Dasgupta, P. K., Chakraborty, M. and Haque, R., *Solvent refined coal from high-ash non-coking coals and washery middlings for use in metallurgical coke making: Part I. Production, testing and characterization,* Fuel Processing Technology, 1996, **47**, 203 –213.

102. Choudhury, S. B, Sakar, S., Chatterjee, P. K., Chatterjee, S. S., Prasad, R. R., Mukherjee, S. N., Ghosh, S. K., Rao, S. R. K., Bose, A. N., Brahmachari, B. B. and Haque, R., *Solvent refined*

*coal from high-ash non/weakly coking coals for use in metallurgical coke making: Part II. Production, testing and characterization,* Fuel Processing Technology, 1997, **51**, 165 –176.

103. Chakraborty, M. and Sakkar, S., *Production of solvent refined coal,* J. Mines,Metals & Fuels, 1977, 139 - 144.

104. Filby, R. H., Shah, K. R. and Sautter, C. A., *A study of trace element distribution in the solvent refined coal (SRC) process using neutron activation analysis,* J. Radioanal. Chem., 1977, **37**, 693 - 704.

105. Hombach, H. P.,*General aspects of coal solubility,* Fuel, 1980, **59**, 465 - 470.

106. Roy, J., Banerjee, P. and Singh, P. N., *Action of dipolar aprotic solvents on coal,* Ind. J. Technol., 1976, **14**.298 –303.

107. Stiller, A. H., Sears, J. T. and Hammack, R. W., *Coal extraction process*, U.S. Pat. No. 4.272,356, 1981.

108. Renganatharan, K., Zondlo, J.W., Mintz, E.A., Kneisel, P. and Stiller, A.H., *Preparation of an ultra-low ash coal extract under mild conditions,* Fuel Processing Technology, 1988, **18**, 273 - 278.

109. Zondlo, J. W. Stansberry, P. G. and Stiller, A. H., *Production of coal derivation products utilizing NMP-type solvent extraction*, U.S. Pat. No. 5,955,375, 1999.

110. Chaudhuri, P. D. and Zondlo, J. W., *A procedure for the production of ultra-pure precursors from coal for the manufacture of value-added carbon products – preparation of an extract,* Fuel Science & Technol. Int. 1996, **14**, 1433 – 1446.

111. Chaudhuri, P. D. and Zondlo, J. W., *Procedure for the production of ultra-pure precursors from coal for the manufacture of value-added carbon products treatment of the residue*, Fuel Science & Technology International, 1996, **14**, 1381 – 1389.

112. Morgan, D.L., *Coal solubilisation,* U.S. Pat. No. 5120430.

113. Ouchi, K., Ozawa, H., Makabe, M. and Itoh, H., *Dissolution of coal with NaOH-alcohol: effect of alcohol species*, Fuel, 1981, **60**, 474 – 476.

114. Sharma, D. K. and Singh, S. K., *Extraction of coal through dilute alkaline treatment at low temperature and atmospheric pressure*, Fuel Processing Technology, 1988, **19**, 73 - 94.

115. Giray, E. S. V., Chen, C., Takanohashi, T. and Iino, M., *Increase of the extraction yield with of by the addition of arromatic amines*, Fuel, 2000, **72**, 1533 - 1538.

116. Iino, M. and Matsuda, M., *Carbon disulphide-pyridine mixture, a new efficient extraction solvent for coal*, Fuel, 1983, **62**, 744 - 746.

117. Takahashi, K., Norinaga, K., Masui, Y. and Iino, M., *Effect of addition of various salts on coal extraction with carbon disulphide/N-meyhl-2-pyrrolidinone mixed solvent*, Energy and Fuels, 2001, **15**, 141 - 146.

118. Iino, M., Takanohashi, T., Ohsuga, H. and Toda, K., *Extraction of coals with $CS_2$-N-methyl-2-pyrrolidinone mixed solvent at room temperature: Effect of coal rank and synergism of mixed solvent*, Fuel, 1988, **67**, 1639 - 1647.

119. Ishizuki, T., Takanohashi, T., Ito, O. and Iino, M., *Effects of additives and oxygen on extraction yield with $CS_2$-NMP mixed solvent for Argone premium coal samples*, Fuel, 1993, **72**, 579 - 580.

120. Morgan, D.L., *Coal solubilisation product, CSIR and Energy Affairs*, South Africa (1996)

121. Risenga, S. and Morgan D.L., *Personal communication.*

122. CRC Handbook of Chemistry and Physics (1913 - 1995) 75$^{th}$ Ed.

123. Lederer, C. M. Hollander, J. M. and Perlman, I., *Table of Isotopes* 6$^{th}$ Ed., John Wiley & Sons, Inc. New York. London. Sydney, 1967, pp594.

124. Stiller, A. H., Zondlo, J. W. and Stansberry, P. G., *Method for producing high quality, high purity, isotropic graphite from coal*, U.S. Pat. No. 5,955,375, 1998.

125. Kgobane, B.L., Mthembi P. M.and Morgan D.L. *The preparation of purified graphite from alkali-enhanced coal extracts*, Presented at the International Conference on Carbon 15 - 19 September 2002 Beijin, China.

126. Walton, H. F. and Rocklin, R. D., *Ion exchange in analytical chemistry*, CRC Press. Boca Raton. Ann Arbor. Boston, 1990, pp229.

127. Strelow, F. W. E., van Zyl, C. R. and Bothma, C. J. C., *Distribution coefficients and cation exchange behavior of elements in hydrochloric acid-ethanol mixtures*, Anal. Chim. Acta, 1969, **45**, 81 – 92.

128. Strelow, F. W. E., *An ion exchange selectivity scale of cations based on equilibrium distribution coefficients,* Anal. Chem., 1960, **32**, 1185 – 1188.

129. Strelow, F. W. E., *Distribution coefficients and ion exchange behavior of 46 elements with a macroreticular cation exchange resin in hydrochloric acid,* Anal. Chem., 1984, **56**, 1053 – 1056.

130. Strelow, F. W. E., *Distribution coefficients and cation exchange behavior of 45 elements with a macroporous resin in hydrochloric acid/methanol mixtures,* Anal. Chim. Acta, 1984, **160**, 31 – 45.

131. Strelow, F. W. E., Victor, A. H., van Zyl, C. R. and Ellof, C., *Distribution coefficients and cation exchange behavior of elements in hydrochloric acid-acetone*, Anal. Chem., 1971, **43**, 870 – 876.

132. Strelow, F. W. E., *Distribution coefficients and ion exchange selectivities for 46 elements with macroporous cation-exchange resin in hydrochloric acid-acetone medium,* Talanta, 1988, **35**, 385 – 395.

133. Siegfried, C. H., Weinert, W. and Strelow, F. W. E., *Cation-exchange in thiourea-hydrochloric acid solutions,* Talanta, 1983, **30**, 413 – 418.

134. Strelow, F. W. E., Hanekom, M. D., Victor, A. H. and Ellof, C., *Distribution coefficients and cation exchange behavior of elements in hydrobromic acid-acetone media*, Anal. Chim. Acta, 1975, **76**, 377 – 391.

135. Strelow, F. W. E. and Sondorp, H., *Distribution coefficients and cation exchange selectivities of elements with AG50W-X8 resins in perchloric acid,* Talanta, 1972, **19**, 1113 – 1120.

136. Strelow, F. W. E., Rathemeyer, R. and Bothma, C. J. C., *Ion exchange selectivity scale for cations in nitric acid and sulfuric acid media with sulfonated polystyrene resin,* Anal. Chem.

1965, **37**, 106 – 111.

137. Strelow, F. W. E. and van der Walt, T. N., *Cation exchange in tartaric acid-nitric acid and in tartaric acid ammonium tartrate solution,* Anal. Chem., 1967, **54**, 457 – 462.

138. Strelow, F. W. E., *Distribution coefficients and anion exchange behavior of some elements in hydrobromic-nitric acid mixtures,* Anal. Chem., 1978, **50**, 1359 – 1361.

139. Strelow, F. W. E., in *Ion exchange and solvent extraction*, Marinsky, J. A. and Marcus, Y., Eds., Marcel Dekker, New York, 1973, chap 2.

140. Strelow, F. W. E. and Bothma, C. J. C., *Anion exchange selectivity scale for elements in sulfuric acid media with strongly basic resin,* Anal. Chem., 1967, **39**, 595 – 599.

141. Boyd, G. E. and Soldano, B. A., *Self-diffusion of cations in and through sulfonated polystyrene cation-exchange polymers*, J. Am. Chem. Soc., 1954, **75**, 6091 – 6099.

142. Boyd, G. E. and Soldano, B. A., *Self-diffusion of cations in hetero-ionic cation-exchangers*, J. Am. Chem. Soc., 1954, **75**, 6107 – 6110.

143. Boyd, G. E. and Soldano, B. A., *Self-diffusion of water molecules and mobile anions in cation-exchangers*, J. Am. Chem. Soc., 1954, **75**, 6105 – 6107.

144. Boyd, G. E. and Soldano, B. A., *Self-diffusion of anions in strong-base anion-exchangers*, J. Am. Chem. Soc., 1954, **75**, 6099 – 6104.

145. Samuelson, O., *Ion exchange separations in analytical chemistry*, Almqvist & Wiksell, Stockholm. Göteborg. Uppsala, John Wiley & Sons, New York. London, 1963, pp474.

146. Bayer AG, *Product information*, Organic Chemicals Business Group, Research/Applications-Lewatit, D-51368.

147. Nicholls, D., *Complexes and first-row transition elements*, Macmillan Education Ltd., 1974, pp215.

148. Battersby, A. R., Jonnes, K. and Snow, R. J., *Novel methods for the demetalating tetrapyrrolic Metallo-Macrocycles,* Angew. Chem. Int. Ed. Engl., 1983, **22**, pp 734 - 735.

149. Lewis, N. J., Pfaltz, A. and Eschenmoser, A., *Acid-catalysed demetalation of nickel-*

*hydrocorphin and cobalt-corrin complexes with 1,3-propanedithiol,* Angew. Chem. Int. Ed. Engl., 1983, **22**, pp 735 - 736.

150. Lewis, N. J., Nussberger, R., Kräuler, B. and Eschenmoser, A., *5,15-Bisnorcobester: an unexpected mode of formation,* Angew. Chem. Int. Ed. Engl., 1983, **22**, pp 736 - 737.

151. Müller, P. M., Farooq, S., Hardegger, B., Salmond, W. S. and Eschenmoser, A., *Metal-free derivatives of the corphin ligand system,* Angew. Chem. Int. Ed. Engl., 1973, **12**, pp 914 - 916.

152. Kolthoff, I. M. and Elving, P. J., *Treatise on analytical chemistry, Part I: Theory and practice, Volume 2* , Interscience publishers, New York-London, 1961, pp1053 – 1093.

153. Claassen, A. and Daamen, A., *The photometric determination of cobalt by extraction with b-nitroso-a-naphthol*, Anal Chim. Acta, 1955, **12**, 547 - 553.

# APPENDICES

## APPENDIX 1

### Table A1.1: Minerals in coal [12,98]

| Mineral group | Mineral constituents | Chemical formulae |
|---|---|---|
| Silicates | Kaolinite (S) | $Al_2Si_2O_5(OH)_4$ |
| (clay minerals) | Illite (S, E) | $(OH)_8K(Mg,Al,Si).(Si_3Al_3)O_{10}$ |
| | Chlorite (S, E) | $(Mg, Fe,Al)_6(AlSi_3)_4O_{10}(OH)_8$ |
| | Feldspar | $(K,Na)_2O.Al_2O_3.6SiO_2$ |
| | Zircon | $ZrSiO_4$ |
| | Kyanite | $Al_2O_3.SiO_2$ |
| | Staurolite | $(2FeO.5Al_2O_3.4SiO_2.2H_2O$ |
| | Topaz | $(AlF)_2O.SiO_4$ |
| | Tourmaline | $H_9Al_3(BOH)_2.Si_4O_{19}$ |
| | Muscovite (S) | $KAl_2(AlSi_3)O_{10}(OH)_2$ |
| | Pyrophillite | $Al_2Si_4O_{10}.(OH)_2$ |
| | Garnet | $3CaO.Al_2O_3.3SiO_2$ |
| | Hornblende | $CaO.3FeO.4SiO_2$ |
| | Epidote | $4CaO.3Al_2O_3.6SiO_2.2H_2O$ |
| | Biotite | $K_2O.MgO.Al_2O_3.3SiO_2.2\ H_2O$ |
| | Pernnite | $5MgO.Al_2O_3.3SiO_2.2H_2O$ |
| | Augite | $CaO.MgO.2SiO_2$ |
| | Montmorillonite (S) | $(AlMg)_8.(Si_4O_{10})_3(OH)_2$ |
| | Mixed-layer illite-montmorillonite (S) | |
| | Paegioclase (S) | $(Na, Ca)Al(SiAl)Si_2O_8$ |

*Note*: S = Syngenetic; E = Epigenetic

**Table A1.1(continue): Minerals in coal [12,98]**

| Mineral group | Mineral constituents | Chemical formulae |
|---|---|---|
| Carbonates | Calcite S, E) | $CaCO_3$ |
| | Dolomite (S, E) | $CaMg(CO_3)_2$ |
| | Aragonite (S, E) | $CaCO_3$ |
| | Ankerite (S, E) | $CaCO_3 . (Mg, Fe, Mn)CO_3$ |
| | Siderite (S) | $FeCO_3$ |
| | Mixed-layer Siderite-Ankerite | |
| Chlorides | Sylvite | KCl |
| | Halite | NaCl |
| Oxides | Quartz (S, E) | $SiO_2$ |
| | Diaspore | $Al_2O_3.3H_2O$ |
| | Lepidocrocite | $Fe_2O_3.3H_2O$ |
| | Hematite (S) | $Fe_3O_4$ |
| | Magnetite | $Fe_2O_3$ |
| | Rutile (S) | $TiO_2$ |
| Sulphates | Gypsum (E) | $CaSO_4 . 2H_2O$ |
| | Jarosite (E) | $KF_3(OH)_6(SO_4)_2$ |
| | Barite | $BaSO_4$ |
| | Themadite (E) | $Na_2SO_4$ |
| Sulphides | Pyrite (S, E) | $FeS_2$ |
| | Marcasite (S, E) | $FeS_2$ |
| | Sphalerite (S, E) | ZnS |
| | Galena (E) | PbS |
| Phosphates | Apatite (S) | $9Ca.3P_2O_5CaX_2$ (X = OH, F, Cl) |

Note: S = Syngenetic; E = Epigenetic

# Table A1.2 Abundance and elemental mode of occurrence in coal [20,21]

| Element | Abundance (ppm) | Modes of occurrence | Level of confidence |
|---|---|---|---|
| Antimony | < 0.1 - 40 | Sulfides, pyrite | 4 |
| Arsenic | < 1 - 250 | As for S in pyrite | 8 |
| Beryllium | < 1 - 30 | Clays?, organic association? | 4 |
| Boron | < 1 - 500 | Clays, organic association | - |
| Cadmium | < 0.1 - 10 | ZnS, clays?, carbonates? | 8 |
| Chlorine | 100 - 8000 | Maceral moisture, NaCl? | - |
| Chromium | 1 - 100 | Clays?, $FeCr_2O_4$?, CrOOH | 2 |
| Cobalt | < 1 - 50 | Sulfides?, clays? | 4 |
| Copper | < 1 - 200 | Sulfides?, organic association? | - |
| Fluorine | < 20 - 1000 | Fluorapatite, clays | - |
| Lead | < 1 - 100 | PbS, pyrite, PbSe | 8 |
| Manganese | 5 - 1000 | Org. association, carbonates, other | 8 |
| Mercury | 0.01 - 10 | Sulfides?, Hg?, org. association? | 6 |
| Molybdenum | 0.5 - 50 | Pyrite, $MoS_2$?, org. association? | - |
| Nickel | < 1 - 100 | Sulfides, organic association? | 2 |
| Selenium | 0.1 - 20 | Organic Se, sulfides, etc. | 8 |
| Tin | 0.1 - 20 | Oxides, sulfides, org. association | - |
| Thallium | 0.1 - 3 | Sulfides | - |
| Thorium | < 0.1 -50 | Monazite, zircon | - |
| Uranium | 0.1 - 50 | Org. association, various minerals | - |
| Vanadium | < 1 - 300 | Clays, organic association? | - |
| Zinc | 1 - 300 | ZnS, organic association? | - |

