The Uranium Processing and Radioactivity Specialists

# TECHNICAL MEMORANDUM: AM_TN_2010_08_06

**SUBMITTED TO: Australasian (iron & steel) Slag Association (ASA)**

**SUBJECT: Assessment of Naturally Occurring Radionuclides in Australian Iron and Steel Slags**


PREPARED BY: Sue Brown, Senior Radiochemist
CHECKED BY: Doug Collier, Manager, Process Development Services

DATE: 20 August 2010

Commercial-in-Confidence


**ANSTO Minerals, Locked Bag 2001 Kirrawee DC NSW 2232 Australia**
**Ph: +61 2 9717 3858 Fax: +61 2 9717 9129**
**E-Mail: ansto.minerals@ansto.gov.au**
**Web: www.anstominerals.com**

## 1. INTRODUCTION

The Australasian (iron & steel) Slag Association Inc (ASA) was formed in 1990 to increase the community, business and government awareness of the benefits derived from the use of iron and steel furnace slag (ISS) in construction and general civil works applications and how the effective and efficient utilisation of these co-products can benefit the environment and economic sustainable development of recovered resources. The associations' charter is to conduct research and development of common interest to members, provide technical forum for information exchange and support the increased market use of iron and steel slags as a material of choice in the construction and other potential end use industries.

In 2005, the Australian Government, Radiation Health and Safety Advisory Council published a document on naturally-occurring radioactive material (NORM)[1] in Australia. One of the main objectives of the discussion paper was to:

> *Develop national guidance on exclusion, exemption and clearance for natural radioactive materials, to enable a uniform approach to establishing criteria that may be used to regulate NORM in all jurisdictions.*

Historically in Australia, the Commonwealth Government and each State and Territory have independently developed regulatory systems for the use of radioactive materials to satisfy radiation protection requirements. The dislocation between state regulations results in uncertainty for generators, processors and users of NORM in the area of commercial reuse, however, COAG have agreed to make the regulations the same in future.

Internationally, considerable attention has been focused on the development of guidelines and regulations relating to radiation protection, with the recommendation of a 1 Bq/g exemption threshold applying to industrial residues[2], which the ASA supports. The ASA acknowledges the importance of issues surrounding NORM, in particular, the need to:

- develop nationally consistent regulation for classification and clearance;
- develop appropriate methods of treatment and disposal, where required; and
- establish appropriate exemption thresholds for naturally occurring radioactive material.

The association has made various representations and submissions to this end, however much of the NORM data available on ISS is either dated and/or unpublished. A substantial program to update and verify the nature of current available ISS is therefore required. This assessment seeks to update data on:

- radionuclide concentrations present in ISS;
- assess consistencies/inconsistencies with published data; and
- compare radionuclide concentrations in ISS in comparison with available background radionuclide concentrations in, for example, soils.

[1] Radiation Health & Safety Advisory Council (RHSAC) – *Naturally-Occurring Radioactive Material (NORM) in Australia: Issues for Discussion*, 2005.
[2] IAEA Safety Guide No. RS-G-1.7, *Table 1*, *Application of the Concepts of Exclusion, Exemption and Clearance*, 2004.

## 2. SAMPLES RECEIVED

A suite of thirty nine (39) slag samples were collected by the ASA from members across Australia, **Figure 1**, and submitted to ANSTO Minerals to determine the concentration of naturally occurring radionuclides present in each sample.

.


**FIGURE 1 Distribution of Members**

The following table sets out the sample identification coding system used to identify each specific iron and steel slag products into their various categories. Chain of Custody (COC) documentation provided by the ASA indicated the samples to be both aggregates and fine dusts. A copy of COC is given in **Appendix A**.

| **Product Description** | **Sample Identification range** | **Number of samples received** |
|---|---|---|
| Granulated Blast Furnace Slag | 101 – 103 | 3 |
| Blast Furnace Slag – Air cooled aggregates | 201 – 203 | 3 |
| Blast Furnace Slag – Air cooled fines | 204 – 209 | 6 |
| Steel Furnace Slag – Air cooled aggregates | 401 – 406 | 6 |
| Electric Arc Furnace Slag – Air cooled aggregates | 601 – 609 | 9 |
| Electric Arc Furnace Slag – Air cooled fines | 801 – 803 | 3 |
| Ladle Furnace Slag – Air cooled fines | 1001 – 1009 | 9 |

Samples were received in 500 mL plastic containers. All samples were dried to constant weight and then pulverised prior to analysis. This information, together with the sample descriptions, is given in **Appendix B**.

## 3. ANALYSIS BY ANSTO MINERALS

The ISS samples were analysed using the following techniques:

- Gamma spectrometry for uranium and thorium decay chain progeny;
- Delayed neutron counting (DNA) for parent uranium;
- Neutron activation analysis (NAA) for parent thorium;
- Alpha spectrometry for $^{210}$Po; and
- X-ray fluorescence spectrometry (XRF) for elemental analysis.

The results are summarised in **Table 1**. The radium equivalent values (see **Section 5.2**) have also been included in this table.

For gamma spectrometry, solid samples were packed into 45 mm plastic Petri dishes and left for 3 weeks to allow for the ingrowth of radium daughters. Samples were then counted using high-purity germanium (HPGe) N-type gamma detectors.

The samples were acid digested for radiochemical analysis for $^{210}$Po.

XRF analysis was carried out for density correction in gamma spectrometry. These results have been provided in **Appendix C**.

## 4. GENERAL INFORMATION

Uranium and thorium are found in trace amounts in virtually all materials in the surface layers of the earth's crust. The $^{238}$U decay chain (**Figure 2**) is made up of the parent, $^{238}$U, and its 13 daughter radionuclides or progeny. Similarly, the $^{232}$Th decay chain (**Figure 3**) is made up of the parent, $^{232}$Th, and its 10 progeny.

Approximately 3.4 million tonnes of iron and steel slag are produced annually in Australasian (Australia and New Zealand) iron and steel plants[3]. A large proportion (~60%) is used as road base, or in cement or concrete applications, with the remainder being stored "on site"[4]. The raw materials for steel production are iron ore, coal (coke) and limestone. There are trace levels of uranium in these raw materials, typically in the order of 20-30 Bq/kg for iron ore and coke and 5 Bq/kg for limestone[5]. The slag from the blast furnace also contains low levels of long-lived radionuclides from both the uranium and thorium decay series, in the order of 2-3 times the levels found in the raw materials[6].

[3] http://www.asa-inc.org.au/Doc/ASA_survey_results_2008.pdf [Accessed October 2010].
[4] ibid.
[5] Brown, S., D. Collier, and P. Kenny. Radionuclides in the Iron Sinter Plant circuit BHP, Port Kembla, ANSTO report to Illawarra Radionuclide Investigations Committee, March 2003.
[6] Crockett, G.M., K.R. Smith, W.B. Otway and S.F. Mobbs. Radiological impact on the UK population of industries which use or produce materials containing enhanced levels of naturally occurring radionuclides, National Radiological Protection Board report, NRPB-W48, Chilton, UK, October 2003.