# Table A1.3. Trace element content in major minerals, ppm[25].

| | Quartz | | | | | | | Kaolinite | Illite | Pyrite | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal bed/ Region | Upper Banner Coal | | | | Fire clay coal | | | West-phalian Region | Ruhr | Pittsburg no. 8 | Upper Freeport |
| As | < 0.5 | < 0.3 | < 0.3 | < 0.2 | < 0.5 | < 0.7 | < 3 | 0.52 | 2.35 | 227 | 1210 |
| Ba | 950 | 550 | < 60 | 630 | <130 | < 120 | <400 | 159 | 840 | < 300 | < 200 |
| Br | 1.4 | < 0.3 | < 0.3 | 0.61 | 2.03 | 0.8 | 6.9 | 14.5 | 4.61 | ND | ND |
| Ce | < 2 | < 1 | < 2 | < 0.6 | 5.8 | 18 | 42 | 73 | 143 | 3.2 | < 2 |
| Cr | < 5 | < 2 | < 5 | < 1 | < 7 | < 7 | < 27 | 8.8 | 167 | 39 | 4.2 |
| Co | < 0.6 | < 0.3 | < 0.5 | < 0.2 | < 1 | < 1 | < 4 | 0.943 | 12.4 | 13.8 | 23.1 |
| Cs | 0.52 | 0.2 | < 0.4 | 0.078 | 0.44 | < 0.5 | 1.8 | 1.99 | 27.4 | < 0.6 | 0.19 |
| Fe (%) | <0.03 | <0.021 | <0.03 | <0.01 | <0.01 | <0.06 | 0.22 | 0.287 | 1.46 | 46.6 | 46.6 |
| Eu | 0.33 | 0.15 | < 0.2 | 0.178 | < 0.4 | < 0.4 | < 1 | 0.157 | 1.6 | 0.058 | 0.092 |
| Hf | 0.56 | 0.16 | 0.65 | 0.157 | 0.73 | 0.5 | 2.7 | 8.88 | 5.21 | 0.24 | < 0.3 |
| K (%) | 0.7 | 0.56 | 0.058 | 0.52 | < 0.1 | < 0.1 | < 0.4 | 0.146 | 5.64 | 0.02 | 0.02 |
| La | 0.41 | 0.5 | 0.26 | 0.271 | 2.26 | 10.2 | 17.7 | 36.4 | 88.7 | 1.64 | 1.31 |
| Lu | <0.04 | <0.02 | <0.02 | <0.01 | 0.063 | <0.06 | < 0.2 | 0.81 | 0.558 | 0.19 | < 0.09 |
| Na (%) | 0.155 | 0.118 | 0.014 | 0.112 | 0.011 | 0.012 | 0.037 | 0.425 | 0.665 | 0.0249 | 0.027 |
| Nd | < 8 | < 5 | < 7 | < 3 | < 11 | < 10 | < 30 | 28.4 | 42 | < 40 | < 30 |
| Ni | < 60 | < 22 | < 40 | < 13 | < 80 | < 80 | < 290 | < 26 | 36 | ND | ND |
| Rb | 25 | 11.5 | < 19 | 10.5 | < 30 | < 30 | < 100 | 7.5 | 273 | < 50 | 12 |
| Sb | < 0.2 | < 0.2 | 0.076 | <0.08 | < 0.2 | < 0.2 | < 0.6 | 0.28 | 0.82 | 2.49 | 2.49 |
| Sc | 0.05 | 0.026 | 0.027 | 0.022 | 0.106 | 0.076 | 0.86 | 11.2 | 24.5 | 0.55 | 0.546 |
| Se | < 6 | < 2 | < 5 | < 1 | < 5 | < 9 | < 13 | < 3 | < 7 | 45 | 32.2 |
| Sm | < 0.6 | 0.041 | 0.029 | 0.018 | 0.438 | 0.96 | 2.51 | 11.03 | 10.21 | 0.16 | 0.194 |
| Sr | < 230 | 74 | < 220 | 54 | < 500 | < 400 | <1200 | < 110 | 189 | < 300 | < 100 |
| Ta | < 0.5 | < 0.3 | < 0.4 | < 0.1 | < 0.8 | < 0.9 | < 3 | 9.9 | 2.06 | < 0.4 | < 0.3 |
| Tb | < 0.2 | < 0.08 | < 0.1 | <0.04 | < 0.2 | < 0.3 | < 0.2 | 2.05 | 0.82 | < 0.6 | < 0.4 |
| Th | 0.77 | 1.2 | 0.6 | 0.22 | 1.1 | 3 | 6.9 | 59.6 | 20.7 | 0.46 | 0.46 |
| U | < 0.4 | < 0.2 | < 0.3 | < 0.1 | < 0.4 | < 0.5 | < 1 | 25.3 | 4.25 | 2 | ND |
| W | < 0.6 | < 0.3 | < 0.3 | < 0.2 | < 0.6 | < 0.8 | < 2 | 8.8 | 5.25 | ND | ND |
| Yb | < 0.3 | < 0.1 | < 0.1 | < 0.1 | <0.3 | < 0.4 | < 1 | 7.3 | 4.7 | < 2 | < 0.5 |
| Zn | < 12 | < 5 | < 0.9 | < 3 | < 20 | < 18 | < 80 | 23 | 36 | 18 | 37 |

*Note:* ND = not determined

**Table A1.4. Average concentrations of elements in coal [14]**

| Element | U.S. average | Worldwide average | Element | U.S. average | Worldwide average |
|---|---|---|---|---|---|
| | | *Concentration (%)* | | | |
| Aluminium, Al | 1.4 | 1.0 | Potassium, K | 0.18 | 0.01 |
| Calcium, Ca | 0.54 | 1.0 | Silicon, Si | 2.6 | 2.8 |
| Iron, Fe | 1.6 | 1.0 | Sodium, Na | 0.06 | 0.02 |
| Magnesium, Mg | 0.12 | 0.02 | Sulfur, S | 2.0 | 2.0 |
| Manganese, Mn | 0.01 | 0.005 | Titanium, Ti | 0.08 | 0.05 |
| Phosphorus, P | - | 0.05 | | | |
| | | *Concentration (ppm)* | | | |
| Antimony, Sb | 1.1 | 3.0 | Lithium, Li | 20 | 65 |
| Arsenic, As | 15 | 5.0 | Lutetium, Lu | 0.08 | 0.07 |
| Barium, Ba | 150 | 500 | Mercury. Hg | 0.18 | 0.012 |
| Beryllium, Be | 2.0 | 3 | Molybdenum, Mo | 3 | 5 |
| Bismuth, Bi | 0.7 | 5.5 | Neodymium, Nd | 37 | 4.7 |
| Boron ,B | 50 | 75 | Nickel, Ni | 15 | 15 |
| Bromine, Br | 2.6 | - | Niobium, Nb | 4.5 | - |
| Cadmium, Cd | 1.3 | - | Praseodymium, Pr | 2.7 | 2.2 |
| Cerium, Ce | 7.7 | 11.5 | Rubidium, Rb | 2.9 | 100 |
| Cesium, Cs | 0.4 | - | Samarium, Sm | 0.42 | 1.6 |
| Chlorine, Cl | 207 | 1000 | Scandium, Sc | 3 | 5 |
| Chromium, Cr | 15 | 10 | Selenium, Se | 4.1 | 3 |
| Cobalt, Co | 7 | 5 | Sliver, Ag | 0.20 | 0.50 |
| Copper, Cu | 19 | 15 | Strontium, Sr | 100 | 500 |
| Dysprosium, Dy | 2.2 | - | Tellurium, Te | 0.1 | - |
| Erbium, Er | 0.34 | 0.6 | Terbium, Tb | 0.1 | 0.3 |
| Europium, Eu | 0.45 | 0.7 | Thorium, Th | 0.1 | - |
| Fluorine, F | 74 | - | Thulium, Tm | 1.9 | - |
| Gadolinium, Gd | 0.17 | 1.6 | Tin, Sn | 1.6 | - |
| Galium, Ga | 7 | 7 | Tungsten, W | 2.5 | - |
| Germanium, Ge | 0.71 | 5 | Uranium, U | 1.6 | 1.0 |
| Hafnium, Hf | 0.60 | - | Vanadium, V | 20 | 25 |
| Holmium, Ho | 0.11 | 0.3 | Ytterbium, Yb | 1 | 0.5 |
| Iodine, I | 1.10 | - | Yttrium, Y | 10 | 10 |
| Lanthanum, La | 6.1 | 10 | Zinc, Zn | 39 | 10 |
| Lead, Pb | 16 | 25 | Zirconium, Zr | 30 | - |

**Table A1.5. Average concentrations of elements in South African coals, ppm [36]**

| Element | Witbank-Heidelberg | Ermelo-Belfast-Piet Retief | South Rand | Ellisras | Orange Free State | Natal |
|---|---|---|---|---|---|---|
| Arsenic, As | 8.1 | 7.8 | 12 | 5.5 | 13.3 | 7.3 |
| Barium, Ba | 243.1 | 220.6 | 512 | 83.5 | 371.2 | 280.9 |
| Beryllium, Be | 1.8 | 2.6 | 3 | 2.5 | 2.2 | 3.6 |
| Cadmium, Cd | 0.12 | 0.12 | 0.1 | 0.15 | 0.15 | 0.27 |
| Chlorine, Cl | 41.8 | 42.7 | 30 | 70 | 45 | 102.7 |
| Chromium, Cr | 27.7 | 28.9 | 97 | 24 | 45.3 | 26.7 |
| Cobalt, Co | 97 | 14.1 | 31 | 24 | 14.3 | 17.3 |
| Copper, Cu | 11.2 | 11 | 20 | 9.5 | 14.7 | 12.9 |
| Fluorine, F | 169.9 | 112.5 | 155 | 97.5 | 116.5 | 117.3 |
| Gallium, Ga | 7 | 7 | 14 | 4 | 11.5 | 6.2 |
| Germanium, Ge | 7.2 | 8.1 | 23 | 7.5 | 14 | 7 |
| Lead, Pb | 11.1 | 13.3 | 24 | 13 | 22.7 | 8 |
| Lithium, Li | 47.9 | 18.5 | 96 | 6 | 56.8 | 22.6 |
| Manganese, Mn | 58.8 | 49.1 | 58 | 82 | 80 | 42.6 |
| Nickel, Ni | 20.1 | 28.3 | 33 | 17.5 | 18.7 | 23.4 |
| Strontium, Sr | 440.7 | 452.8 | 822 | 69.5 | 491.2 | 399.7 |
| Vanadium, V | 26.6 | 29 | 42 | 50.5 | 33.3 | 32.4 |
| Zinc, Zn | 12.5 | 20.3 | 17 | 43.5 | 17.2 | 16.8 |

**Table A1.6. Average concentration (ppm) of trace elements in Tshikondeni coal and Refcoal.**

| Element | Original coal | Refcoal | Washed with HOAc | Washed with HCl | Washed with HF + HCl |
|---|---|---|---|---|---|
| Antimony, Sb | 0.7 | 0.1 | 0.5 | 0.1 | 0.1 |
| Arsenic, As | 1.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Boron, B | 17 | 2 | 3 | 2 | ND |
| Cadmium, Cd | 0.0 | 0.7 | 0.2 | 0.3 | 0.1 |
| Calcium, Ca | 4582 | 112 | 103 | 46 | 114 |
| Cesium, Ce | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| Chromium, Cr | 15.9 | 6.1 | 7.6 | 6.3 | 5.6 |
| Cobalt, Co | 4.8 | 2.8 | 3.8 | 2.3 | 2.4 |
| Copper, Cu | 9.1 | 6.3 | 6.9 | 6.1 | 7.6 |
| Europium, Eu | 0.4 | 0.1 | 0.1 | 0.1 | 0.1 |
| Galium, Ga | 6.2 | 1.1 | 1.7 | 1.4 | 1.3 |
| Hafnium, Hf | 3.8 | 2.5 | 2.8 | 2.4 | 2.0 |
| Iron, Fe | 6662 | 162 | 239 | 110 | 107 |
| Lanthanum, La | 11.0 | 1.4 | 2.1 | 1.5 | 2.0 |
| Lithium, Li | 8.8 | 0.5 | 0.7 | 0.7 | 0.2 |
| Magnesium, Mg | 817 | 22 | 22 | 17 | 14 |
| Manganese, Mn | 68.1 | 1.3 | 1.1 | 0.3 | 0.2 |
| Mercury, Hg | 0.1 | 0.2 | 0.4 | 0.4 | 0.6 |
| Molybdenum, Mo | 4.2 | 0.7 | 1.1 | 1.0 | 0.9 |
| Nickel, Ni | 14 | 8 | 10 | 9 | 8 |
| Phosphorus, P | 2152 | 143 | 171 | 108 | 30 |
| Rubidium, Rb | 4.4 | 0.2 | 0.2 | 0.2 | 0.0 |
| Scandium, Sc | 4.4 | 1.6 | 1.9 | 1.3 | 1.8 |
| Silicon, Si | 28419 | 1344 | 1727 | 1530 | 1565 |
| Sulfur, S | 10433 | 2678 | 4162 | 3240 | 2780 |
| Strontium, Sr | 140 | 23 | 26 | 19 | 18 |
| Tantalum, Ta | 0.6 | 0.5 | 0.7 | 0.6 | 0.7 |
| Tin, Sn | 2.4 | 1.1 | 1.3 | 1.1 | 1 |
| Titanium, Ti | 1029 | 475 | 626 | 528 | 418 |
| Vanadium, V | 12.9 | 4.9 | 5.7 | 4.9 | 5.1 |
| Ytterbium, Yb | 1.7 | 0.5 | 0.7 | 0.6 | 0.7 |
| Yttrium, Y | 10.8 | 4.9 | 5.9 | 4.3 | 6.2 |
| Zirconium, Zr | 129 | 100 | 127 | 107 | 75 |