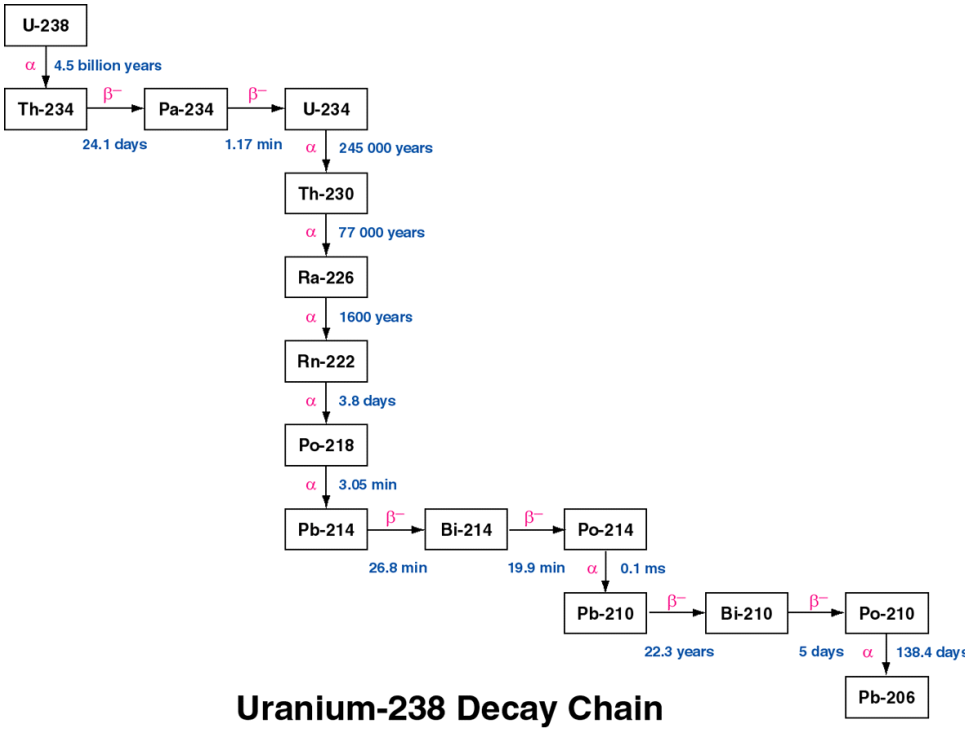


**FIGURE 2**

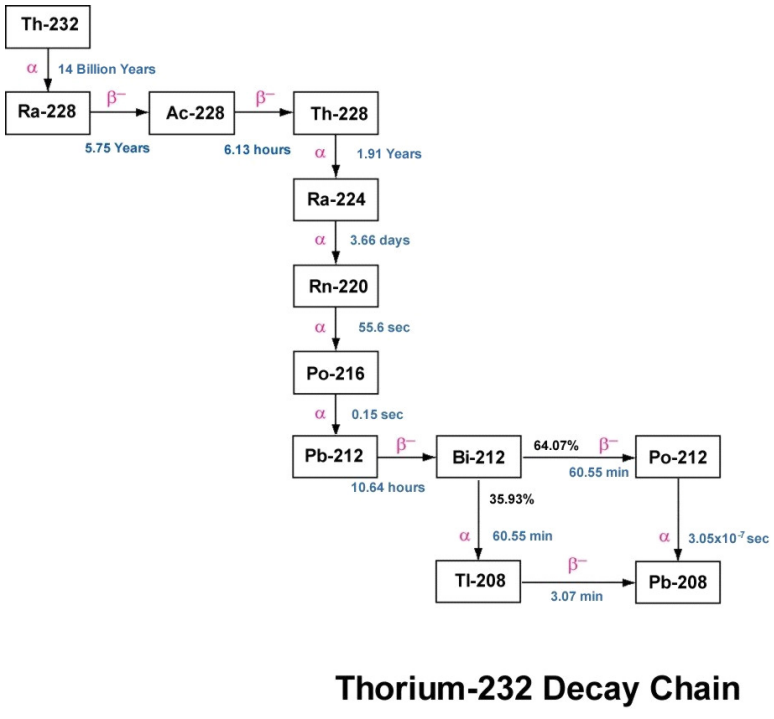


**FIGURE 3**

### *Gamma Spectrometry*

The activities of radionuclides in the $^{238}$U and $^{232}$Th decay chains are determined by gamma spectrometry. A chain is said to be in secular equilibrium if the measured activity concentrations (Bq/kg of solid) of the decay chain radionuclides are statistically the same (± 10%). This is generally the case in older, primary geological deposits. During chemical and thermal processing, however, the radionuclides behave according to their individual physical and chemical characteristics and hence disequilibrium often results. When this occurs, $^{238}$U and $^{232}$Th activities must be determined using other analytical techniques (as discussed below).

Not all radionuclides in the respective decay chains emit gamma radiation. The activity of $^{238}$U and its progeny (see **Figure 2**) are determined by measuring the gamma-emitting radionuclides $^{234}$Th, $^{234m}$Pa, $^{230}$Th, $^{214}$Pb, $^{214}$Bi and $^{210}$Pb. If the measured activities of the progeny are the same (i.e. secular equilibrium), the activity of $^{238}$U can then be inferred from the measured activity of its immediate daughter, $^{234}$Th. If the decay chain is not in equilibrium, the sample must be left for 4 months to allow ingrowth[7] of $^{234}$Th from its parent $^{238}$U, or the $^{238}$U concentration determined independently. Polonium-210 is an alpha emitter and is measured using alpha spectrometry (see below).

In a similar manner, $^{232}$Th and its progeny (see **Figure 3**) are determined by measuring the gamma-emitting radionuclides $^{228}$Ac, $^{228}$Th, $^{224}$Ra, $^{212}$Pb, $^{212}$Bi and $^{208}$Tl. If the decay chain is in secular equilibrium, the activity of $^{232}$Th is inferred from the measured activity of $^{228}$Ac, a short-lived daughter[8] (6.13 h) of $^{228}$Ra.

### *DNA and NAA*

The most accurate methods for measuring $^{238}$U and $^{232}$Th are DNA and NAA, respectively. Both are selective, sensitive and rapid nuclear techniques used to determine these elements at ppm levels or lower.

### *Radiochemistry*

In this work, $^{210}$Po was determined using alpha spectrometry. Polonium was extracted from 6 M hydrochloric acid using diethyl ammonium diethyl dithiocarbamate (DDTC) in chloroform. After autodeposition onto a silver disc, $^{210}$Po was alpha counted.

## 5. DISCUSSION OF RESULTS

During processing, radionuclides partition according to both their physical and chemical properties. Typically, the more volatile radionuclides ($^{210}$Pb, $^{210}$Bi and $^{210}$Po) accumulate in dusts and stack emissions while the more refractory elements (U, Th and Ra) report to the slag[9]. These refractory radionuclides are more concentrated in the slag because of the mass ratio of slag to the ore. Radioactivity released to the atmosphere during combustion consists primarily of gaseous $^{222}$Rn.

In iron and steel making, the main accumulation of radioactivity in the sinter plant is due to $^{210}$Pb and $^{210}$Po in the dust collected from the gas cleaning systems. The concentrations of $^{210}$Pb and $^{210}$Po

[7] The half-life of $^{234}$Th is 24.10 days. $^{234}$Th will be in equilibrium with its parent, $^{238}$U, after 5 half-lives or 120 days.
[8] The half-life of $^{228}$Ac is 6.13 hours. $^{228}$Ac will be in equilibrium with its parent, $^{228}$Ra, after 5 half-lives or 31 hours.
[9] Safety Guide *Management of Naturally Occurring Radioactive Material (NORM)*, Radiation Protection Series No. 15, ARPANSA, August 2008.

become further enhanced because of recycling of the dust to the sinter plant in order to reduce dust emissions[8] and maximize iron recovery.

### 5.1 Radionuclide Concentrations in ISS

The results of this study (see **Table 1**) have shown that the slag samples contain low concentrations of radioactivity and accordingly would not be considered radioactive from a regulatory perspective. A material is classified as radioactive for the purpose of trading if the concentration of any single radionuclide is above the limit[2] of 1 Bq/g (or 1000 Bq/kg) for radionuclides of natural origin or above 10,000 Bq/kg for $^{40}$K.

### 5.2 Activity Concentration Indices

For end-use products, the radium equivalent activity is an index commonly used to compare the activity concentrations of building materials that contain varying amounts of Ra, Th and K. It is defined[10] as the weighted sum of the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K and is based on the estimation that 370 Bq/kg of $^{226}$Ra, 259 Bq/kg of $^{232}$Th and 4810 Bq/kg of $^{40}$K produce the same gamma dose. A radium equivalent of 370 Bq/kg in building materials can produce an exposure of about 1.5 mSv/y to the inhabitants[9].

The radium equivalent, $Ra_{eq}$, is defined as:

$$Ra_{eq} = A_{Ra} + (A_{Th} \times 1.43) + (A_K \times 0.077)$$

where $A_{Ra}$, $A_{Th}$ and $A_K$ are the activities of $^{226}$Ra, $^{232}$Th and $^{40}$K, respectively.

The $Ra_{eq}$ values for the ISS in this study are given in **Table 1**. The values ranged from 0.015 to 0.22 Bq/g. Based on these results, if any of these ISS were blended for use in, for example, concrete, at a ratio of say, 5% by weight[11], the contribution of the slag to the total gamma ray dose from the concrete would be well below 1.5 mSv/y.

[10] UNSCEAR, *Ionising Radiation: Sources and Biological Effects*, United Nations Scientific Committee on the Effects of Atomic Radiation, 1982.
[11] Beretka, J. and Mathew, P.J., *Natural radioactivity of Australian fly ashes*, 2nd International Conference on Ash Technology and Marketing, London, September 16-21, 1984.

**TABLE 1**
**Gamma Spectrometry, DNA, NAA and Radiochemistry Results**

| Sample | | DNA | | Gamma | | | Radiochemistry | | NAA | | Gamma | | | Radium Equivalent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Type | $^{238}$U | | $^{230}$Th | $^{226}$Ra | $^{210}$Pb | $^{210}$Po* | Sampling Date | $^{232}$Th | | $^{228}$Ra | $^{228}$Th | $^{40}$K | |
| | | ppm | Bq/g | Bq/g | Bq/g | Bq/g | Bq/g | | ppm | Bq/g | Bq/g | Bq/g | Bq/g | Bq/g |
| 101 | Granulated BFS | 10 | 0.13 | < 0.2 | 0.14 | < 0.02 | 0.016 | 12-Mar-10 | 7.9 | 0.032 | 0.061 | 0.061 | 0.10 | 0.19 |
| 102 | Granulated BFS | 9.4 | 0.12 | < 0.2 | 0.13 | < 0.02 | 0.04 | 12-Mar-10 | 10 | 0.040 | 0.071 | 0.060 | 0.14 | 0.20 |
| 103 | Granulated BFS | 10 | 0.12 | < 0.2 | 0.14 | < 0.03 | 0.05 | 12-Mar-10 | 8.7 | 0.035 | 0.065 | 0.063 | 0.10 | 0.20 |
| 201 | 10 mm Aggregate | 11 | 0.14 | < 0.2 | 0.13 | < 0.02 | 0.11 | 12-Mar-10 | 6.7 | 0.027 | 0.067 | 0.062 | 0.091 | 0.18 |
| 202 | 10 mm Aggregate | 11 | 0.14 | < 0.2 | 0.14 | < 0.02 | 0.09 | 12-Mar-10 | 6.7 | 0.027 | 0.072 | 0.067 | < 0.08 | 0.055 |
| 203 | 10 mm Aggregate | 11 | 0.14 | < 0.2 | 0.14 | < 0.02 | 0.59 | 12-Mar-10 | 14 | 0.058 | 0.064 | 0.065 | < 0.08 | 0.099 |
| 401 | 10 mm Aggregate | 0.57 | 0.0070 | < 0.2 | 0.010 | < 0.03 | 0.08 | 12-Mar-10 | 14 | 0.058 | < 0.01 | 0.004 | < 0.03 | 0.095 |
| 402 | 10 mm Aggregate | 0.70 | 0.0087 | < 0.2 | 0.012 | < 0.03 | 0.015 | 12-Mar-10 | 14 | 0.058 | < 0.01 | 0.005 | < 0.03 | 0.097 |
| 403 | 10 mm Aggregate | 0.71 | 0.0088 | < 0.2 | 0.009 | < 0.02 | 0.023 | 12-Mar-10 | 15 | 0.061 | < 0.01 | 0.003 | < 0.02 | 0.099 |
| 204 | -7 mm Dust | 11 | 0.13 | < 0.2 | 0.13 | < 0.03 | 0.032 | 12-Mar-10 | 15 | 0.059 | 0.066 | 0.062 | < 0.08 | 0.10 |
| 205 | -7 mm Dust | 10 | 0.13 | < 0.2 | 0.12 | < 0.03 | 0.006 | 12-Mar-10 | 15 | 0.061 | 0.063 | 0.058 | 0.11 | 0.22 |
| 206 | -7 mm Dust | 11 | 0.13 | < 0.2 | 0.12 | < 0.02 | 0.011 | 12-Mar-10 | 0.71 | 0.0029 | 0.061 | 0.056 | 0.12 | 0.13 |

* $^{210}$Po activity on sampling date.