ND = Not determined due to contamination

# Table A1.7. Sensitivities of different methods for coal analysis

| | NAA$^a$ (g) | SSMS (ng) | CIMS | ICPAES (µg/ml) | NFAAS | XRFS (µg) | ASV | ICPMS$^b$ µg/g | LAICPMS$^b$ µg/g | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ag | $10^{-10}$ - $10^{-9}$ | 0.2 | | 0.004 | 0.001ng/m*l* | 1.2 | 0.25ppb | 0.0019 | 0.001 | |
| Al | $10^{-10}$ - $10^{-9}$ | 0.02 | - | 0.002 | $1x10^{-2}$ g | 5.0 | - | 0.66 | 1.80 | |
| As | $10^{-10}$ - $10^{-9}$ | 0.06 | - | - | - | 0.11 | - | 0.022 | 0.008 | |
| Au | $10^{-12}$ - $10^{-11}$ | 0.2 | - | 0.04 | $1x10^{-12}$ g | 0.001 /cm$^2$ | 1.0ppb | 0.0005 | 0.001 | |
| B | - | - | - | - | - | - | - | 0.15 | 8 | |
| Ba | $10^{-10}$ - $10^{-9}$ | 0.2 | - | 0.01 | $6x10^{-12}$ g | 0.12 | - | 0.017 | 0.028 | |
| Be | - | 0.008 | - | 0.005 | $3x10^{-14}$ g | - | - | 0.0015 | 0.024 | |
| Bi | $10^{-8}$ - $10^{-7}$ | 0.2 | - | 0.05 | $4x10^{-12}$ g | 0.61 | 0.01ng/m*l* | 0.0001 | 0.001 | |
| Br | - | - | - | - | - | - | - | 8.4 | 17 | |
| Ca | $10^{-8}$ - $10^{-7}$ | 0.03 | - | 0.00007 | $4x10^{-13}$ g | 0.1 | - | 3.9 | 9.00 | |
| Cd | $10^{-9}$ - $10^{-8}$ | 0.3 | - | 0.002 | 0.03ng/m*l* | 0.40 | 0.005ng/m*l* | 0.0007 | 0.011 | |
| Ce | $10^{-9}$ - $10^{-8}$ | 0.1 | - | 0.007 | - | 0.17 | - | 0.004 | 0.003 | |
| Co | $10^{-10}$ - $10^{-9}$ | 0.05 | $1x10^{-11}$ | 0.003 | $2x10^{-12}$ g | 0.05 | - | 0.012 | 0.022 | |
| Cr | $10^{-8}$ - $10^{-7}$ | 0.05 | $1x10^{-11}$ | 0.001 | $1.2x10^{-12}$ g | 0.00006 | - | 0.017 | 0.001 | |
| Cs | $10^{-9}$ - $10^{-8}$ | 0.1 | - | | | 0.15 | - | 0.0001 | 0.0004 | |
| Cu | $10^{-10}$ - $10^{-9}$ | 0.08 | $1x10^{-11}$ | 0.001 | $6x10^{-13}$ g | 0.00002 | 0.005ng/m*l* | 0.041 | 0.140 | |
| Dy | $10^{-13}$ - $10^{-12}$ | 0.5 | $5x10^{-11}$ | 0.004 | $2.2x10^{-10}$ g | - | - | 0.0002 | 0.003 | |
| Er | $10^{-10}$ - $10^{-9}$ | 0.5 | $5x10^{-11}$ | 0.001 | $3.7x10^{-11}$ g | - | - | 0.0007 | 0.002 | |
| Eu | $10^{-13}$ - $10^{-12}$ | 0.2 | $5x10^{-11}$ | 0.001 | $3x10^{-11}$ g | 0.66 | - | 0.0001 | 0.003 | |
| Fe | $10^{-6}$ - $10^{-5}$ | 0.05 | $1x10^{-11}$ | 0.005 | $2x10^{-13}$ g | 0.0085 | - | 0.36 | 0.50 | |
| Ga | $10^{-10}$ - $10^{-9}$ | 0.09 | - | 0.014 | $1x10^{-12}$ g | 0.01 | 0.4ng/m*l* | 0.003 | 0.008 | |
| Gd | $10^{-9}$ - $10^{-8}$ | 0.5 | $5x10^{-11}$ | 0.007 | - | - | - | 0.0002 | 0.014 | |
| Hf | $10^{-11}$ - $10^{-10}$ | - | - | 0.01 | - | - | - | 0.0062 | 0.003 | |
| Hg | $10^{-10}$ - $10^{-9}$ | 0.6 | - | 0.2 | $8x10^{-11}$ g | 0.24 | $4x10^{-9}$ *M* | 0.008 | 0.060 | |
| Ho | $10^{-11}$ - $10^{-10}$ | 0.1 | $5x10^{-11}$ | 0.01 | $3.3x10^{-10}$ g | - | - | 0.00002 | 0.0005 | |
| I | - | - | - | - | - | - | - | 0.41 | 0.37 | |
| In | $10^{-12}$ - $10^{-11}$ | 0.1 | - | 0.03 | $4x10^{-13}$ g | 1.1 | 0.1ng/m*l* | - | - | |
| Ir | $10^{-11}$ - $10^{-10}$ | 0.3 | - | - | - | - | - | 0.00004 | - | |
| K | - | 0.03 | - | - | - | 0.52 | $1x10^{-5}$ *M* | 4.6 | 60 | |
| La | $10^{-11}$ - $10^{-10}$ | 0.1 | $5x10^{-11}$ | 0.003 | 0.1ng/m*l* | 0.12 | - | 0.001 | 0.006 | |
| Li | - | 0.0006 | - | - | - | - | - | 0.028 | 12 | |
| Lu | $10^{-10}$ - $10^{-9}$ | 0.1 | $5x10^{-11}$ | 0.008 | - | - | - | 0.00006 | 0.002 | |
| Mg | $10^{-8}$ - $10^{-7}$ | 0.03 | - | 0.0007 | $4x10^{-14}$ g | - | - | 2.7 | 17 | |
| Mn | $10^{-12}$ - $10^{-11}$ | 0.05 | $1x10^{-11}$ | 0.0007 | $2x10^{-13}$ g | 0.00015 | - | 0.03 | 1.20 | |
| Mo | $10^{-9}$ - $10^{-8}$ | 0.3 | - | 0.005 | $3x10^{-12}$ g | 0.072 | - | 0.024 | 0.018 | |
| Na | $10^{-10}$ - $10^{-9}$ | 0.02 | - | 0.0002 | $1x10^{-12}$ g | - | - | 6.9 | 11.0 | |
| Nb | - | 0.08 | - | 0.01 | 12.0µg/m*l* | | - | - | 0.0012 | 0.004 |
| Nd | - | 0.4 | $5x10^{-11}$ | 0.05 | - | 0.30 | - | 0.002 | 0.005 | |
| Ni | $10^{-8}$ - $10^{-7}$ | - | $1x10^{-11}$ | 0.006 | $4x10^{-12}$ g | 0.06 | 0.1g/m*l* | 0.074 | 0.620 | |
| Os | $10^{-9}$ - $10^{-8}$ | 0.4 | - | - | - | - | - | - | - | |
| P | - | - | - | - | - | 0.01 | - | 0.37 | 1.500 | |
| Pb | $10^{-7}$ - $10^{-6}$ | 0.3 | - | 0.008 | 0.002ng/m*l* | 0.0003 | 0.01ng/m*l* | 0.009 | 0.002 | |
| Pd | $10^{-10}$ - $10^{-9}$ | 0.3 | $1x10^{-11}$ | 0.007 | $4x10^{-12}$ g | - | - | 0.0033 | 0.003 | |
| Pr | $10^{-10}$ - $10^{-9}$ | 0.1 | $5x10^{-11}$ | 0.07 | - | - | - | 0.0002 | 0.002 | |
| Pt | $10^{-9}$ - $10^{-8}$ | 0.5 | $1x10^{-11}$ | 0.08 | $1x10^{-11}$ g | - | $1x10^{-9}$ *m* | 0.0004 | 0.002 | |
| Rb | - | - | - | - | - | 0.0075 | - | 0.007 | 0.010 | |
| Re | $10^{-11}$ - $10^{-10}$ | 0.2 | - | - | - | - | - | 0.00002 | 0.001 | |
| Rh | $10^{-11}$ - $10^{-10}$ | 0.09 | $1x10^{-11}$ | 0.003 | $8x10^{-12}$ g | 103µg/m*l* | 0.1ng/m*l* | 0.00009 | - | |
| Ru | $10^{-9}$ - $10^{-8}$ | 0.03 | $1x10^{-11}$ | - | - | - | - | 0.0003 | 0.004 | |
| S | - | - | - | - | - | - | - | 25 | 26 | |
| Sb | $10^{-10}$ - $10^{-9}$ | - | - | - | - | - | - | 0.0013 | 0.007 | |
| Sc | $10^{-10}$ - $10^{-9}$ | 0.04 | - | 0.003 | - | 0.38 | - | 0.0005 | 0.003 | |
| Se | - | - | - | - | - | - | - | 0.19 | 0.111 | |
| Si | - | - | - | - | - | - | - | 5.4 | 14000 | |
| Sm | $10^{-11}$ - $10^{-10}$ | 0.5 | $5x10^{-11}$ | 0.02 | - | 4.1µg/m*l* | - | 0.0003 | 0.003 | |
| Sn | - | 0.3 | - | 0.3 | $2x10^{-12}$ g | 3.9ppm | 2.0ng/*l* | 0.034 | 0.019 | |
| Sr | $10^{-9}$ - $10^{-8}$ | 0.09 | - | 0.00002 | $1x10^{-12}$ g | 0.00007 | - | 0.013 | 0.045 | |
| Ta | $10^{-9}$ - $10^{-8}$ | 0.2 | - | 0.07 | 7.0µg/m*l* | - | - | 0.0008 | 0.003 | |
| Tb | $10^{-9}$ - $10^{-8}$ | 0.1 | $5x10^{-11}$ g | 0.2 | - | 159µg/m*l* | - | 0.0001 | 0.001 | |
| Te | $10^{-9}$ - $10^{-7}$ | - | - | - | - | 0.12 | - | 0.0047 | 0.018 | |
| Th | $10^{-9}$ - $10^{-8}$ | 0.2 | - | 0.003 | - | 6.5µg/m*l* | - | 0.0017 | 0.001 | |
| Ti | $10^{-8}$ - $10^{-7}$ | 0.05 | - | 0.003 | $1x10^{-12}$ g | 0.001 | - | 0.47 | 0.05 | |

*NOTE:* Continued on next page

## Table A1.7.(continued). Sensitivities of different methods for coal analysis

| | NAA[a] (ng) | SSMS (g) | CIMS | ICPAES (μg/ml) | NFAAS | XRFS (μg) | ASV | ICPMS[b] μg/g | LAICPMS[b] μg/g | |
|---|---|---|---|---|---|---|---|---|---|---|
| Tl | $10^{-8}$ - $10^{-7}$ | 0.2 | - | 0.2 | $1x10^{-12}$ g | - | 0.1ng/ml | 0.0006 | 0.004 | |
| Tm | $10^{-9}$ - $10^{-8}$ | 0.1 | $5x10^{-12}$ g | 0.007 | - | - | - | 0.00003 | 0.000 | |
| U | $10^{-10}$ - $10^{-9}$ | - | - | 0.03 | - | 0.00002 | - | 0.0005 | 0.000 | |
| V | $10^{-11}$ - $10^{-10}$ | 0.04 | $1x10^{-11}$ g | 0.006 | $5x10^{-11}$ g | - | - | 0.016 | 0.005 | |
| W | $10^{-10}$ - $10^{-9}$ | 0.5 | - | 0.002 | 1.0μg/ml | - | - | 0.0054 | 0.001 | |
| Y | - | - | - | 0.002 | 10μg/ml | 0.22 | - | 0.0012 | 0.006 | |
| Yb | $10^{-10}$ - $10^{-9}$ | 0.5 | $5x10^{-11}$ g | 0.00009 | - | 6.8μg/ml | - | 0.0001 | 0.006 | |
| Zn | $10^{-8}$ - $10^{-7}$ | 0.1 | $1x10^{-11}$ g | 0.002 | $2x10^{-14}$ g | 0.00004 | 0.04μg/ml | | 0.15 | 0.146 |
| Zr | $10^{-8}$ - $10^{-7}$ | 0.1 | - | 0.005 | 5.0μg/ml | 0.00002 | - | 0.018 | 0.016 | |

*NOTE:* [a]: From Dulka and Risby [81] [b]: From Roduskin et al [58]

NAA = neutron activation analysis; SSMS = spark source mass spectrometry; CIMS = chemical ionization mass spectrometry; ICPAES = inductively coupled plasma atomic emission spectrometry; NFAAS = none-flame atomic absorption spectrometry; XRFS = X-ray fluorescence spectrometry; ASV = anodic stripping voltametry; ICPMS = inductively coupled plasma mass spectrometry; LAICPMS = laser ablation inductively coupled plasma mass spectrometry

## Table A1.8. Concentration (μg/g) of trace elements in SRC as determined by AA [30].

| Elemenet | Pittsburg No.8 feed coal | Amax feed coal | Monterey feed coal | Illinois feed coal | Western Kentucky feed coal |
|---|---|---|---|---|---|
| Al | 147 | 171 | 77.8 | 32 | 107 |
| Ca | 105 | 23.7 | 93.5 | 5486 | 1297 |
| Cd | <0.07 | 2.8 | 0.5 | 0.3 | 0.3 |
| Co | <2 | 19.2 | 12 | 5 | 4.8 |
| Cr | 5.9 | 5.7 | 11.2 | 11.9 | 3.7 |
| Cu | 12.4 | 3.2 | 3.6 | 0.8 | 1.4 |
| Fe | 423 | 11797 | 714 | 738 | 3300 |
| K | 113 | 22.3 | 27.2 | 40.9 | 33.5 |
| Mg | 24.3 | 58.9 | 29 | 8.3 | 8 |
| Mn | 21.6 | 4.4 | 39.6 | 8.7 | 3.6 |
| Ni | 12 | 16.4 | 13.8 | 7.7 | 3.3 |
| Pb | <0.5 | 12.8 | 23.7 | 4.9 | 2.1 |

**Table A1.9 Concentration (μg/g) of trace elements in SRC as determined by INAA [103].**

| Element | Coal | SRC |
|---|---|---|
| AS | 13.6 | 1.39 |
| Ba | 62.6 | 2.48 |
| Br | 3.51 | 3.95 |
| Ce | 17 | 0.553 |
| Co | 3.7 | 0.31 |
| Cr | 14 | 2.68 |
| Cs | 0.89 | 0.023 |
| Eu | 0.292 | 0.013 |
| Fe, % | 1.73 | 0.068 |
| Hg | 0.436 | 0.025 |
| K | 1500 | 315 |
| Lu | 0.125 | 0.004 |
| Na | 148 | 9.55 |
| Ni | 20 | 2.7 |
| Rb | 22.4 | 0.57 |
| Sb | 0.5 | 0.074 |
| Sc | 2.8 | 0.13 |
| Se | 1.53 | 0.148 |
| Sm | 1.37 | 0.04 |
| Sr | 152 | 4.4 |
| Tb | 0.437 | 0.014 |
| Th | 1.66 | 0.055 |

**TableA1.9. Trace elements in NMP coal extract. Concentration in ppm**

| | Water precipitated | Vacuum-evaporation |
|---|---|---|
| **Ash%** | 0.06 | 0.08 |
| Al | 11 | 24 |
| Ca | 7.8 | 46 |
| Cr | 6.7 | 7.4 |
| Cu | 5.9 | 17 |
| Fe | 170 | 225 |
| K | 1.8 | 3.3 |
| Mg | 2.4 | 13 |
| Mn | 0.2 | 1.2 |
| Na | 3.3 | 34 |
| Ni | 7.6 | 11 |
| P | 7.7 | 8.8 |
| Si | 31 | 68 |
| Ti | 52 | 82 |
| V | 2.7 | 3.9 |
| Zn | 5.9 | 22 |
| As Oxides % | 0.06 | 0.09 |

**Table A1.10. Analysis and extent of extraction in NMP of various coals**

| | **Proximate analysis** | | | **Ultimate analysis** | | | | |
|---|---|---|---|---|---|---|---|---|
| **Coal** | **%Moisture** | **% Ash** | **%C** | **%C** | **%H** | **%N** | **%S** | **%C Extraction** |
| Hlobane Gus | 1.2 | 10.9 | 77 | 87 | 4.9 | 2.2 | 0.6 | 41.3 |
| Hlobane Dundus | 1.1 | 13.4 | 74 | 87 | 5.2 | 2.2 | 0.7 | 54.9 |
| Vryheid Coronation, Vrede | 2 | 14.4 | 71 | 85 | 5.2 | 2.1 | 0.7 | 36.5 |
| Vryheid Coronation, Leeuwnek | 1.2 | 14.5 | 74 | 87 | 5.1 | 2.3 | 0.9 | 67 |
| Moatize | 0.9 | 19 | 71 | 88 | 5 | 2.1 | 0.9 | 80.3 |
| Tshikondeni Floatation Product | 0.9 | 7.8 | 81 | 89 | 5.2 | 2.1 | 0.8 | 90.3 |
| Upper Freeport | 1.13 | 13.03 | 73 | 86 | 4.7 | 1.6 | | 85.8 |
| Wyodak | 28.09 | 6.31 | 49 | 75 | 5.4 | 1.1 | | 6 |
| Illnois # 6 | 7.97 | 14.25 | 60 | 78 | 5 | 1.4 | | 14.4 |
| Pittsburgh # 8 | 1.65 | 9.1 | 74 | 83 | 5.3 | 1.6 | | 25.3 |
| Pocahantas # 3 | 0.65 | 4.74 | 86 | 91 | 4.4 | 1.3 | | 76.9 |
| Blind Canyons | 4.63 | 4.49 | 73 | 81 | 5.8 | 1.6 | | 16.2 |
| Stockton | 2.42 | 19.36 | 65 | 83 | 5.3 | 1.6 | | 17.5 |
| Beulah Zap | 32.24 | 6.59 | 45 | 73 | 4.8 | 1.2 | | 6.4 |
| Polish coal | 1.6 | 0.65 | 80 | 87 | 5.4 | 1.8 | 0.7 | 41.2 |