**TABLE 1 (continued)**
**Gamma Spectrometry, DNA, NAA and Radiochemistry Results**

| Sample | | DNA | | Gamma | | | Radiochemistry | | NAA | | Gamma | | | Radium Equivalent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Type | $^{238}$U | | $^{230}$Th | $^{226}$Ra | $^{210}$Pb | $^{210}$Po* | Sampling Date | $^{232}$Th | | $^{228}$Ra | $^{228}$Th | $^{40}$K | |
| | | ppm | Bq/g | Bq/g | Bq/g | Bq/g | Bq/g | | ppm | Bq/g | Bq/g | Bq/g | Bq/g | Bq/g |
| 801 | -6 mm Dust | 0.47 | 0.0058 | < 0.2 | < 0.01 | < 0.03 | 0.016 | 12-Mar-10 | 0.71 | 0.0028 | < 0.01 | < 0.01 | < 0.03 | 0.016 |
| 802 | -6 mm Dust | 0.50 | 0.0062 | < 0.2 | < 0.01 | < 0.03 | 0.029 | 12-Mar-10 | 0.72 | 0.0029 | < 0.01 | < 0.01 | < 0.03 | 0.016 |
| 803 | -6 mm Dust | 0.76 | 0.0094 | < 0.2 | < 0.01 | < 0.03 | 0.010 | 12-Mar-10 | 0.96 | 0.0039 | < 0.01 | < 0.01 | < 0.03 | 0.018 |
| 601 | Air-cooled EAF | 0.82 | 0.010 | < 0.2 | 0.012 | < 0.03 | 0.008 | 9-Mar-10 | 1.8 | 0.0074 | < 0.01 | 0.006 | < 0.03 | 0.025 |
| 602 | Air-cooled EAF | 0.78 | 0.0097 | < 0.2 | 0.010 | < 0.02 | 0.042 | 9-Mar-10 | 1.4 | 0.0056 | < 0.01 | 0.005 | < 0.02 | 0.020 |
| 603 | Air-cooled EAF | 0.69 | 0.0086 | < 0.2 | 0.012 | < 0.03 | 0.005 | 9-Mar-10 | 1.5 | 0.0061 | < 0.01 | 0.006 | < 0.02 | 0.022 |
| 1001 | Ladle Furnace Slag | 0.82 | 0.010 | < 0.2 | 0.012 | < 0.03 | 0.018 | 12-Mar-10 | 2.0 | 0.0082 | < 0.01 | 0.008 | < 0.03 | 0.026 |
| 1002 | Ladle Furnace Slag | 1.2 | 0.014 | < 0.2 | 0.011 | < 0.02 | 0.015 | 12-Mar-10 | 2.0 | 0.0081 | < 0.01 | 0.007 | < 0.04 | 0.026 |
| 1003 | Ladle Furnace Slag | 0.89 | 0.011 | < 0.2 | 0.011 | < 0.03 | 0.03 | 12-Mar-10 | 1.9 | 0.0076 | < 0.01 | 0.006 | < 0.04 | 0.025 |
| 607 | Air-cooled EAF | 0.48 | 0.0059 | < 0.2 | 0.008 | < 0.02 | 0.016 | 9-Mar-10 | 0.95 | 0.0039 | < 0.01 | 0.004 | < 0.02 | 0.015 |
| 608 | Air-cooled EAF | 0.39 | 0.0048 | < 0.2 | 0.009 | < 0.03 | 0.074 | 9-Mar-10 | 0.84 | 0.0034 | < 0.01 | 0.003 | < 0.02 | 0.015 |
| 609 | Air-cooled EAF | 0.82 | 0.010 | < 0.2 | 0.011 | < 0.03 | 0.012 | 9-Mar-10 | 1.6 | 0.0065 | < 0.01 | 0.006 | < 0.03 | 0.023 |

* $^{210}$Po activity on sampling date.

**TABLE 1 (continued)**
**Gamma Spectrometry, DNA, NAA and Radiochemistry Results**

| Sample | | DNA | | Gamma | | | Radiochemistry | | NAA | | Gamma | | | Radium Equivalent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Type | $^{238}$U | | $^{230}$Th | $^{226}$Ra | $^{210}$Pb | $^{210}$Po* | Sampling Date | $^{232}$Th | | $^{228}$Ra | $^{228}$Th | $^{40}$K | |
| | | ppm | Bq/g | Bq/g | Bq/g | Bq/g | Bq/g | | ppm | Bq/g | Bq/g | Bq/g | Bq/g | Bq/g |
| 1007 | Ladle Furnace Slag | 1.9 | 0.023 | < 0.2 | 0.021 | < 0.02 | 0.017 | 2-Mar-10 | 4.1 | 0.017 | < 0.02 | 0.017 | < 0.03 | 0.048 |
| 1008 | Ladle Furnace Slag | 1.4 | 0.018 | < 0.2 | 0.014 | < 0.02 | 0.025 | 2-Mar-10 | 3.1 | 0.012 | < 0.01 | 0.010 | < 0.03 | 0.033 |
| 1009 | Ladle Furnace Slag | 2.0 | 0.025 | < 0.2 | 0.015 | < 0.02 | 0.11 | 2-Mar-10 | 4.0 | 0.016 | < 0.02 | 0.017 | < 0.02 | 0.039 |
| 604 | Air-cooled EAF | 0.83 | 0.010 | < 0.2 | 0.011 | < 0.03 | 0.012 | 9-Mar-10 | 1.3 | 0.0054 | < 0.01 | 0.006 | < 0.02 | 0.020 |
| 605 | Air-cooled EAF | 0.84 | 0.010 | < 0.2 | 0.012 | < 0.03 | 0.025 | 9-Mar-10 | 1.5 | 0.0060 | < 0.01 | 0.006 | < 0.02 | 0.022 |
| 606 | Air-cooled EAF | 0.86 | 0.011 | < 0.2 | 0.011 | < 0.02 | 0.015 | 9-Mar-10 | 1.3 | 0.0053 | < 0.01 | 0.006 | < 0.01 | 0.019 |
| 1004 | Ladle Furnace Slag | 2.1 | 0.025 | < 0.2 | 0.025 | < 0.02 | 0.014 | 9-Mar-10 | 5.1 | 0.021 | 0.018 | 0.021 | < 0.03 | 0.057 |
| 1005 | Ladle Furnace Slag | 1.3 | 0.017 | < 0.2 | 0.017 | < 0.03 | 0.021 | 9-Mar-10 | 2.4 | 0.0098 | < 0.01 | 0.010 | < 0.03 | 0.033 |
| 1006 | Ladle Furnace Slag | 1.1 | 0.014 | < 0.2 | 0.015 | < 0.02 | 0.006 | 9-Mar-10 | 2.5 | 0.010 | < 0.01 | 0.010 | < 0.03 | 0.032 |

* $^{210}$Po activity on sampling date.

**TABLE 1 (continued)**
**Gamma Spectrometry, DNA, NAA and Radiochemistry Results**

| Sample | | DNA | | Gamma | | | Radiochemistry | | NAA | | Gamma | | | Radium Equivalent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Type | $^{238}$U | | $^{230}$Th | $^{226}$Ra | $^{210}$Pb | $^{210}$Po* | Sampling Date | $^{232}$Th | | $^{228}$Ra | $^{228}$Th | $^{40}$K | |
| | | ppm | Bq/g | Bq/g | Bq/g | Bq/g | Bq/g | | ppm | Bq/g | Bq/g | Bq/g | Bq/g | Bq/g |
| 207 | Air-cooled BFS | 12 | 0.15 | < 0.2 | 0.15 | < 0.03 | 0.40 | 23-Feb-10 | 10 | 0.041 | 0.048 | 0.042 | < 0.06 | 0.21 |
| 208 | Air-cooled BFS | 11 | 0.14 | < 0.2 | 0.14 | < 0.02 | 0.034 | 23-Feb-10 | 9.9 | 0.040 | 0.044 | 0.041 | < 0.06 | 0.20 |
| 209 | Air-cooled BFS | 11 | 0.14 | < 0.2 | 0.14 | < 0.03 | 0.011 | 23-Feb-10 | 9.5 | 0.038 | 0.050 | 0.039 | < 0.06 | 0.20 |
| 404 | Air-cooled SFS | 2.4 | 0.029 | < 0.2 | 0.029 | < 0.03 | 0.09 | 23-Feb-10 | 4.3 | 0.017 | < 0.02 | 0.017 | < 0.03 | 0.056 |
| 405 | Air-cooled SFS | 1.6 | 0.019 | < 0.2 | 0.019 | < 0.03 | 0.014 | 23-Feb-10 | 1.5 | 0.0061 | < 0.01 | 0.007 | < 0.03 | 0.030 |
| 406 | Air-cooled SFS | 1.5 | 0.018 | < 0.2 | 0.020 | < 0.03 | 0.028 | 23-Feb-10 | 1.8 | 0.0073 | < 0.01 | 0.007 | < 0.03 | 0.033 |

* $^{210}$Po activity on sampling date.

## 5.3 Comparison with Previous Studies

The radionuclide concentrations in ISS depend on the origin of the raw materials and the type of processing employed. The typical worldwide concentrations in blast furnace slag are given in UNSCEAR 2000[12]. The stated total contained activity values are 150 Bq/kg for both uranium, thorium and their respective decay chain progeny. It should be noted however, that these values assume secular equilibrium in each of the decay chains, which is not normally observed in process samples such as ISS.

El-Taher et al.[13] assessed the natural radioactivity and radiation hazards associated with the cement industry in Egypt. The $^{226}$Ra concentration in the slag used for production was high compared to average world values[11], most likely due to higher concentrations in the iron ore used. The results are given in **Table 2**.

Sofilic et al.[14] studied the radiochemical characteristics of electric arc furnace slags from steelmaking in Croatia and the results for $^{238}$U, $^{226}$Ra, $^{232}$Th and $^{40}$K are given in **Table 2**.

Kovler[15] assessed the radiological constraints of using building materials and industrial by-products in construction in terms of legislation and standards. The values given for typical and maximum concentrations for $^{226}$Ra, $^{232}$Th and $^{40}$K in common building materials and industrial by-products in Europe are given in **Table 2**. These values have been taken from European Commission document RP-112[16].

Turhan[17] examined twelve blast furnace slags in his study of Turkish cement and its raw materials and the concentrations for $^{226}$Ra, $^{232}$Th and $^{40}$K are given in **Table 2**.

The iron and steel industry in Sweden uses raw materials from Swedish mines in two plants. Soderman et al.[18] found that the concentrations of naturally occurring radionuclides were low in raw materials, but blast furnace slag contained enriched concentrations of radionuclides. The $^{226}$Ra concentration given was 250 Bq/kg.

El-Afifi et al.[19] evaluated radionuclide concentrations in common building materials used for construction in Egypt. They did not detect $^{226}$Ra, $^{232}$Th or $^{40}$K in the iron slag waste from iron and steel production.

---

[12] UNSCEAR, *Sources and Effects of Ionising Radiation*, United Nations Scientific Committee on the Effects of Atomic Radiation, Volume I: Sources Annex B, 2000.

[13] El-Taher, A., Makhluf, S., Nossair, A. and Abdel Halim, A.S., *Assessment of natural radioactivity and radiation hazards due to cement industry*, Applied Radiation and Isoptopes, 68, 169-174, 2010.

[14] Sofilic, T., Barisic, D., Rastovcan, M. and Sofilic, U., *Radionuclides in steel slag intended for road construction*, J. Radioanal. Nucl. Chem, 248, 73-77, 2010.

[15] Kovler, K., *Radiological constraints of using building materials and industrial by-products in construction*, Construction and Building Materials, 23, 246-253, 2009.

[16] European Commission RP-112, Radiological Protection Principles concerning the Natural Radioactivity of Building Materials, 1999.

[17] Turhan, S., *Assessment of the natural radioactivity and radiological hazards in Turkish cement and its raw materials*, Journal of Environmental Radioactivity, 99, 404-414, 2009.

[18] Soderman, A.L., Brewitz, E and More, H., *Investigation of NORM activities in Sweden*, in Naturally Occurring Radioactive Material (NORM V) Proceedings of an International Symposium, Seville, Spain, 19–22 March 2007.

[19] El Afifi, E.M., Hilal, M.A., Khalifa, S.M. and Aly, H.F., *Evaluation of U, Th and K and emanated radon in some NORM and TENORM samples*, Radiation Measurements, 41, 627-633, 2006.

**TABLE 2**
**Radionuclide Concentrations (Bq/kg) in Steel Production Slags and Maximum and Minimum Concentrations for ISS in this Study**

| | $^{238}$U | $^{230}$Th | $^{226}$Ra | $^{210}$Pb | $^{210}$Po | $^{232}$Th | $^{228}$Ra | $^{228}$Th | $^{235}$U | $^{227}$Th | $^{40}$K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| UNSCEAR, 2000[11] | | | | | | | | | | | |
| | 150 | *150* | *150* | *150* | *150* | 150 | *150* | *150* | | | |
| El-Taher et al., 2010[12] | | | | | | | | | | | |
| | | | 299 | | | 24 | | | | | 166 |
| Sofilic et al., 2010[13] | | | | | | | | | | | |
| | 9-24 | | 13- 24 | | | 7-14 | | | | | 8-37 |
| Kovler, 2009[14] | | | | | | | | | | | |
| typical | | | 270 | | | 70 | | | | | 240 |
| maximum | | | 2100 | | | 340 | | | | | 1000 |
| | | | | | | | | | | | |
| Turhan, 2008[16] | | | | | | | | | | | |
| value | | | 308 | | | 148 | | | | | 243 |
| range | | | 8-308 | | | 1.6 - 337 | | | | | 18 -389 |
| Soderman et al., 2007[17] | | | | | | | | | | | |
| | | | 250 | | | | | | | | |
| El Afifi et al., 2006[18] | | | | | | | | | | | |
| | | | ND | | | ND | | | | | ND |
| Crockett et al., 2003[5] | | | | | | | | | | | |
| | 88 | 88 | 88 | 88 | | 49 | 49 | 49 | 4 | 4 | |
| Beretka and Mathew, 1985[20] | | | | | | | | | | | |
| | | | 181 | | | 100 | | | | | 141 |
| Maximum and Minimum Radionuclide Concentrations for ISS (in this study) | | | | | | | | | | | |
| Maximum | 150 | < 200 | 150 | < 30 | 400 | 61 | 72 | 67 | | | |
| Minimum | 6 | | 8 | | 6 | 3 | < 10 | < 10 | | | |

In their study of the radiological impact on the UK population from steel production, Crockett et al.[5] stated that Australia is a source of raw materials used in UK steel production. Typical radionuclide concentrations for slag removed from blast and BOS furnaces (not distinguished) are given in **Table 2**.

Hofmann et al.[20] stated in their report to the European Commission that iron ore production and refining processes do not increase the NORM content in the product, by-product, refuse or equipment. This is because there are large additions of other materials to the process, which results

[20] European Commission Nuclear Safety and the Environment Report EUR 19264, *Natural Radionuclide Concentrations in Materials Processed in the Chemical Industry and the Related Radiological Impact*, J. Hofmann, R. Leicht, H. Wingender and J. Worner, August 2000.

in a dilution of the radionuclides in the slag. Because of this, the iron ore industry was not studied further.

Beretka and Mathews[21] measured natural radioactivity in Australian building materials. Slag samples included air-cooled, granulated and pelletized[22] blast furnace slag from New South Wales and air-cooled slag from South Australia. At that time, Small quantities of pelletized slag was being used as lightweight aggregate in concrete in New South Wales, granulated slag for glass-making and air-cooled slag as road base or civil engineering applications. The results are given in **Table 2**.

The data in **Table 2** indicate that the Australian ISS samples in this study are "typical" when compared to similar iron and steel production samples used in building materials in other parts of the world.