**Table A1.11. Properties of Nuclear Grade Graphite [5]**

| **Property** | **Anisotropic graphite** | **Isotropic graphite** |
|---|---|---|
| Density, g/cm$^3$ | 1.71 | 1.86 |
| Resistance, μΩ . Cm | 735 | 1000 |
| Tensile strength, kPa | 9930 | 46172 |
| Coefficient of thermal expansion (CTE), $10^{-6}$/°C | | |
| with grain | 2.2 | 5.3 |
| against grain | 3.8 | 5.3 |
| Anisotropy ratio (CTE ratio) | 1.73 | 1 |
| Total ash, ppm | 740 | 400 |
| Boron content, ppm | 0.4 | 0.3 |

# APPENDIX 2

## Table A2.1. The progress of extraction with NaOH only

| Time, min | | 0 | 5 | 10 | 15 | 30 | 45 | 60 | 90 | 120 | 180 | 240 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RUN 1 | Mass, g | 0.109 | 0.108 | 0.109 | 0.102 | 0.111 | 0.105 | 0.103 | 0.102 | 0.101 | 0.103 | 0.109 | 0.101 |
| | Absorbance | 0.000 | 0.000 | 0.000 | 0.006 | 0.112 | 0.230 | 0.357 | 0.608 | 0.813 | 0.945 | 1.046 | 1.008 |
| | Corrected Absorbance | 0.000 | 0.000 | 0.000 | 0.006 | 0.101 | 0.218 | 0.348 | 0.597 | 0.802 | 0.917 | 0.961 | 0.998 |
| RUN 2 | Mass, g | 0.106 | 0.104 | 0.103 | 0.101 | 0.100 | 0.104 | 0.104 | 0.112 | 0.110 | 0.101 | 0.103 | 0.106 |
| | Absorbance | 0.000 | 0.000 | 0.005 | 0.021 | 0.202 | 0.355 | 0.527 | 0.793 | 0.940 | 0.933 | 0.991 | 1.044 |
| | Corrected Absorbance | 0.000 | 0.000 | 0.005 | 0.021 | 0.201 | 0.341 | 0.509 | 0.709 | 0.856 | 0.927 | 0.965 | 0.984 |
| RUN 3 | Mass, g | 0.104 | 0.140 | 0.120 | 0.122 | 0.107 | 0.117 | 0.117 | 0.112 | 0.101 | 0.101 | 0.108 | 0.124 |
| | Absorbance | 0.000 | 0.000 | 0.000 | 0.013 | 0.100 | 0.252 | 0.387 | 0.670 | 0.765 | 0.863 | 0.987 | 1.188 |
| | Corrected Absorbance | 0.000 | 0.000 | 0.000 | 0.011 | 0.093 | 0.215 | 0.330 | 0.600 | 0.757 | 0.854 | 0.912 | 0.955 |
| RUN 4 | Mass, g | 0.115 | 0.108 | 0.103 | 0.114 | 0.102 | 0.117 | 0.102 | 0.143 | 0.113 | 0.111 | 0.113 | 0.116 |
| | Absorbance | 0.000 | 0.002 | 0.006 | 0.047 | 0.170 | 0.308 | 0.415 | 0.874 | 0.897 | 0.986 | 1.043 | 1.069 |
| | Corrected Absorbance | 0.000 | 0.002 | 0.006 | 0.041 | 0.167 | 0.264 | 0.408 | 0.611 | 0.796 | 0.892 | 0.921 | 0.925 |
| RUN 5 | Mass, g | 0.100 | 0.127 | 0.111 | 0.111 | 0.110 | 0.106 | 0.107 | 0.120 | 0.100 | 0.108 | 0.106 | 0.119 |
| | Absorbance | 0.000 | 0.005 | 0.008 | 0.024 | 0.166 | 0.288 | 0.482 | 0.836 | 0.822 | 1.005 | 1.042 | 1.172 |
| | Corrected Absorbance | 0.000 | 0.004 | 0.007 | 0.022 | 0.150 | 0.272 | 0.451 | 0.695 | 0.826 | 0.934 | 0.985 | 0.987 |
| Average Corrected Absorbance | | 0.000 | 0.003 | 0.006 | 0.020 | 0.142 | 0.262 | 0.409 | 0.642 | 0.807 | 0.905 | 0.949 | 0.970 |

**Table A2.2. The progress of extraction with $Na_2S$ only**

| Time, min | | 0 | 5 | 10 | 15 | 30 | 45 | 60 | 90 | 120 | 180 | 240 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.34g $Na_2S$ | Mass, g | 0.114 | 0.116 | 0.106 | 0.108 | 0.106 | 0.106 | 0.118 | 0.119 | 0.120 | 0.105 | 0.118 | 0.103 |
| | Absorbance | 0.016 | 0.044 | 0.058 | 0.097 | 0.148 | 0.174 | 0.181 | 0.192 | 0.176 | 0.164 | 0.194 | 0.172 |
| | Corrected Absorbance | 0.014 | 0.038 | 0.055 | 0.090 | 0.140 | 0.150 | 0.154 | 0.162 | 0.171 | 0.156 | 0.164 | 0.167 |
| 12.61g $Na_2S$ | Mass, g | 0.107 | 0.103 | 0.121 | 0.111 | 0.111 | 0.108 | 0.104 | 0.113 | 0.104 | 0.103 | 0.110 | 0.111 |
| | Absorbance | 0.014 | 0.017 | 0.040 | 0.054 | 0.169 | 0.220 | 0.265 | 0.312 | 0.305 | 0.293 | 0.306 | 0.295 |
| | Corrected Absorbance | 0.013 | 0.016 | 0.033 | 0.048 | 0.153 | 0.204 | 0.254 | 0.275 | 0.294 | 0.283 | 0.278 | 0.266 |
| 25.17g $Na_2S$ | Mass, g | 0.101 | 0.114 | 0.103 | 0.104 | 0.107 | 0.108 | 0.102 | 0.109 | 0.113 | 0.107 | 0.120 | 0.102 |
| | Absorbance | 0.009 | 0.057 | 0.175 | 0.227 | 0.432 | 0.526 | 0.478 | 0.460 | 0.387 | 0.250 | 0.253 | 0.215 |
| | Corrected Absorbance | 0.009 | 0.050 | 0.170 | 0.219 | 0.402 | 0.488 | 0.470 | 0.424 | 0.341 | 0.234 | 0.211 | 0.211 |
| 25.17g $Na_2S$ | Mass, g | 0.110 | 0.104 | 0.107 | 0.116 | 0.106 | 0.104 | 0.104 | 0.105 | 0.108 | 0.108 | 0.104 | 0.106 |
| | Absorbance | 0.012 | 0.021 | 0.067 | 0.179 | 0.346 | 0.415 | 0.455 | 0.415 | 0.371 | 0.290 | 0.244 | 0.245 |
| | Corrected Absorbance | 0.011 | 0.020 | 0.065 | 0.154 | 0.328 | 0.398 | 0.436 | 0.396 | 0.344 | 0.269 | 0.234 | 0.231 |
| Average Corrected Absorbance | | 0.010 | 0.035 | 0.118 | 0.187 | 0.365 | 0.443 | 0.453 | 0.410 | 0.343 | 0.252 | 0.223 | 0.221 |

# Table A2.3. The progress of extraction with NaOH and $Na_2S$

| Time,min | | 0 | 5 | 10 | 15 | 30 | 45 | 60 | 90 | 120 | 180 | 240 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10:1 NaOH :$Na_2S$ | Mass, g | 0.106 | 0.104 | 0.105 | 0.103 | 0.109 | 0.112 | 0.105 | 0.101 | 0.107 | 0.105 | 0.105 | 0.127 |
| mole ratio | Absorbance | 0.023 | 0.053 | 0.086 | 0.239 | 0.339 | 0.385 | 0.506 | 0.506 | 0.618 | 0.618 | 0.723 | 0.769 |
| | Corrected Absorbance | 0.011 | 0.022 | 0.051 | 0.084 | 0.022 | 0.303 | 0.367 | 0.503 | 0.579 | 0.690 | 0.732 | 0.729 |
| 8:1 NaOH :$Na_2S$ | Mass, g | 0.106 | 0.107 | 0.110 | 0.118 | 0.121 | 0.102 | 0.111 | 0.113 | 0.110 | 0.104 | 0.117 | 0.116 |
| mole ratio | Absorbance | 0.006 | 0.046 | 0.108 | 0.158 | 0.325 | 0.510 | 0.534 | 0.820 | 0.928 | 0.894 | 1.035 | 1.027 |
| | Corrected Absorbance | 0.006 | 0.043 | 0.095 | 0.143 | 0.276 | 0.423 | 0.525 | 0.742 | 0.824 | 0.861 | 0.882 | 0.884 |
| 4:1 NaOH :$Na_2S$ | Mass, g | 0.104 | 0.106 | 0.104 | 0.101 | 0.113 | 0.100 | 0.109 | 0.104 | 0.106 | 0.111 | 0.108 | 0.108 |
| mole ratio | Absorbance | 0.013 | 0.015 | 0.047 | 0.075 | 0.205 | 0.226 | 0.343 | 0.458 | 0.566 | 0.754 | 0.765 | 0.793 |
| | Corrected Absorbance | 0.012 | 0.014 | 0.045 | 0.074 | 0.182 | 0.225 | 0.314 | 0.440 | 0.536 | 0.679 | 0.699 | 0.736 |
| 2:1 NaOH :$Na_2S$ | Mass, g | 0.110 | 0.100 | 0.109 | 0.106 | 0.107 | 0.101 | 0.104 | 0.102 | 0.104 | 0.112 | 0.145 | 0.107 |
| mole ratio | Absorbance | 0.126 | 0.180 | 0.251 | 0.291 | 0.401 | 0.406 | 0.464 | 0.502 | 0.558 | 0.623 | 0.900 | 0.727 |
| | Corrected Absorbance | 0.114 | 0.180 | 0.231 | 0.274 | 0.373 | 0.400 | 0.446 | 0.494 | 0.536 | 0.594 | 0.675 | 0.681 |
| 1:1 NaOH :$Na_2S$ | Mass, g | 0.108 | 0.110 | 0.105 | 0.101 | 0.112 | 0.108 | 0.111 | 0.105 | 0.111 | 0.112 | 0.103 | 0.103 |
| mole ratio | Absorbance | 0.048 | 0.265 | 0.306 | 0.350 | 0.475 | 0.515 | 0.584 | 0.575 | 0.556 | 0.387 | 0.249 | 0.234 |
| Run 1 | Corrected Absorbance | 0.044 | 0.242 | 0.282 | 0.347 | 0.423 | 0.475 | 0.525 | 0.547 | 0.499 | 0.347 | 0.241 | 0.227 |
| 1:1 NaOH :$Na_2S$ | Mass, g | 0.113 | 0.108 | 0.106 | 0.101 | 0.116 | 0.119 | 0.121 | 0.124 | 0.112 | 0.110 | 0.108 | 0.111 |
| mole ratio | Absorbance | 0.124 | 0.265 | 0.289 | 0.386 | 0.546 | 0.642 | 0.677 | 0.657 | 0.474 | 0.331 | 0.277 | 0.261 |
| Run 2 | Corrected Absorbance | 0.110 | 0.245 | 0.272 | 0.384 | 0.472 | 0.540 | 0.560 | 0.531 | 0.423 | 0.301 | 0.257 | 0.235 |
| 1:1 NaOH :$Na_2S$ | Mass, g | 0.116 | 0.116 | 0.116 | 0.095 | 0.108 | 0.099 | 0.112 | 0.112 | 0.102 | 0.125 | 0.121 | 0.115 |
| mole ratio Run | Absorbance | 0.005 | 0.283 | 0.430 | 0.381 | 0.504 | 0.505 | 0.581 | 0.558 | 0.455 | 0.408 | 0.304 | 0.272 |
| 3 | Corrected Absorbance | 0.005 | 0.244 | 0.371 | 0.401 | 0.467 | 0.511 | 0.520 | 0.496 | 0.445 | 0.327 | 0.251 | 0.236 |
| Average Corrected Absorbance | | 0.053 | 0.244 | 0.308 | 0.377 | 0.454 | 0.509 | 0.535 | 0.525 | 0.456 | 0.325 | 0.250 | 0.233 |

# APPENDIX 3

**Table A3.1. Concentrations of trace elements in Coal and Refcoal precipitated from water (ppm).**

| | | Sample | La | Br | Sm | U | Hf | Tb | Th | Sc | Cs | Eu | Co | Cr | Ta | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | | C1 | 11.6 | 7.20 | 2.70 | 2.52 | 3.04 | 0.56 | 4.87 | 3.32 | 0.90 | | 5.45 | 8.45 | 0.55 | 3400 |
| | | C2 | 20.6 | 0.98 | 2.7 | 1.44 | 2.26 | | 3.21 | 5.31 | 0.99 | 0.46 | 8.29 | 5.88 | 0.72 | |
| | | C3 | | | | | 3.01 | | 5.81 | 7.38 | 1.22 | 0.6 | 10.57 | 14.59 | 0.68 | |
| | | C4 | | | | | 2.84 | | 5.81 | 6.92 | 1.24 | 0.61 | 10.41 | 14.87 | 0.62 | |
| | | Average | 15.8 | 4.1 | 2.7 | 2 | 2.8 | 0.6 | 4.9 | 5.7 | 1.1 | 0.6 | 8.7 | 11 | 0.6 | 3400 |
| Refcoal | No | RCW16 | 2.16 | nd | 0.83 | 1.30 | 2.40 | 0.08 | 3.20 | 3.15 | 0.13 | 0.18 | 7.58 | | 0.68 | 200 |
| | | RCW18 | 1.80 | 0.20 | 0.76 | 0.96 | 1.21 | 0.38 | 5.44 | 1.37 | 0.80 | | 7.04 | 4.28 | 0.68 | 800 |
| | $Na_2S$ | RCW19 | 2.17 | 0.45 | 1.10 | 0.72 | 2.18 | 0.24 | 2.73 | 4.46 | nd | | 6.51 | 9.61 | 0.23 | 300 |
| | | RCW22 | 1.79 | 0.65 | 0.26 | 1.18 | 0.44 | | 0.87 | 0.85 | 0.13 | 0.06 | 4.19 | 6.64 | 0.14 | |
| | | RCW24 | nd | 2.42 | nd | nd | 2.09 | | 0.78 | 3.82 | 0.22 | nd | 9.37 | 8.18 | 0.47 | |
| | | Average | 1.6 | 0.7 | 0.6 | 0.8 | 1.7 | 0.2 | 2.6 | 2.7 | 0.3 | 0.08 | 6.9 | 7.2 | 0.4 | 433 |
| | With | RCW17a | 44.8 | nd | 4.75 | 1.46 | 3.45 | nd | 15.3 | 1.73 | 0.2 | | 4.08 | 6.00 | 0.44 | 7800 |
| | | RCW17b | | | | | nd | | 1.88 | 2.06 | 0.11 | 0.13 | 5.5 | 7.27 | 0.43 | |
| | $Na_2S$ | RCW20a | 5.82 | 0.32 | 1.38 | 0.79 | 1.86 | 1.32 | 2.55 | 3.94 | nd | | 6.47 | 9.05 | 0.45 | 400 |
| | | RCW21 | 3.84 | 2.30 | 0.85 | 1.53 | 0.40 | | 0.80 | 0.78 | 0.14 | 0.06 | 3.80 | 6.13 | 0.13 | |
| | | Average | 4.8 | 0.9 | 2.3 | 1.3 | 1.9 | 0.7 | 1.7 | 2.2 | 0.1 | 0.1 | 4.8 | 7.1 | 0.3 | 4100 |