### 5.4 Comparison with Background Concentrations in Soil

Uranium is found in all soils and the concentration varies according to the type of rock the soil is derived from. **Table 3** summarises a selection of average natural radionuclide concentrations in soils found in the literature. The maximum and minimum radionuclide concentrations for ISS in this study have been included for comparison.

The maximum radionuclide concentrations for ISS generally exceed the ranges given in **Table 3** for $^{238}U$, $^{226}Ra$, $^{232}Th$, however, given that ISS would most likely be mixed with other components for use in building materials, these concentrations would be significantly diluted. The minimum radionuclide concentrations for ISS are at the lower end of the ranges given in **Table 3**.

## 6. CONCLUSION

The results of this study have shown that ISS samples in this study contain low concentrations of radioactivity and would not be considered radioactive from a regulatory perspective (< 1 Bq/g).

These samples were typical of ISS used in the building and construction industry in other parts of the world.

The use of the types of slags in this study in similar applications in building and construction should not pose a significant OH&S risk to workers or the public. Dilution would further reduce the radionuclide concentrations and therefore the associated risk.

[21] Beratka, J. and Mathews, P.J., *Natural radioactivity of Australian building materials, industrial wastes and by-products*, Health Physics, 48, 87-95, 1985.
[22] Pelletized blast furnace slag is no longer manufactured in Australia.

**TABLE 3**
**Average Radionuclide Concentrations in Soils and Maximum and Minimum Concentrations for ISS in this Study**

| Reference | Concentration in soil (Bq/kg) | | | |
|---|---|---|---|---|
| | $^{238}$U | $^{226}$Ra | $^{232}$Th | $^{40}$K |
| *Background Concentrations (general)* | | | | |
| Karunakara et al.[23] | - | 31 (15 – 61) | 26 (11 – 42) | 160 (78 – 255) |
| UNSCEAR[11] | 35 (16 – 110) | 35 (17 – 60) | 30 (11 – 64) | 400 (140 – 850) |
| IAEA[24] | 25 (10 – 50) | 25 (10 – 50) | 25 (7 – 50) | 370 (100- 700) |
| NRC[25] | 22 | - | - | - |
| Eisenbud and Gesell[26] | 22 | - | 37 | 400 |
| Myrick et al.[27] (world) | 24 (12 – 49) | 29 (18 – 73) | 24 (8 – 48) | - |
| Myrick et al.[28] (USA) | 37 (4 – 141) | 37 (4 – 141) | 36 (4 – 126) | - |
| *Background Concentrations (around U production sites)* | | | | |
| Ramli et al.[29] | 59 – 485 | - | 60 - 1204 | - |
| Tome et al.[30] | 93 – 328 | 191 – 492 | 14 – 48 | - |
| Read and Pickering[31] | 2.3 | < 17 | - | - |
| Ibraham and Whicker[32] | 50 | - | 44 | - |
| *Maximum and Minimum Radionuclide Concentrations for ISS (in this study)* | | | | |
| Maximum | 150 | 150 | 61 | 140 |
| Minimum | 6 | 8 | 3 | 10 |

[23] Karunakara, N., Somashekarappa, H.M., Avadhani, D.N., Mahesh, H.M., Narayana, Y. and Siddappa, K., Radium-226, $^{232}$Th and $^{40}$K distribution in the environment of Kaiga of south-west coast of India. *Health Physics*, 80, 470-476, 2001.

[24] IAEA, *Generic Procedures for Assessment and Response during a Radiological Emergency*, IAEA TECDOC Series No. 1162, 2000.

[25] NRC, *Evaluation of Guidelines for Exposures to Technologically Enhanced Naturally Occurring Radioactive Materials*, 1999.

[26] Eisenbud, M. and Gesell, T., *Environmental Radioactivity from Natural, Industrial and Military Sources*, 4th Edition, 1997.

[27] Myrick, T.E., Bervan, B.A. and Haywood, F.F., *State Background Radiation Levels: Results of Measurements Taken During 1975-1979*. ORNL/TM-7343. Oak Ridge National Laboratory, 1981.

[28] Myrick, T.E., Bervan, B.A. and Haywood, F.F., *State Background Radiation Levels: Results of Measurements Taken During 1975-1979*. ORNL/TM-7343. Oak Ridge National Laboratory, 1981.

[29] Ramli, A.T., Hussein, A.W. and Wood, A.K., Environmental $^{238}$U and $^{232}$Th concentration measurements in an area of high level natural background radiation at Palong, Johor, Malaysia. *Journal of Environmental Radioactivity*, 80, 287-304, 2005.

[30] Tome, F.V., Rodriguez, P.B. and Lozano, J.C., Distribution and mobilisation of U, Th and $^{226}$Ra in the plant-soil compartments of a mineralised uranium area in south-west Spain, .*Journal of Envoronmental Radioactivity*, 59, 41-60, 2002.

[31] Read, J. and Pickering, R., *Ecological and toxicological effects of exposure to an acidic, radioactive tailings storage. Environmental Monitoring and Assessment*, 54, 69-85.

[32] Ibraham, S.A., and Whicker, F.W., Comparative uptake of U and Th by native plants at a U production site. *Health Physics*, 54, 413-419, 1988.

# APPENDIX A

## Samples Received

ASA Commercial-in-Confidence

### ANALYSIS REQUEST AND CHAIN OF CUSTODY

Australasian (iron & steel) Slag Association, PO Box 1194, Wollongong NSW 2500, Telephone: +61 2 4228 1389, Facsimile: +61 2 4228 1777, Mobile: 0418 885 290, Email: info@asa-inc.org.au

| | | | |
|---|---|---|---|
| **Company Name:** | Australasian (iron & steel) Slag Association | | |
| **Project Name:** | NORMS | | |
| **Contact Name:** | Mona Forghani | | |
| **Address:** | PO Box 1194 Wollongong NSW 2500 | **Phone:** | (02) 42258466 |
| **Email:** | mforghani@hbmgroup.com.au | **Fax:** | (02) 42281777 |

| Matrix Codes | | Preservative Codes | | Container Codes | |
|---|---|---|---|---|---|
| CW | – Clean Water | P1 | – Chilled 4°C | C1 | – 125LPET |
| WW | – Waste Water | P2 | – Frozen | C2 | – 500mL PET |
| GW | – Ground Water | P3 | – Filtered | C3 | – 200mL PET |
| EF | – Effluent | P4 | – $HNO_3$ PH<2 | C4 | – 100mL PET |
| BS | – Biosolid | P5 | – $H_2SO_4$ PH<2 | C5 | – 1L Glass |
| SL | – Soil | P6 | – HCl PH<2 | C6 | – Amber Glass |
| SD | – Sediment | P7 | – Lugol's Iodine | C7 | – Sterile |
| OT | – *Other | P8 | – *Other | C8 | – *Other |

### ANALYSES REQUIRED

| Client Sample ID | Description | Sample Date[1] | Matrix | No. Of Containers | Container Type + Preservative | | | | | | | ANALYSIS REQUIRED | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | NORM | |
| 101 | Granulated Blast Furnace Slag | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 102 | Granulated Blast Furnace Slag | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 103 | Granulated Blast Furnace Slag | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 201 | 10mm Aggregates | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 202 | 10mm Aggregates | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 203 | 10mm Aggregates | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |

[1] Sample means date of production, i.e. sample collected within 1 or 2 days of production

Form : Analysis Request and Chain of Custody

Page: 1 of 1

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 204 | 7mm Dust | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 205 | 7mm Dust | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 206 | 7mm Dust | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 207 | Blast Furnace Slag – air cooled | 23.2.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 208 | Blast Furnace Slag – air cooled | 23.2.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 209 | Blast Furnace Slag – air cooled | 23.2.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 401 | 10mm Aggregate | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 402 | 10mm Aggregate | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 403 | 10mm Aggregate | 12.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 404 | Steel Furnace Slag – air cooled | 23.2.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 405 | Steel Furnace Slag – air cooled | 23.2.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 406 | Steel Furnace Slag – air cooled | 23.2.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 601 | Electric Arc Furnace Slag – air cooled | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 602 | Electric Arc Furnace Slag – air cooled | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 603 | Electric Arc Furnace Slag – air cooled | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 604 | Electric Arc Furnace Slag – air cooled | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 605 | Electric Arc Furnace Slag – air cooled | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 606 | Electric Arc Furnace Slag – air cooled | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 607 | Air Cooled EAF | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 608 | Air Cooled EAF | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |
| 609 | Air Cooled EAF | 9.3.10 | OT | 1 | C2 | P8 | | | | | | Yes | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 801 | 6mm Dust | 12.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 802 | 6mm Dust | 12.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 803 | 6mm Dust | 12.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1001 | Ladle Furnace Slag | 12.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1002 | Ladle Furnace Slag | 12.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1003 | Ladle Furnace Slag | 12.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1004 | Ladle Furnace Slag | 9.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1005 | Ladle Furnace Slag | 9.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1006 | Ladle Furnace Slag | 9.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1007 | Ladle Furnace Slag | 2.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1008 | Ladle Furnace Slag | 2.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |
| 1009 | Ladle Furnace Slag | 2.3.10 | OT | 1 | C2 | P8 | | | | | Yes | |

**Samples relinquished by: M Forghani** **Date/Time: 17/3/2010**

**Samples received by:** **Date/Time:**

**COMMENTS:**

**Please retain sample until: /12/2010**

# APPENDIX B

## Sample Identification, Weights (as received) and Dry Weights (105ºC)

| Sample ID | Sample Type | ANSTO ID | Wt as Rec'd | Dry Wt |
|---|---|---|---|---|
| 101 | Granulated BFS | ASA-220410-1 | 470.1g | 450.3g |
| 102 | | ASA-220410-2 | 479.5g | 461.1g |
| 103 | | ASA-220410-3 | 516.5g | 494.3g |
| 201 | 10 mm aggregate | ASA-220410-4 | 540.5g | 524.5g |
| 202 | | ASA-220410-5 | 691.4g | 669.0g |
| 203 | | ASA-220410-6 | 648.4g | 629.6g |
| 401 | 10 mm aggregate | ASA-220410-7 | 632.3g | 623.3g |
| 402 | | ASA-220410-8 | 739.7g | 726.1g |
| 403 | | ASA-220410-9 | 668.3g | 654.3g |
| 204 | -7 mm Dust | ASA-220410-10 | 670.3g | 644.3g |
| 205 | | ASA-220410-11 | 670.2g | 651.0g |
| 206 | | ASA-220410-12 | 672.0g | 652.0g |
| 801 | -6 mm Dust | ASA-220410-13 | 920.1g | 903.5g |
| 802 | | ASA-220410-14 | 898.8g | 883.1g |
| 803 | | ASA-220410-15 | 773.4g | 748.1g |
| 601 | Air-cooled EAF | ASA-220410-16 | 657.7g | 663.8g |
| 602 | | ASA-220410-17 | 841.4g | 831.0g |
| 603 | | ASA-220410-18 | 789.9g | 787.9g |
| 1001 | Ladle Furnace Slag | ASA-220410-19 | 821.6g | 793.5g |
| 1002 | | ASA-220410-20 | 901.0g | 874.2g |
| 1003 | | ASA-220410-21 | 750.0g | 711.6g |
| 607 | Air-cooled EAF | ASA-220410-22 | 558.6g | 556.3g |
| 608 | | ASA-220410-23 | 391.7g | 391.0g |
| 609 | | ASA-220410-24 | 339.8g | 335.4g |
| 1007 | Ladle Furnace Slag | ASA-220410-25 | 146.3g | 146.0g |
| 1008 | | ASA-220410-26 | 128.1g | 127.4g |
| 1009 | | ASA-220410-27 | 158.8g | 156.9g |
| 604 | Air-cooled EAF | ASA-220410-28 | 1000.5g | 982.2g |
| 605 | | ASA-220410-29 | 933.3g | 917.3g |
| 606 | | ASA-220410-30 | 996.7g | 978.8g |
| 1004 | Ladle Furnace Slag | ASA-220410-31 | 802.7g | 760.3g |
| 1005 | | ASA-220410-32 | 819.2g | 779.4g |
| 1006 | | ASA-220410-33 | 815.8g | 770.2g |
| 207 | Air-cooled BFS | ASA-220410-34 | 530.0g | 529.3g |
| 208 | | ASA-220410-35 | 540.0g | 539.4g |
| 209 | | ASA-220410-36 | 529.0g | 526.9g |
| 404 | Air-cooled SFS | ASA-220410-37 | 905.6g | 904.5g |
| 405 | | ASA-220410-38 | 763.1g | 761.5g |
| 406 | | ASA-220410-39 | 807.6g | 804.8g |

# APPENDIX C

## XRF Results

**REPORT NUMBER: 1001321 XRF**
**Job Description: ASA Craig Heindrich**
**Report Date: 17th May 2010**
**Fusion: 1 g sample + 8 g 12:22 flux (Li tetraborate:Li metaborate)**
**Program: Minerals REE + U**