NOTE: nd = Not Detected

## Table A3.2. Concentrations of trace elements in Refcoal derived from Refcoal gel treated with acid (ppm).

| Acid | | Sample | La | Br | Sm | U | Hf | Tb | Th | Sc | Cs | Eu | Co | Cr | Ta | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HCl | No $Na_2S$ | RCA44 | 2.2 | 0.73 | 0.43 | 0.89 | nd | nd | 2.59 | 0.18 | nd | | 6.89 | 7.29 | 0.53 | 200 |
| | | RCA48 | nd | 4.48 | 0.06 | 4.35 | 0.4 | nd | 0.08 | 0.19 | nd | nd | 2.58 | 3.54 | 0.39 | 100 |
| | | RCA44b | nd | 4.82 | nd | 0.87 | 1.85 | | 1.43 | 0.87 | 0.1 | nd | 7.43 | 6.11 | 0.64 | |
| | | RCA73 | nd | 0.37 | 0.04 | nd | 0.91 | | 0.98 | 0.36 | nd | nd | 4.98 | 3 | 0.63 | |
| | | Average | 0.6 | 2.6 | 0.1 | 1.5 | 0.8 | nd | 1.3 | 0.4 | 0.03 | nd | 5.5 | 5 | 0.5 | 150 |
| | With | RCA46 | 0.18 | 1.81 | 0.06 | nd | 0.40 | nd | nd | 0.6 | nd | | 2.79 | 3.07 | 0.42 | 100 |
| | | RCA60 | 0.32 | 2.67 | 0.06 | 0.37 | 0.72 | | 0.17 | 0.30 | 0.06 | 0.01 | 4.71 | 4.98 | 0.59 | |
| | $Na_2S$ | Average | 0.7 | 2.2 | 0.06 | 0.2 | 0.6 | nd | 0.09 | 0.5 | 0.3 | 0.01 | 2.4 | 4 | 0.5 | 100 |
| HF | No $Na_2S$ | RCA41 | 1.60 | 0.53 | 0.33 | 1.54 | 2.31 | nd | 2.21 | 0.10 | nd | | 6.89 | 5.16 | 0.41 | nd |
| | | RCA45b | nd | 4.67 | 0.07 | 0.54 | 0.33 | | 3.61 | 0.13 | nd | nd | 7.75 | 9.32 | 0.66 | |
| | | RCA49 | 0.30 | 4.25 | 0.11 | 2.1 | 0.2 | nd | 0.15 | 0.11 | nd | | 2.97 | 4.41 | 0.50 | 40 |
| | | Average | 0.6 | 3.2 | 0.1 | 1.4 | 0.9 | nd | 2 | 0.1 | nd | nd | 5.9 | 6.3 | 0.51 | 40 |
| | With | RCA43 | 1.30 | 0.92 | 0.30 | 1.25 | 1.64 | 1.75 | nd | 0.54 | nd | | 4.12 | 5.34 | 0.50 | nd |
| | | RCA47 | 0.23 | 1.29 | 0.07 | nd | 0.10 | nd | 0.08 | 0.07 | nd | | 2.61 | 2.68 | 0.48 | nd |
| | $Na_2S$ | RCA62 | 0.30 | 2.77 | 0.05 | 1.11 | 3.09 | | 0.88 | 1.13 | 0.20 | 0.07 | 7.81 | 8.89 | 0.80 | |
| | | RCA74 | nd | 3.22 | nd | nd | 0.21 | | 0.69 | 0.06 | 0.08 | nd | 5.91 | 4.63 | 0.69 | |
| | | Average | 0.5 | 2.1 | 0.1 | 0.6 | 1.3 | 0.9 | 0.4 | 0.5 | 0.08 | 0.05 | 5.1 | 5.4 | 0.6 | nd |

NOTE: nd = Not Detected

**Table A3.3. Concentrations of trace elements in Refcoal derived from Refcoal solution treated with chelating resins (ppm).**

| | Resin | Sample | La | Br | Sm | U | Hf | Tb | Th | Sc | Cs | Eu | Co | Cr | Ta | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No | TP260 | RCR17a | 3.50 | 11.30 | 0.92 | 1.73 | 1.99 | 0.22 | 3.07 | 2.93 | 0.18 | 0.18 | 6.36 | | 0.65 | 200 |
| | | RCR31 | 1.30 | 1.27 | 0.64 | 1.05 | 0.99 | nd | 1.51 | 1.81 | nd | | 3.38 | 6.07 | 0.08 | 200 |
| $Na_2S$ | | Average | 2.4 | 6.3 | 0.8 | 1.4 | 1.5 | 0.1 | 2.3 | 2.4 | 0.09 | 0.2 | 4.9 | 6.1 | 0.4 | 200 |
| | TP208 | RCR19a | 0.01 | 0.02 | 0.01 | 0.02 | 0.83 | 0.10 | 1.46 | 1.36 | 0.11 | 0.08 | 3.18 | | 0.32 | 100 |
| | | RCR19b | 2.30 | 0.72 | 0.86 | 1.71 | 3.23 | nd | 3.22 | 1.22 | nd | | 3.80 | 4.01 | 0.21 | nd |
| | | RCR29 | 2.20 | 0.58 | 0.74 | 1.48 | 2.58 | 0.37 | 2.65 | 2.56 | nd | | 9.87 | 9.57 | nd | 200 |
| | | RCR51 | 5.02 | 3.77 | 0.31 | 1.12 | 1.82 | ND | 6.75 | 3.29 | 0.15 | 0.04 | 7.71 | 5.89 | 0.57 | |
| | | Average | 0.7 | 0.4 | 0.5 | 1.1 | 2.2 | 0.2 | 2.4 | 1.7 | 0.07 | 0.04 | 5.6 | 6.8 | 0.2 | 100 |
| | TP214 | RCR16 | 3.26 | 11.53 | 1.64 | 0.99 | 1.90 | 0.22 | 2.93 | 2.76 | 0.23 | 0.17 | 6.12 | | 0.64 | 200 |
| | | RCR32 | 0.04 | 2.34 | 0.88 | 1.34 | 1.19 | nd | 1.82 | 2.58 | nd | | 4.23 | 9.04 | 0.36 | 100 |
| | | Average | 1.7 | 6.9 | 1.3 | 1.2 | 1.5 | 0.1 | 2.4 | 2.7 | 0.1 | 0.2 | 5.2 | 9.0 | 0.5 | 200 |
| With | TP260 | RCR6 | 2.40 | 10.87 | 0.71 | 1.11 | 1.08 | 0.23 | 2.93 | 2.95 | 0.09 | 0.15 | 7.25 | | 0.60 | 100 |
| | | RCR23 | 2.60 | 0.30 | 0.73 | 1.35 | 2.27 | nd | 2.55 | 1.96 | nd | | 7.57 | 8.54 | 0.40 | 200 |
| $Na_2S$ | | Average | 2.5 | 5.6 | 0.7 | 1.2 | 1.7 | 0.1 | 2.7 | 2.5 | 0.04 | 0.2 | 7.4 | 8.5 | 0.50 | 200 |
| | TP208 | RCR18 | 1.00 | 4.86 | 0.31 | nd | nd | 0.27 | 1.88 | 1.68 | nd | | 4.02 | 8.21 | 0.34 | 300 |
| | | RCR24 | 2.20 | 1.49 | 0.76 | 1.45 | 2.95 | nd | 2.59 | 2.32 | nd | | 8.75 | 9.45 | 0.48 | 300 |
| | | RCR8 | 3.07 | 10.34 | 0.77 | 1.38 | 1.74 | 0.18 | 2.64 | 2.40 | 0.12 | 0.15 | 5.47 | | 0.58 | 100 |
| | | Average | 1.6 | 3.2 | 0.5 | 0.7 | 1.5 | 0.1 | 2.2 | 2.0 | 0.040 | 0.2 | 6.2 | 8.8 | 0.4 | 300 |
| | TP214 | RCR14 | 3.51 | 12.53 | 0.83 | 1.09 | 2.01 | 0.18 | 2.62 | 2.68 | 0.15 | | 6.40 | | 0.51 | 200 |
| | | RCR25 | 1.80 | 2.27 | 0.27 | 2.00 | 6.25 | 0.09 | 2.50 | 0.02 | 0.10 | | 6.07 | 6.35 | 0.38 | nd |
| | | RCR9 | 3.35 | 10.62 | 0.81 | 1.59 | 1.67 | 0.17 | 2.54 | 2.34 | 0.18 | 0.16 | 5.35 | | 0.51 | 200 |
| | | Average | 2.7 | 7.4 | 0.6 | 1.5 | 4.1 | 0.1 | 2.6 | 1.4 | 0.1 | 0.2 | 6.2 | 6.4 | 0.5 | 100 |

NOTE: nd = Not Detected

**Table A3.4.Concentrations of trace elements in Refcoal derived from Refcoal gel treated with chelating resins (ppm).**

| | Resin | Sample | La | Br | Sm | U | Hf | Tb | Th | Sc | Cs | Eu | Co | Cr | Ta | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No | TP260 | RCR22 | 0.02 | 1.08 | 0.02 | nd | 0.04 | nd | 0.03 | 0.10 | nd | nd | 5.51 | | 0.56 | 40 |
| $Na_2S$ | | RCR35 | 1.28 | 1.96 | 0.18 | nd | 0.21 | nd | 0.15 | 0.10 | nd | | 3.41 | 3.24 | 0.12 | nd |
| | | RCR43 | nd | 0.05 | nd | nd | 0.06 | | 2.13 | 0.12 | 0.07 | nd | 4.73 | 5.19 | 0.57 | nd |
| | | RCR58 | nd | 0.74 | nd | nd | 0.20 | | 0.21 | 0.05 | nd | nd | 5.50 | 5.53 | 0.70 | |
| | | Average | 0.3 | 1.0 | 0.05 | nd | 0.1 | nd | 0.6 | 0.09 | 0.02 | nd | 4.8 | 4.7 | 0.5 | 10 |
| | TP208 | RCR21 | 0.23 | 1.25 | 0.03 | nd | 0.06 | nd | 0.08 | 0.10 | nd | nd | 5.52 | | 0.57 | 40 |
| | | RCR36 | 0.50 | 1.60 | 0.11 | nd | 0.11 | nd | 2.02 | 0.10 | nd | nd | 3.99 | 4.90 | 0.53 | 100 |
| | | RCR42 | 1.73 | 0.60 | 0.85 | 1.520 | 0.08 | nd | 0.30 | 0.11 | 0.06 | | 3.00 | 4.16 | 0.45 | nd |
| | | RCR48 | 0.36 | 3.89 | 0.05 | nd | 0.03 | | 0.01 | 0.03 | 0.04 | nd | 3.84 | 3.37 | 0.67 | |
| | | RCR52 | | 3.42 | 0.78 | nd | 0.29 | | 1.11 | 0.04 | 0.09 | nd | 5.20 | 4.22 | 0.58 | |
| | | Average | 0.7 | 2.2 | 0.4 | 0.3 | 0.1 | nd | 0.7 | 0.08 | 0.04 | nd | 4.3 | 4.2 | 0.6 | 50 |
| | TP214 | RCR20 | 0.75 | 1.69 | 0.03 | nd | 0.04 | nd | 0.03 | 0.10 | 0.03 | nd | 5.52 | | 0.61 | 40 |
| | | RCR34 | 1.61 | 2.06 | 0.31 | nd | 0.08 | nd | 1.84 | 0.10 | 0.10 | nd | 4.16 | 4.15 | 0.51 | nd |
| | | RCR44 | 0.04 | 0.24 | 0.09 | 0.11 | 0.16 | nd | nd | 0.07 | nd | | 2.27 | 3.79 | nd | 100 |
| | | RCR50 | 3.01 | 1.85 | 0.76 | 0.64 | 0.04 | | 0.88 | 0.03 | 0.09 | nd | 4.72 | 2.43 | nd | |

NOTE: nd = Not Detected

**Table A3.4(Continued). Concentrations of trace elements in Refcoal derived from Refcoal gel treated with chelating resins (ppm).**

| | Resin | Sample | La | Br | Sm | U | Hf | Tb | Th | Sc | Cs | Eu | Co | Cr | Ta | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RCR54 | 3.670 | 0.760 | 0.540 | 0.430 | 0.070 | | 3.440 | 0.050 | nd | 0.03 | 5.760 | 4.340 | 0.640 | |
| | | Average | 1.8 | 1.3 | 0.3 | 0.2 | 0.08 | nd | 1.240 | 0.08 | 0.04 | 0.008 | 4.490 | 3.680 | 0.30 | 50 |
| | | RCR39 | 0.04 | 3.570 | 0.04 | nd | 0.09 | nd | nd | 0.07 | nd | nd | 2.800 | 3.850 | 0.470 | 200 |
| | | RCR46 | 0.02 | 5.100 | 0.01 | 0.210 | 0.03 | | 0.14 | 0.03 | 0.05 | 0.01 | 4.050 | 3.120 | 0.500 | |
| | | Average | 0.03 | 4.30 | 0.03 | 0.110 | 0.12 | nd | 0.07 | 0.05 | 0.03 | 0.005 | 3.420 | 3.480 | 0.480 | 200 |
| | | RCR40 | 0.09 | 1.85 | 0.03 | nd | 0.08 | nd | 0.10 | 0.400 | nd | nd | 0.400 | 4.000 | 0.490 | nd |
| | | RCR45 | 0.19 | 3.88 | 0.03 | 1.250 | 0.32 | nd | 0.03 | 0.03 | 0.060 | nd | 4.300 | 4.780 | 0.630 | |
| | | Average | 0.7 | 2.9 | 0.03 | 0.650 | 0.200 | nd | 0.07 | 0.210 | 0.03 | nd | 2.4 | 4.4 | 0.6 | nd |
| | | RCR38 | nd | 3.180 | 0.04 | nd | nd | nd | 0.100 | 0.07 | nd | nd | 3.290 | 3.720 | nd | 100 |
| | | RCR47 | 0.07 | 4.040 | 0.05 | 0.800 | 0.09 | | 0.18 | 0.03 | 0.05 | nd | 4.540 | 4.300 | 0.630 | |
| | | Average | 0.04 | 3.610 | 0.04 | 0.400 | 0.04 | nd | 0.140 | 0.05 | 0.03 | nd | 3.910 | 4.0 | 0.310 | 100 |