| Sample name | Al (%) | Ca (%) | Cr (%) | Cs (%) | Fe (%) | Mg (%) | Mn (%) | S (%) | Si (%) | Sr (%) | Ti (%) | V (%) | Zr (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ASA-220410-1** | 7.5 | 30 | 0.008 | 0.043 | 0.74 | 2.9 | 0.28 | 0.46 | 16 | 0.16 | 0.52 | 0.022 | 0.12 |
| **ASA-220410-2** | 7.3 | 30 | 0.014 | 0.041 | 1.00 | 2.9 | 0.31 | 0.41 | 16 | 0.16 | 0.54 | 0.025 | 0.11 |
| **ASA-220410-3** | 7.2 | 29 | 0.017 | 0.042 | 0.63 | 2.8 | 0.30 | 0.44 | 17 | 0.16 | 0.52 | 0.023 | 0.12 |
| **ASA-220410-4** | 7.2 | 28 | 0.018 | 0.040 | 0.36 | 2.8 | 0.39 | 0.40 | 15 | 0.16 | 0.57 | 0.027 | 0.11 |
| **ASA-220410-5** | 7.4 | 30 | 0.024 | 0.041 | 0.34 | 2.9 | 0.40 | 0.41 | 16 | 0.16 | 0.58 | 0.030 | 0.11 |
| **ASA-220410-6** | 7.4 | 30 | 0.032 | 0.041 | 0.44 | 2.9 | 0.41 | 0.43 | 16 | 0.16 | 0.57 | 0.033 | 0.12 |
| **ASA-220410-7** | 1.9 | 28 | 0.23 | 0.047 | 19 | 5.6 | 3.4 | 0.073 | 4.8 | 0.12 | 0.57 | 0.86 | 0.035 |
| **ASA-220410-8** | 1.9 | 27 | 0.25 | 0.047 | 19 | 5.6 | 3.4 | 0.066 | 4.7 | 0.12 | 0.55 | 0.84 | 0.043 |
| **ASA-220410-9** | 1.6 | 28 | 0.23 | 0.055 | 18 | 6.1 | 3.0 | 0.067 | 5.1 | 0.12 | 0.56 | 0.77 | 0.044 |
| **ASA-220410-10** | 7.1 | 30 | 0.010 | 0.044 | 0.54 | 3.0 | 0.32 | 0.51 | 16 | 0.16 | 0.59 | 0.027 | 0.11 |
| **ASA-220410-11** | 8.2 | 35 | 0.017 | 0.047 | 0.50 | 3.5 | 0.37 | 0.55 | 18 | 0.15 | 0.68 | 0.031 | 0.12 |
| **ASA-220410-12** | 7.1 | 30 | 0.012 | 0.040 | 0.45 | 3.0 | 0.32 | 0.52 | 16 | 0.16 | 0.59 | 0.026 | 0.11 |
| **ASA-220410-13** | 1.3 | 24 | 0.21 | 0.049 | 27 | 5.3 | 2.8 | 0.060 | 4.1 | 0.11 | 0.49 | 0.68 | 0.039 |
| **ASA-220410-14** | 1.3 | 28 | 0.21 | 0.044 | 18 | 6.1 | 3.1 | 0.073 | 4.6 | 0.12 | 0.55 | 0.76 | 0.043 |
| **ASA-220410-15** | 1.6 | 28 | 0.18 | 0.047 | 16 | 5.7 | 2.9 | 0.077 | 4.7 | 0.12 | 0.51 | 0.70 | 0.041 |
| **ASA-220410-16** | 3.5 | 19 | 1.1 | 0.044 | 24 | 5.4 | 4.2 | 0.076 | 6.1 | 0.13 | 0.28 | 0.081 | 0.069 |
| **ASA-220410-17** | 3.0 | 18 | 1.1 | 0.041 | 28 | 4.2 | 3.7 | 0.090 | 4.5 | 0.12 | 0.24 | 0.074 | 0.059 |
| **ASA-220410-18** | 3.1 | 18 | 1.1 | 0.044 | 27 | 4.4 | 4.0 | 0.086 | 4.8 | 0.12 | 0.25 | 0.081 | 0.056 |
| **ASA-220410-19** | 2.6 | 23 | 0.46 | 0.038 | 14 | 7.2 | 2.4 | 0.12 | 7.9 | 0.13 | 0.22 | 0.042 | 0.072 |
| **ASA-220410-20** | 2.5 | 22 | 0.47 | 0.038 | 13 | 7.4 | 2.6 | 0.11 | 7.6 | 0.13 | 0.23 | 0.048 | 0.069 |

# APPENDIX C

## XRF Results (continued)

| Sample name | Al (%) | Ca (%) | Cr (%) | Cs (%) | Fe (%) | Mg (%) | Mn (%) | S (%) | Si (%) | Sr (%) | Ti (%) | V (%) | Zr (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ASA-220410-21** | 2.5 | 23 | 0.41 | 0.035 | 12 | 7.4 | 2.7 | 0.12 | 8.3 | 0.13 | 0.23 | 0.045 | 0.076 |
| **ASA-220410-22** | 2.0 | 20 | 2.4 | 0.049 | 28 | 3.8 | 4.9 | 0.079 | 4.8 | 0.13 | 0.21 | 0.14 | 0.073 |
| **ASA-220410-23** | 1.7 | 21 | 1.7 | 0.049 | 27 | 4.2 | 5.5 | 0.075 | 4.4 | 0.12 | 0.17 | 0.13 | 0.059 |
| **ASA-220410-24** | 2.3 | 21 | 2.2 | 0.045 | 23 | 4.0 | 4.6 | 0.112 | 6.7 | 0.13 | 0.22 | 0.13 | 0.086 |
| **ASA-220410-25** | 2.2 | 37 | 0.14 | 0.048 | 1.5 | 2.4 | 1.3 | 0.188 | 15 | 0.14 | 0.26 | 0.012 | 0.085 |
| **ASA-220410-26** | 1.9 | 33 | 0.14 | 0.044 | 0.84 | 6.2 | 1.5 | 0.151 | 16 | 0.14 | 0.33 | 0.027 | 0.100 |
| **ASA-220410-27** | 2.4 | 35 | 0.47 | 0.041 | 0.99 | 4.0 | 0.86 | 0.084 | 16 | 0.14 | 0.29 | 0.022 | 0.089 |
| **ASA-220410-28** | 2.7 | 22 | 1.3 | 0.049 | 22 | 6.2 | 3.4 | 0.068 | 6.0 | 0.13 | 0.34 | 0.081 | 0.062 |
| **ASA-220410-29** | 2.8 | 22 | 1.2 | 0.044 | 21 | 6.3 | 3.4 | 0.074 | 6.0 | 0.13 | 0.34 | 0.079 | 0.061 |
| **ASA-220410-30** | 2.8 | 22 | 1.2 | 0.045 | 21 | 6.2 | 3.5 | 0.074 | 6.2 | 0.14 | 0.34 | 0.079 | 0.062 |
| **ASA-220410-31** | 3.5 | 27 | 0.42 | 0.042 | 10 | 7.1 | 2.2 | 0.13 | 8.9 | 0.14 | 0.36 | 0.038 | 0.082 |
| **ASA-220410-32** | 2.4 | 27 | 0.48 | 0.043 | 11 | 7.4 | 2.4 | 0.14 | 8.5 | 0.13 | 0.32 | 0.047 | 0.077 |
| **ASA-220410-33** | 2.4 | 24 | 0.41 | 0.039 | 16 | 6.4 | 3.8 | 0.12 | 8.2 | 0.12 | 0.30 | 0.040 | 0.067 |
| **ASA-220410-34** | 5.6 | 27 | 0.012 | 0.036 | 1.8 | 6.6 | 0.11 | 0.54 | 16 | 0.18 | 0.19 | 0.009 | 0.11 |
| **ASA-220410-35** | 5.4 | 27 | 0.008 | 0.043 | 4.5 | 6.4 | 0.15 | 0.56 | 16 | 0.17 | 0.19 | 0.012 | 0.10 |
| **ASA-220410-36** | 5.4 | 27 | 0.005 | 0.040 | 3.8 | 6.3 | 0.15 | 0.57 | 16 | 0.17 | 0.19 | 0.012 | 0.10 |
| **ASA-220410-37** | 2.7 | 26 | 0.12 | 0.045 | 18 | 5.7 | 2.3 | 0.07 | 6.7 | 0.12 | 0.32 | 0.062 | 0.060 |
| **ASA-220410-38** | 1.5 | 26 | 0.12 | 0.047 | 22 | 5.6 | 2.0 | 0.061 | 6.3 | 0.12 | 0.28 | 0.070 | 0.048 |
| **ASA-220410-39** | 1.7 | 27 | 0.13 | 0.046 | 19 | 5.8 | 2.1 | 0.073 | 6.7 | 0.12 | 0.29 | 0.066 | 0.062 |