NOTE: nd = Not Detected

# APPENDIX 4

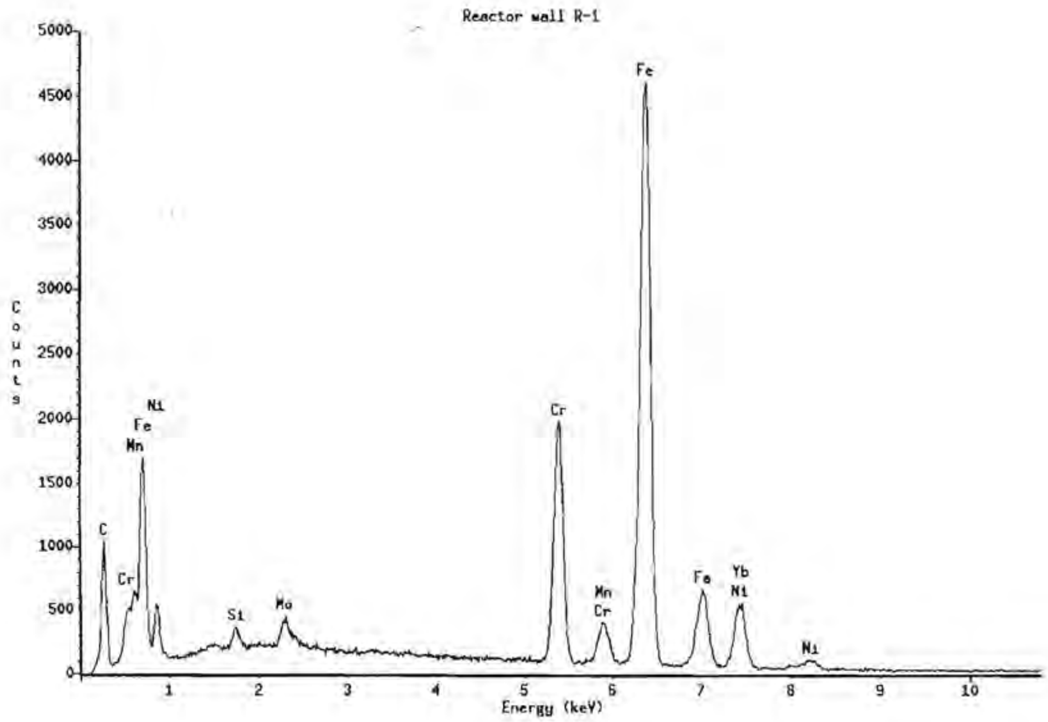


**Figure A4.1.TEM spectrum of reactor wall sample**

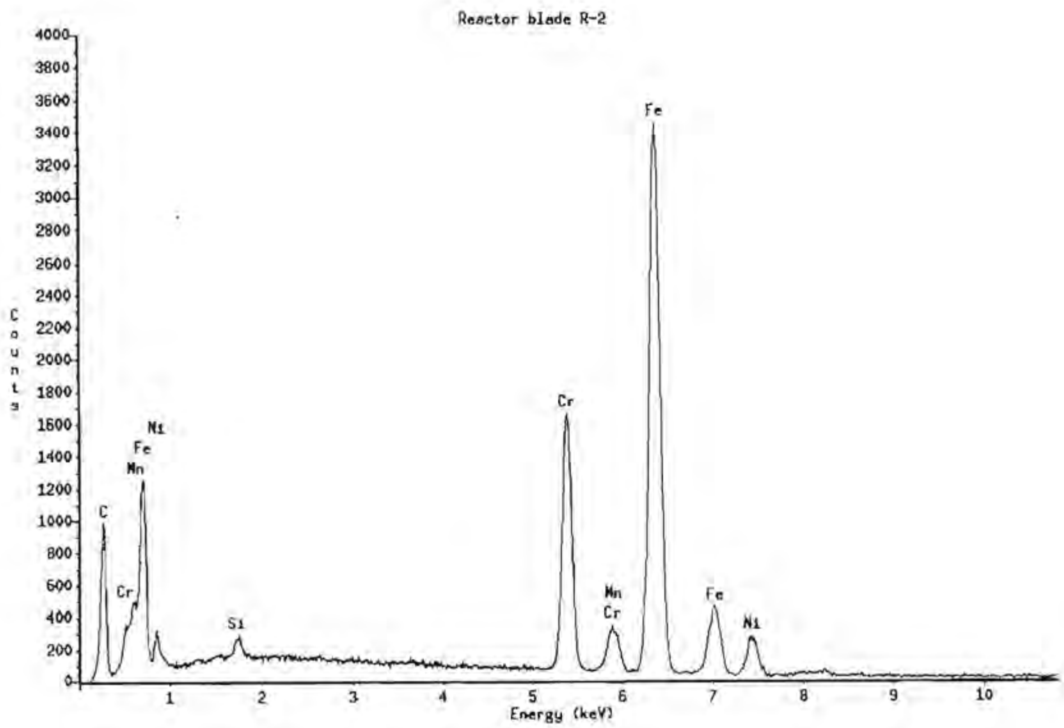


**Figure A4.2.TEM spectrum of reactor blade sample**

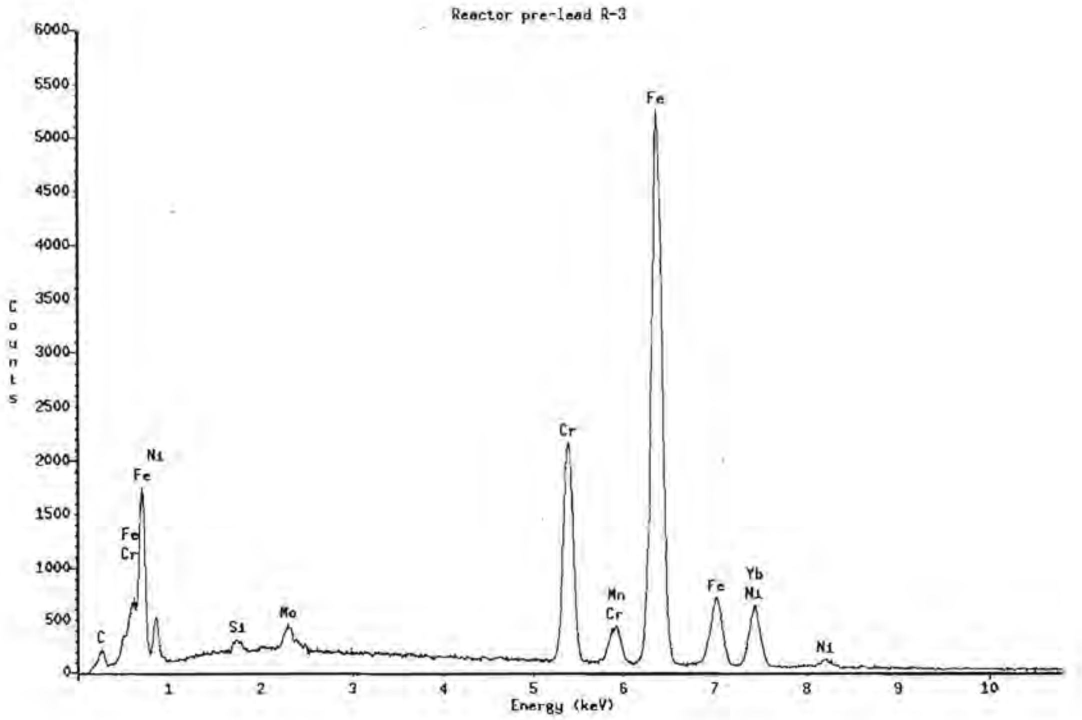


**Figure A4.3.TEM spectrum of reactor pre-lid**

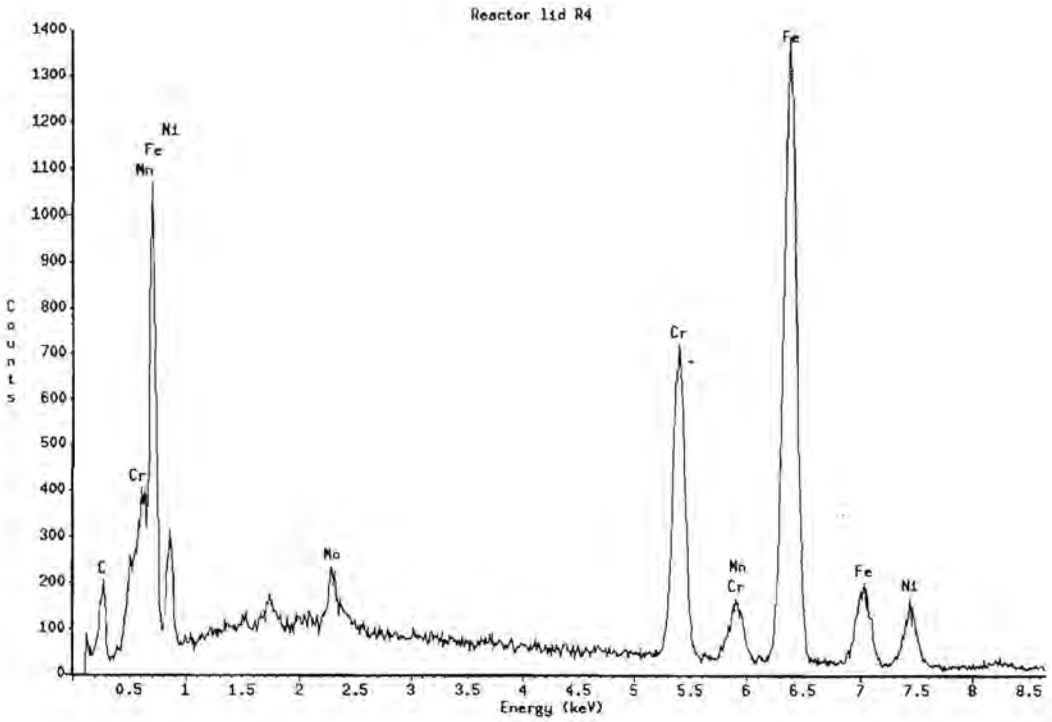


**Figure A4.4.TEM spectrum of reactor lid**

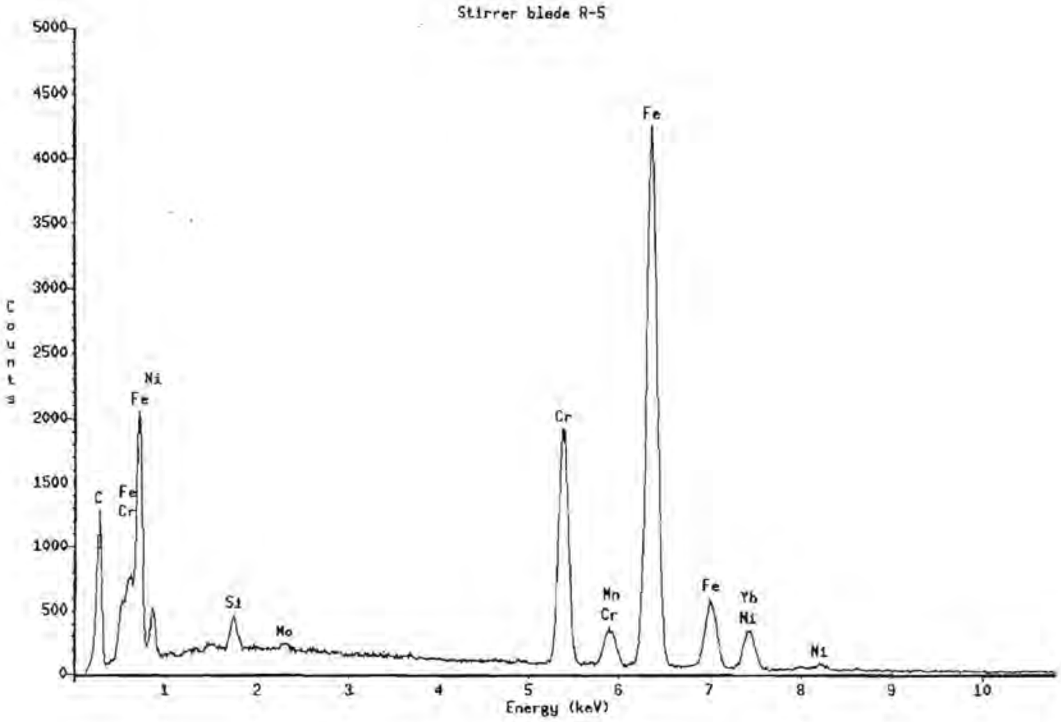


**Figure A4.5.TEM spectrum of stirrer blade**

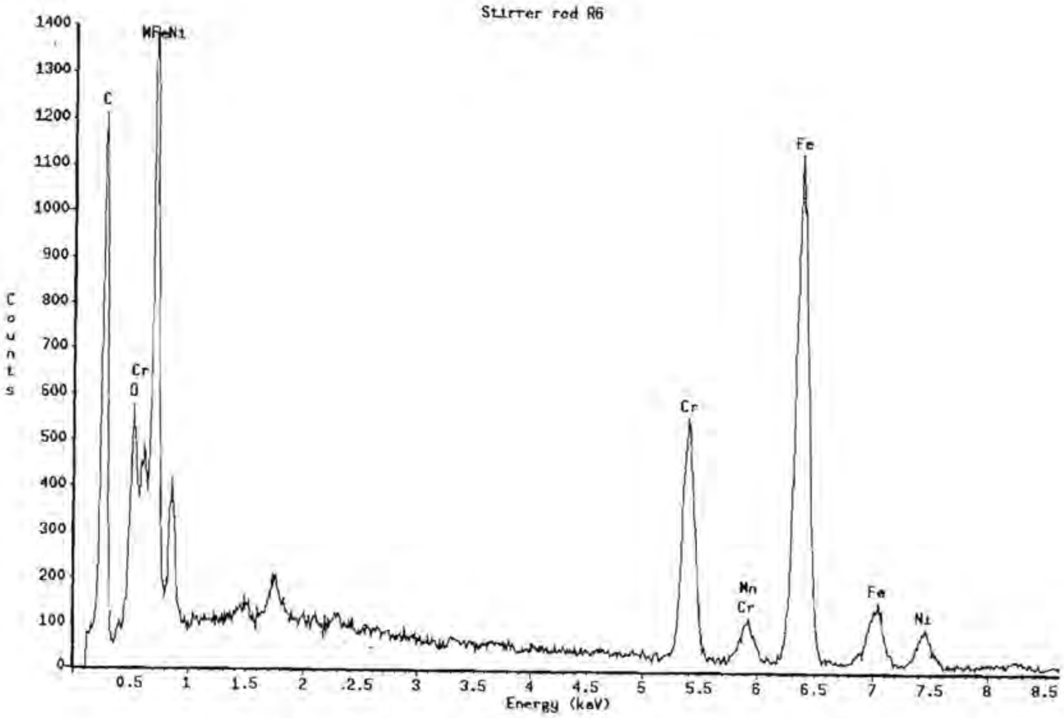


**Figure A4.6TEM spectrum of stirrer rod**

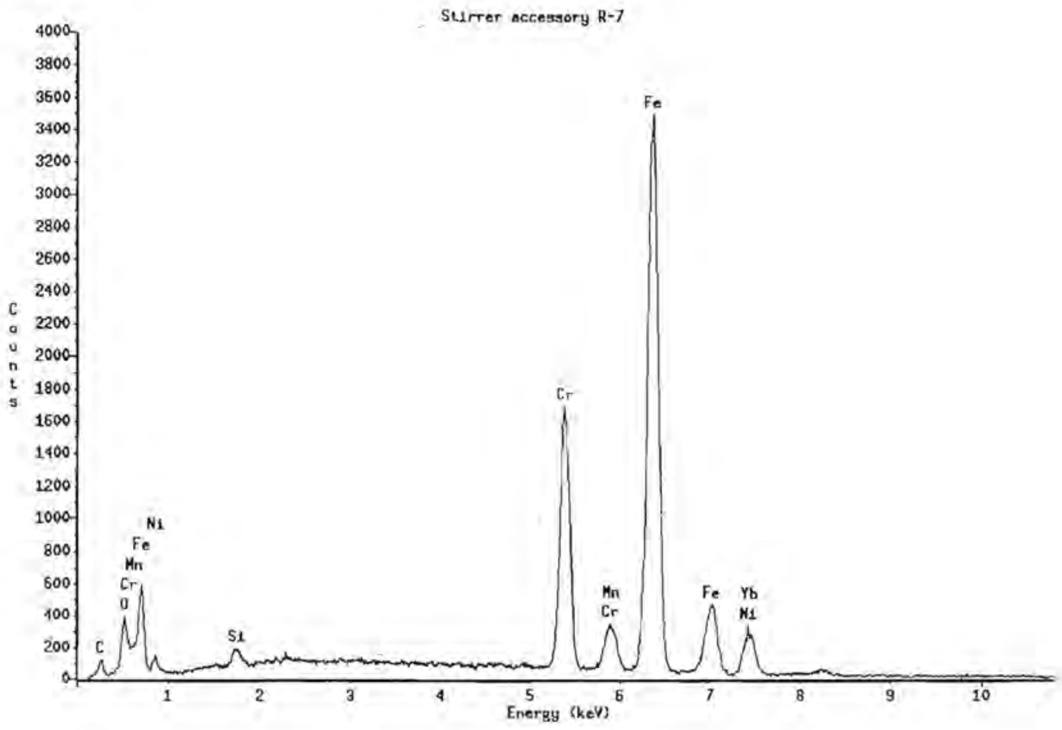


**Figure A4.7.TEM spectrum of stirrer accessory**

# APPENDIX 5

Symbols used in the last column of the table are:

$\beta^-$ Negative $\beta$-particle (negatron) emission

$\beta^+$ Positive $\beta$-particle (positron) emission

EC Orbital electron capture

$\alpha$ Alpha-particle emission

IT Isomeric transition (decay from an excited metastable state to a lower state)

**Table A5.1.Isotopes and their neutron activated reactions**

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x $10^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| ${}^{6}_{3}$Li | 7.5 | 71 | (n,$\alpha$) ${}^{3}_{1}$H | 12.26 yrs | 1455.09 | $\beta^-$ |
| ${}^{7}_{3}$Li | 92.5 | | | | | |
| ${}^{9}_{4}$Be | 100 | 8 mb | (n,$\alpha$) ${}^{6}_{2}$He | 0.797 s | 0.13 | |
| ${}^{9}_{4}$Be | | | (n,p) ${}^{9}_{3}$Li | 0.176 s | | |
| ${}^{9}_{4}$Be | | | (n,$\gamma$) ${}^{10}_{4}$Be | 2.5 x $10^6$ yrs | | |
| ${}^{10}_{5}$B | 19.9 | 7.6 x $10^2$ | (n,$\alpha$) ${}^{7}_{3}$Li | | 10000 | $\alpha$ |
| ${}^{11}_{5}$B | 80.1 | | (n,p) ${}^{11}_{4}$Be | 13.6 s | | $\beta^-$ |
| ${}^{12}_{6}$C | 98.89 | 3.6 mb | | | 0.04 | |
| ${}^{13}_{6}$C | 1.11 | | | | | |
| ${}^{14}_{7}$N | 99.624 | 1.9 | (n,p) ${}^{14}_{6}$C | 5730 yrs | 19.3 | $\beta^-$ |
| ${}^{15}_{7}$N | 0.366 | | (n,$\gamma$) ${}^{16}_{7}$N | 7.22 s | | $\beta^-$ |
| ${}^{23}_{11}$Na | 100 | 0.525 | (n,p) ${}^{23}_{10}$Ne | 40.2 s | 3.25 | $\beta^-$ |
| ${}^{23}_{11}$Na | | | (n,$\gamma$) ${}^{24}_{11}$Na | 15.1 hrs | | $\beta^-$ |
| ${}^{24}_{12}$Mg | 78.99 | 63 mb | | | 0.37 | |
| ${}^{25}_{12}$Mg | 10 | | (n,p) ${}^{25}_{11}$Na | 60 s | | $\beta^-$ |
| ${}^{26}_{12}$Mg | 11.01 | | (n,p) ${}^{26}_{11}$Na | 1.04 s | | $\beta^-$ |
| ${}^{26}_{12}$Mg | | | (n,$\gamma$) ${}^{27}_{12}$Mg | 9.46 min. | | $\beta^-$ |

**Table A5.1 (continued).Isotopes and their neutron activated reactions**

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x $10^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| $^{27}_{13}Al$ | 100 | 0.23 | (n,γ) $^{28}_{13}Al$ | 2.31 min. | 1.21 | $\beta^-$ |
| $^{28}_{14}Si$ | 92.33 | 0.166 | | | 0.84 | |
| $^{29}_{14}Si$ | 4.67 | | | | | |
| $^{30}_{14}Si$ | 3.1 | | (n,p) $^{30}_{13}Al$ | 3 s | | $\beta^-$ |
| $^{30}_{14}Si$ | | | (n,γ) $^{31}_{14}Si$ | 2.62 hrs | | $\beta^-$ |
| $^{31}_{15}P$ | 100 | 0.16 | (n,γ) $^{32}_{15}P$ | 14.3 d | 0.73 | $\beta^-$ |
| $^{32}_{16}S$ | 95.02 | 0.54 | (n,p) $^{32}_{15}P$ | 14.28 d | 2.4 | $\beta^-$ |
| $^{33}_{16}S$ | 0.75 | | (n,p) $^{33}_{15}P$ | 24.8 d | | $\beta^-$ |
| $^{34}_{16}S$ | 4.21 | | (n,p) $^{34}_{15}P$ | 12.7 s | | $\beta^-$ |
| $^{34}_{16}S$ | | | (n,γ) $^{35}_{16}S$ | 87.9 d | | $\beta^-$ |
| $^{36}_{16}S$ | 0.02 | | (n,γ) $^{37}_{16}S$ | 5.04 min | | $\beta^-$ |
| $^{39}_{19}K$ | 93.2851 | 2.1 | | | 7.64 | |
| $^{40}_{19}K$ | 0.0117 | | | 1.2 x $10^9$ yrs | | $\beta^-$(89%) |
| $^{41}_{19}K$ | 6.7302 | | (n,γ) $^{41}_{19}K$ | 12.4 hrs | | $\beta^-$ |
| $^{40}_{20}Ca$ | 96.941 | 0.43 | (n,γ) $^{41}_{20}Ca$ | 4 x $10^4$ yrs | 1.53 | EC |
| $^{42}_{20}Ca$ | 0.647 | | | | | |
| $^{43}_{20}Ca$ | 0.135 | | | | | |
| $^{44}_{20}Ca$ | 2.086 | | (n,γ) $^{45}_{20}Ca$ | 165 d | | $\beta^-$ |
| $^{44}_{20}Ca$ | | | (n,p) $^{44}_{19}K$ | 22.0 min | | $\beta^-$ |
| $^{46}_{20}Ca$ | 0.004 | | (n,γ) $^{47}_{20}Ca$ | 4.53 d | | $\beta^-$ |
| $^{48}_{20}Ca$ | 0.187 | | (n,γ) $^{49}_{20}Ca$ | 8.8 min. | | $\beta^-$ |
| $^{45}_{21}Sc$ | 100 | 27.2 | (n,γ) $^{46}_{21}Sc$ | 84.2 d | 86.07 | $\beta^-$ |
| $^{46}_{22}Ti$ | 8.25 | 6.1 | | | 18.12 | |
| $^{47}_{22}Ti$ | 7.44 | | | | | |
| $^{48}_{22}Ti$ | 73.72 | | | | | |
| $^{49}_{22}Ti$ | 5.41 | | | | | |
| $^{50}_{22}Ti$ | 5.18 | | (n,p) $^{50}_{21}Sc$ | 1.7 min | | $\beta^-$ |

# Table A5.1 (continued).Isotopes and their neutron activated reactions

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x $10^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| ${}^{50}_{22}Ti$ | | | (n,γ) ${}^{51}_{22}Ti$ | 5.8 min. | | $\beta^-$ |
| ${}^{50}_{23}V$ | 0.25 | 5 | | | 13.96 | |
| ${}^{51}_{23}V$ | 99.75 | | (n,γ) ${}^{52}_{23}V$ | 3.75 min. | | $\beta^-$ |
| ${}^{50}_{24}Cr$ | 4.345 | 3 | (n,γ) ${}^{51}_{24}Cr$ | 27.8 d | 8.21 | $\beta^-$ |
| ${}^{52}_{24}Cr$ | 83.79 | | | | | |
| ${}^{53}_{24}Cr$ | 9.5 | | (n,p) ${}^{53}_{23}V$ | 2.0 min | | $\beta^-$ |
| ${}^{54}_{24}Cr$ | 2.365 | | (n,p) ${}^{54}_{23}V$ | 55 s | | $\beta^-$ |
| ${}^{54}_{24}Cr$ | | | (n,γ) ${}^{55}_{24}Cr$ | 3.52 min | | $\beta^-$ |
| ${}^{55}_{25}Mn$ | 100 | 13.3 | (n,γ) ${}^{56}_{25}Mn$ | 2.58 hrs | 34.44 | $\beta^-$ |
| ${}^{54}_{26}Fe$ | 5.85 | 2.6 | (n,γ) ${}^{55}_{26}Fe$ | 2.6 yrs | 6.62 | EC |
| ${}^{56}_{26}Fe$ | 91.75 | | | | | |
| ${}^{57}_{26}Fe$ | 2.12 | | (n,p) ${}^{57}_{25}Mn$ | 1.7 min. | | $\beta^-$ |
| ${}^{58}_{26}Fe$ | 0.28 | | (n,p) ${}^{58}_{25}Mn$ | 1.1 min. | | $\beta^-$ |
| ${}^{58}_{26}Fe$ | | | (n,γ) ${}^{59}_{26}Fe$ | 45.6 d | | $\beta^-$ |
| ${}^{59}_{27}Co$ | 100 | 37.19 | (n,γ) ${}^{60}_{27}Co$ | 2.56 yrs | 89.77 | $\beta^-$ |
| ${}^{58}_{28}Ni$ | 68.077 | 4.5 | (n,γ) ${}^{59}_{28}Ni$ | 8 x $10^4$ yrs | 10.91 | EC |
| ${}^{60}_{28}Ni$ | 26.223 | | | | | |
| ${}^{61}_{28}Ni$ | 1.14 | | (n,p) ${}^{61}_{27}Co$ | 99.0 min. | | $\beta^-$ |
| ${}^{62}_{28}Ni$ | 3.634 | | (n,p) ${}^{62}_{27}Co$ | 13.9 min | | $\beta^-$ |
| ${}^{64}_{28}Ni$ | 0.926 | | (n,γ) ${}^{65}_{28}Ni$ | 2.56 hrs | | $\beta^-$ |
| ${}^{64}_{28}Ni$ | | | (n,α) ${}^{61}_{26}Fe$ | 6.0 min. | | $\beta^-$ |
| ${}^{63}_{29}Cu$ | 69.17 | 3.8 | (n,γ) ${}^{64}_{29}Cu$ | 12.8 hrs | 8.51 | EC(43%),$\beta^-$ |
| ${}^{65}_{29}Cu$ | 30.83 | | (n,γ) ${}^{66}_{29}Cu$ | 5.10 min. | | $\beta^-$ |
| ${}^{64}_{30}Zn$ | 48.6 | 1.1 | (n,γ) ${}^{65}_{30}Zn$ | 245 d | 2.39 | EC(98.3%),$\beta^-$(1 7%) |
| ${}^{66}_{30}Zn$ | 27.9 | | | | | |
| ${}^{67}_{30}Zn$ | 4.1 | | (n,p) ${}^{67}_{29}Cu$ | 58.5 hrs | | $\beta^-$ |

## Table A5.1 (continued).Isotopes and their neutron activated reactions

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x $10^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| $^{68}_{30}Zn$ | 18.8 | | (n,p) $^{68}_{29}Cu$ | 30 s | | $\beta^-$ |
| $^{68}_{30}Zn$ | | | (n,γ) $^{69}_{30}Zn$ | 57 min. | | $\beta^-$ |
| $^{70}_{30}Zn$ | 0.6 | | (n,α) $^{67}_{28}Ni$ | 50 s | | β |
| $^{70}_{30}Zn$ | | | (n,γ) $^{71}_{30}Zn$ | 2.4 min. | | $\beta^-$ |
| $^{69}_{31}Ga$ | 60.108 | 2.9 | (n,γ) $^{70}_{31}Ga$ | 20 min | 5.92 | $\beta^-$ |
| $^{71}_{31}Ga$ | 39.892 | | (n,γ) $^{72}_{31}Ga$ | 14.3 hrs | | $\beta^-$ |
| $^{71}_{31}Ga$ | | | (n,α) $^{68}_{29}Cu$ | 58.5 hrs | | $\beta^-$ |
| $^{70}_{32}Ge$ | 21.23 | 2.9 | (n,γ) $^{71}_{32}Ge$ | 11.4 d | 5.68 | EC |
| $^{72}_{32}Ge$ | 27.66 | | | | | |
| $^{73}_{32}Ge$ | 7.73 | | (n,p) $^{73}_{31}Ga$ | 5.0 hrs | | $\beta^-$ |
| $^{74}_{32}Ge$ | 35.94 | | (n,p) $^{74}_{31}Ga$ | 8.0 min. | | $\beta^-$ |
| $^{74}_{32}Ge$ | | | (n,γ) $^{75}_{32}Ge$ | 82 min. | | $\beta^-$ |
| $^{76}_{32}Ge$ | 7.44 | | (n,p) $^{76}_{31}Ga$ | 32 s | | $\beta^-$ |
| $^{76}_{32}Ge$ | | | (n,γ) $^{77}_{32}Ge$ | 11.3 hrs | | $\beta^-$ |
| $^{75}_{33}As$ | 100 | 4 | (n,p) $^{75}_{32}Ge$ | 79 min | 7.59 | $\beta^-$ |
| $^{75}_{33}As$ | | | (n,γ) $^{76}_{33}As$ | 26.2 hrs | | $\beta^-$ |
| $^{74}_{34}Se$ | 0.89 | 12 | (n,γ) $^{75}_{34}Se$ | 127 d | 21.62 | EC |
| $^{76}_{34}Se$ | 9.36 | | (n,γ) $^{77m}_{34}Se$ | 17.5 s | | IT |
| $^{77}_{34}Se$ | 7.63 | | | | | |
| $^{78}_{34}Se$ | 23.78 | | (n,p) $^{78}_{33}As$ | 91 min | | $\beta^-$ |
| $^{78}_{34}Se$ | | | (n,γ) $^{79m}_{34}Se$ | 3.91 min | | IT |
| $^{80}_{34}Se$ | 49.61 | | (n,γ) $^{81}_{34}Se$ | 18.6 min | | $\beta^-$ |
| $^{82}_{34}Se$ | 8.73 | | (n,α) $^{79}_{33}As$ | 9.0 min | | $\beta^-$ |
| $^{82}_{34}Se$ | | | (n,γ) $^{83}_{34}Se$ | 26 min | | $\beta^-$ |
| $^{85}_{37}Rb$ | 72.17 | 0.39 | (n,α) $^{82}_{35}Br$ | 31.7 min | 0.65 | $\beta^-$ |
| $^{85}_{37}Rb$ | | | (n,γ) $^{86}_{37}Rb$ | 18.66 d | | $\beta^-$ |
| $^{87}_{37}Rb$ | 27.83 | | (n,γ) $^{88}_{37}Rb$ | 18 min | | $\beta^-$ ($\beta^-$) |

## Table 5.1 (continued).Isotopes and their neutron activated reactions

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x 10$^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| ${}^{84}_{38}Sr$ | 0.56 | | (n,γ) ${}^{85}_{38}Sr$ | 63.9 d | 1.95 | EC |
| ${}^{86}_{38}Sr$ | 9.86 | | (n,γ) ${}^{87}_{38}Sr$ | 2.88 hrs | | IT(99.4%), |
| ${}^{87}_{38}Sr$ | 7 | | | | | |
| ${}^{88}_{38}Sr$ | 82.58 | | (n,γ) ${}^{89}_{38}Sr$ | 50.5 d | | $\beta^-$ |
| ${}^{92}_{42}Mo$ | 14.84 | 2.5 | (n,γ) ${}^{93}_{42}Mo$ | 6.95 hrs | 3.71 | EC |
| ${}^{94}_{42}Mo$ | 9.25 | | | | | |
| ${}^{95}_{42}Mo$ | 15.92 | | | | | |
| ${}^{96}_{42}Mo$ | 16.68 | | | | | |
| ${}^{97}_{42}Mo$ | 9.55 | | | | | |
| ${}^{98}_{42}Mo$ | 24.13 | | (n,γ) ${}^{99}_{42}Mo$ | 66.7 hrs | | $\beta^-$ |
| ${}^{98}_{42}Mo$ | | | (n,p) ${}^{98}_{41}Nb$ | 51 min. | | $\beta^-$ |
| ${}^{100}_{42}Mo$ | 9.63 | | (n,γ) ${}^{101}_{42}Mo$ | 14.6 min | | $\beta^-$ |
| ${}^{100}_{42}Mo$ | | | (n,p) ${}^{100}_{41}Nb$ | 11 min. | | $\beta^-$ |
| ${}^{107}_{47}Ag$ | 51.839 | 62 | (n,γ) ${}^{108}_{47}Ag$ | 2.42 min. | 81.76 | $\beta^-$ |
| ${}^{109}_{47}Ag$ | 48.161 | | (n,γ) ${}^{110}_{47}Ag$ | 24.4 s | | $\beta^-$ |
| ${}^{106}_{48}Cd$ | 1.25 | 2.5 x 10$^3$ | (n,γ) ${}^{107}_{48}Cd$ | 6.49 hrs | 3188.92 | EC |
| ${}^{108}_{48}Cd$ | 0.89 | | (n,γ) ${}^{109}_{48}Cd$ | 453 d | | EC |
| ${}^{110}_{48}Cd$ | 12.49 | | (n,γ) ${}^{111}_{48}Cd$ | 48.6 min. | | IT |
| ${}^{111}_{48}Cd$ | 12.8 | | | | | |
| ${}^{112}_{48}Cd$ | 24.13 | | (n,γ) ${}^{113}_{48}Cd$ | 13.6 yrs | | $\beta^-$ |
| ${}^{113}_{48}Cd$ | 12.22 | | | | | |
| ${}^{114}_{48}Cd$ | 28.73 | | (n,γ) ${}^{115}_{48}Cd$ | 53.5 hrs | | $\beta^-$ |
| ${}^{116}_{48}Cd$ | 7.49 | | (n,γ) ${}^{117}_{48}Cd$ | 2.4 hrs | | $\beta^-$ |
| ${}^{112}_{50}Sn$ | 0.97 | 0.61 | (n,γ) ${}^{113}_{50}Sn$ | 118 d | 0.73 | EC |
| ${}^{114}_{50}Sn$ | 0.65 | | | | | |
| ${}^{115}_{50}Sn$ | 0.34 | | | | | |
| ${}^{116}_{50}Sn$ | 14.53 | | (n,γ) ${}^{117}_{50}Sn$ | 140 d | | IT |

# Table A5.1 (continued).Isotopes and their neutron activated reactions

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x $10^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| $^{117}_{50}$Sn | 7.68 | | | | | |
| $^{118}_{50}$Sn | 24.23 | | (n,γ) $^{119}_{50}$Sn | ≈ 250 d | | IT |
| $^{118}_{50}$Sn | | | (n,p) $^{118}_{49}$In | 5.0 s | | $\beta^-$ |
| $^{119}_{50}$Sn | 8.59 | | | | | |
| $^{120}_{50}$Sn | 32.59 | | (n,γ) $^{121}_{50}$Sn | 27.5 hrs | | $\beta^-$ |
| $^{120}_{50}$Sn | | | (n,p) $^{120}_{49}$In | 3.2 s | | $\beta^-$ |
| $^{122}_{50}$Sn | 4.63 | | (n,γ) $^{123}_{50}$Sn | 125 d | | $\beta^-$ |
| $^{122}_{50}$Sn | | | (n,p) $^{122}_{49}$In | 8 s | | $\beta^-$ |
| $^{124}_{50}$Sn | 5.79 | | (n,p) $^{124}_{49}$In | ≈ 3.6 s | | $\beta^-$ |
| $^{121}_{51}$Sb | 57.21 | 5.3 | (n,γ) $^{122}_{51}$Sb | 2.80 d | 6.19 | $\beta^-$ (97%), EC |
| $^{121}_{51}$Sb | | | (n,α) $^{118}_{49}$In | 3 s | | $\beta^-$ |
| $^{123}_{51}$Sb | 42.79 | | (n,γ) $^{124}_{51}$Sb | 60.4 d | | $\beta^-$ |
| $^{123}_{51}$Sb | | | (n,p) [illegible] Sb | 21 min | | IT |
| $^{133}_{55}$Cs | 100 | 30.4 | (n,α) $^{130}_{53}$I | 12.3 hrs | 32.54 | $\beta^-$ |
| $^{133}_{55}$Cs | | | (n,γ) $^{134}_{55}$Cs | 2.046 yrs | | $\beta^-$ |
| $^{130}_{56}$Ba | 0.106 | 1.3 | (n,γ) $^{131}_{56}$Ba | 12.0 d | 1.35 | EC |
| $^{132}_{56}$Ba | 0.101 | | (n,γ) $^{133}_{56}$Ba | 7.2 yrs | | EC |
| $^{134}_{56}$Ba | 2.417 | | | | | |
| $^{135}_{56}$Ba | 6.592 | | (n,p) $^{135}_{55}$Cs | 53 min | | IT |
| $^{136}_{56}$Ba | 7.854 | | | | | |
| $^{137}_{56}$Ba | 11.23 | | | | | |
| $^{138}_{56}$Ba | 71.7 | | (n,γ) $^{139}_{56}$Ba | 82.9 min | | $\beta^-$ |
| [illegible] Ba | | | (n,p) $^{138}_{55}$Cs | 32.1 | | $\beta^-$ |
| [illegible] Ba | | | (n,α) $^{135}_{54}$Xe | 9.2 hrs | | $\beta^-$ |
| $^{138}_{57}$La | 0.0902 | 9.2 | | 1.12 x $10^{11}$ yrs | 9.42 | $\beta^-$ |
| $^{139}_{57}$La | 99.9098 | | (n,γ) $^{140}_{57}$La | 40.22 hrs | | $\beta^-$ |
| $^{136}_{58}$Ce | 0.19 | 0.64 | (n,γ) $^{137}_{58}$Ce | 9.0 hrs | 0.65 | EC |

# Table A5.1 (continued).Isotopes and their neutron activated reactions

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x $10^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| $^{138}_{58}$Ce | 0.25 | | (n,γ) $^{139}_{58}$Ce | 140 d | | EC |
| $^{140}_{58}$Ce | 88.43 | | (n,γ) $^{141}_{58}$Ce | 33.1 d | | $\beta^-$ |
| $^{142}_{58}$Ce | 11.13 | | (n,p) $^{142}_{57}$La | 77 min | | $\beta^-$ |
| $^{142}_{58}$Ce | | | (n,γ) $^{143}_{58}$Ce | 33 hrs | | $\beta^-$ |
| $^{141}_{59}$Pr | 100 | 11.5 | (n,γ) $^{142}_{59}$Pr | 19.2 hrs | 11.61 | $\beta^-$ |
| $^{141}_{59}$Pr | | | (n,p) $^{141}_{58}$Ce | 33.1 d | | $\beta^-$ |
| $^{142}_{60}$Nd | 27.13 | 51 | | | 50.3 | |
| $^{143}_{60}$Nd | 12.18 | | | | | |
| $^{144}_{60}$Nd | 23.8 | | | | | |
| $^{145}_{60}$Nd | 8.3 | | | | | |
| $^{146}_{60}$Nd | 17.19 | | (n,p) $^{146}_{59}$Pr | 24.0 min | | $\beta^-$ |
| $^{146}_{60}$Nd | | | (n,γ) $^{147}_{60}$Nd | 11.1 d | | $\beta^-$ |
| $^{148}_{60}$Nd | 5.76 | | (n,p) $^{148}_{59}$Pr | 2.0 min | | $\beta^-$ |
| $^{148}_{60}$Nd | | | (n,γ) $^{149}_{60}$Nd | 2.0 hrs | | $\beta^-$ |
| $^{150}_{60}$Nd | 5.64 | | (n,γ) $^{151}_{60}$Nd | 12 min | | $\beta^-$ |
| $^{144}_{62}$Sm | 3.1 | 5.6 x $10^3$ | (n,γ) $^{145}_{62}$Sm | 340 d | 5297.95 | EC |
| $^{147}_{62}$Sm | 15 | | (n,2n) $^{146}_{62}$Sm | 7 x $10^4$ yrs | | α |
| $^{148}_{62}$Sm | 11.3 | | | | | |
| $^{149}_{62}$Sm | 13.8 | | | | | |
| $^{150}_{62}$Sm | 7.4 | | (n,γ) $^{151}_{62}$Sm | 120 yrs | | $\beta^-$ |
| $^{152}_{62}$Sm | 26.7 | | (n,γ) $^{153}_{62}$Sm | 46.8 hrs | | $\beta^-$ |
| $^{152}_{62}$Sm | | | (n,p) $^{152}_{61}$Pm | 6.5 min. | | $\beta^-$ |
| $^{154}_{62}$Sm | 22.7 | | (n,γ) $^{155}_{62}$Sm | 21.9 min. | | $\beta^-$ |
| $^{151}_{63}$Eu | 47.8 | 4570 | (n,γ) $^{152}_{63}$Eu | 12.7 yrs | 4277.84 | $\beta^-$(28%),EC(72 |
| $^{153}_{63}$Eu | 52.2 | | (n,γ) $^{154}_{63}$Eu | 16 yrs | | $\beta^-$ |
| $^{152}_{64}$Gd | 0.2 | 48.8 x $10^3$ | (n,γ) $^{153}_{64}$Gd | 242 d | 44144.99 | EC |
| $^{154}_{64}$Gd | 2.18 | | | | | |

# Table A5.1 (continued).Isotopes and their neutron activated reactions

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x $10^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| $^{155}_{64}$Gd | 14.8 | | | | | |
| $^{156}_{64}$Gd | 20.17 | | | | | |
| $^{157}_{64}$Gd | 15.65 | | | | | |
| $^{158}_{64}$Gd | 24.84 | | (n,γ) $^{159}_{64}$Gd | 18.0 hrs | | $\beta^-$ |
| $^{160}_{64}$Gd | 21.86 | | (n,α) $^{157}_{62}$Sm | 0.5 min. | | $\beta^-$ |
| $^{160}_{64}$Gd | | | (n,p) $^{160}_{63}$Eu | ≈ 2.5 min. | | $\beta^-$ |
| $^{159}_{65}$Tb | 100 | 23.2 | (n,γ) $^{160}_{65}$Tb | 6.9 d | 20.77 | $\beta^-$ |
| $^{156}_{66}$Dy | 0.06 | 9.5 x $10^2$ | | | 831.62 | |
| $^{158}_{66}$Dy | 0.1 | | (n,γ) $^{159}_{66}$Dy | 144 d | | EC |
| $^{160}_{66}$Dy | 2.34 | | | | | |
| $^{161}_{66}$Dy | 18.9 | | | | | |
| $^{162}_{66}$Dy | 25.5 | | (n,p) $^{162}_{65}$Tb | 7.48 min. | | $\beta^-$ |
| $^{163}_{66}$Dy | 24.9 | | (n,p) $^{163}_{65}$Tb | 6.5 hrs | | $\beta^-$ |
| $^{164}_{66}$Dy | 28.2 | | (n,γ) $^{165}_{66}$Dy | 139.2 min. | | $\beta^-$ |
| $^{162}_{68}$Er | 0.14 | 169 | | | 143.73 | |
| $^{164}_{68}$Er | 1.61 | | (n,γ) $^{165}_{68}$Er | 10.4 hrs | | EC |
| $^{166}_{68}$Er | 33.6 | | (n,γ) $^{167m}_{68}$Er | 2.3 s | | IT |
| $^{167}_{68}$Er | 22.95 | | | | | |
| $^{168}_{68}$Er | 26.8 | | (n,γ) $^{169}_{68}$Er | 9.4 d | | $\beta^-$ |
| $^{170}_{68}$Er | 14.9 | | (n,α) $^{167}_{66}$Dy | 4.4 min | | $\beta^-$ |
| $^{170}_{68}$Er | | | (n,p) $^{170}_{67}$Er | 45 s | | $\beta^-$ |
| $^{170}_{68}$Er | | | (n,γ) $^{171}_{68}$Er | 7.52 hrs | | $\beta^-$ |
| $^{174}_{72}$Hf | 0.162 | 106 | (n,γ) $^{175}_{72}$Hf | 23.6 hrs | 84.48 | EC |
| $^{176}_{72}$Hf | 5.206 | | | | | |
| $^{177}_{72}$Hf | 18.606 | | | | | |
| $^{178}_{72}$Hf | 27.297 | | (n,γ) $^{179m}_{72}$Hf | 18.6 s | | IT |
| $^{179}_{72}$Hf | 13.629 | | | | | |

# Table A5.1 (continued).Isotopes and their neutron activated reactions

| Isotope | Natural Abundance, % | Thermal Neutron Cross-section, barns | Neutron activated reaction type and product | Half-life | Equivalent Boron, x $10^3$ ppm | Radioactive Decay |
|---|---|---|---|---|---|---|
| $^{180}_{72}Hf$ | 35.1 | | (n,γ) $^{181}_{72}Hf$ | 42.5 d | | $\beta^-$ |
| $^{180}_{74}W$ | 0.12 | 18 | (n,γ) $^{181}_{74}W$ | 140 d | 13.93 | EC |
| $^{182}_{74}W$ | 26.5 | | (n,γ) $^{183m}_{74}W$ | 5.5 s | | IT |
| $^{183}_{74}W$ | 14.31 | | | | | |
| $^{184}_{74}W$ | 30.43 | | (n,p) $^{184}_{73}Ta$ | 8.7 hrs | | $\beta^-$ |
| $^{184}_{74}W$ | | | (n,γ) $^{185}_{74}W$ | 75 d | | $\beta^-$ |
| $^{186}_{74}W$ | 28.43 | | (n,γ) $^{187}_{74}W$ | 23.9 hrs | | $\beta^-$ |
| $^{186}_{74}W$ | | | (n,α) $^{183}_{72}Hf$ | 65 min | | $\beta^-$ |
| $^{186}_{74}W$ | | | (n,p) $^{186}_{73}Ta$ | 10.5 min | | $\beta^-$ |
| $^{196}_{80}Hg$ | 0.15 | 3.7 x $10^2$ | | | 262.39 | |
| $^{198}_{80}Hg$ | 9.97 | | | | | |
| $^{199}_{80}Hg$ | 16.87 | | | | | |
| $^{200}_{80}Hg$ | 23.1 | | | | | |
| $^{201}_{80}Hg$ | 13.18 | | | | | |
| $^{202}_{80}Hg$ | 29.86 | | (n,γ) $^{203}_{80}Hg$ | 46.9 d | | $\beta^-$ |
| $^{204}_{80}Hg$ | 6.87 | | (n,α) $^{201}_{78}Pt$ | 2.3 min | | $\beta^-$ |
| $^{204}_{80}Hg$ | | | (n,γ) $^{205}_{80}Hg$ | 5.5 min | | $\beta^-$ |
| $^{204}_{82}Pb$ | 1.4 | 0.172 | (n,γ) $^{205}_{82}Pb$ | 3.0 x $10^5$ yrs | 0.12 | EC |
| $^{206}_{82}Pb$ | 24.1 | | | | | |
| $^{207}_{82}Pb$ | 22.1 | | | | | |
| $^{208}_{82}Pb$ | 52.4 | | (n,γ) $^{209}_{82}Pb$ | 3.30 hrs | | $\beta^-$ |
| $^{209}_{83}Bi$ | 100 | 0.034 | (n,γ) $^{210}_{83}Bi$ | 5.0 d | 0.02 | $\beta^-$ |
| $^{209}_{83}Bi$ | | | (n,γ) $^{210m}_{83}Bi$ | 2.6 x $10^6$ yrs | | $\beta^-$ (0.4%), α |
| $^{232}_{90}Th$ | 100 | 7.4 | (n,γ) $^{233}_{90}Th$ | 22.5 min | 4.54 | $\beta^-$ |