Affinity of Dual Energy X-ray Transmission Sensors on Minerals Bearing Heavy Rare Earth Elements

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ABSTRACT

This work demonstrates the effective use of automatic sensor-based sorting technology as a viable separation method for rare earth element (REE) rich ores composed primarily of xenotime minerals with gagarinite-(Y) and fluocerite-(Ce, La) inclusions. A dual energy x-ray transmission (DE-XRT) sensor affinity was used to evaluate forty-two heavy rare earth element (HREE) ore grab samples from the Madeira deposit. These samples and separated products were scanned by the sensor under many operating parameters. Subsequent analyses, including petrographic and multi-element chemical analyses were performed on the grab samples. Specific mass tests were also compared with energy attenuation curves from the sensor, which correlated strongly with every concentration stage – the highest achieved density being 3.01g/cm³. The best estimated HREE recovery from laboratory-scale sorting of the samples identified by the sensor was effectively 100%, however this occurred in conjunction with a mass recovery equal to 97% of the feed. Such results are expected knowing that the sample method was not entirely representative. Ongoing research into automatic sorting technology for the upgrading of Brazilian ores is being performed by the Federal University of Rio Grande do Sul (UFRGS), Brazil.

KEY-WORDS: DE-XRT, rare earth elements, attenuated energy x-ray, sensor-based sorting equipment

1. INTRODUCTION

Pre-concentration of mineral ores through the use of sensor based sorting (SBS) technology offers many avenues for improving mine productivity and profitability. First, it reduces the amount of material which must be crushed, screened and processed downstream, thereby reducing the waste processed by the mineral processing plant and stored in tailings ponds after processing. Second, it reduces the water requirements during the beneficiation processing. Third, since both the amount of waste material and the water are reduced in the processing steps, it also reduces the electrical consumption of the mineral processing plant. Fourth, the drastic reduction of tailings dam size and processing water/electric requirements may critically reduce the complexities involved with permitting and reclaiming mining operations, thus reducing the cost of the entire operation[1-4]. Alternatively, this
process could increase the productivity for an existing operation through upgrading the ore feed grade and eliminating waste or sub-economic ore being processed.

Due to the high cost of SBS equipment, prospective distributors of automatic sorting equipment recommend a run of mine (ROM) production capacity requirement equal or superior to 300 kt per annum to be economic [5]. Currently in Brazil, there are ten sorting equipment operations: nine are installed in mining facilities and one is dedicated to wood classification [5]. The mining facilities known to implement SBS equipment are primarily limestone, quartz, and talc operations that use image (camera) or near infrared (NIR) sensors.

This research investigates the practicality of dual energy x-ray transmission (DE-XRT) SBS to ores that bear rare earth elements (REE). These are initial investigations as part of the pioneering work on evaluating sorting technology for beneficiating REE bearing ores. Thus far, researchers have only investigated this technology on artificial generated REE samples [6, 7].

The REE ore samples used in this study were sourced from the Madeira/Pitinga deposit in Brazil. This heavy REE (HREE) anomaly has been previously studied and indicated as an ideal ore body for rich HREE supply for Brazil [8-11]. While this deposit is the focus of the study, other deposits have been found with similar characteristics and could be applicable for the use of this technology [12].

1.1 SBS OPERATING PRINCIPLES

Generally, SBS technology operation analyzes and classifies particles without having invasive contact with the material. Signals from the sensors are analyzed by computer to determine the unique properties of each particle and classify them against predetermined thresholds for levels of product or waste material content [13, 14]. After the product streams of particles are determined, physical separation of the particles is carried out by compressed air ejector nozzles or mechanic ejection systems (flaps) [13, 15].

The SBS process involves four steps. First, the material is crushed and screened to uniform size before being transported to the sensor via a small conveyor belt. Then, it is exposed to the sensor and scanned for its material properties. The data from the scan is then passed to the computer data analysis, and finally the material is separated through a metal flap [16].
Figure 1. SBS operating layout

Figure 1 illustrates the four steps along with the functionality of the equipment installed in the Laboratório de Processamento Mineral (LAPROM) of Universidade do Rio Grande do Sul (UFRGS) [17, 18].

1.2 DUAL ENERGY X-RAY TRANSMISSION SENSOR PRINCIPLES

The DE-XRT sensor operates as a line scanner. Particles pass through x-ray radiation via conveyor belt and pixel data is generated for the field of view perpendicular to the direction of the conveyor belt movement. Data are generated from the resulting radiation energy signal that penetrates the object, and represent a direct measure of the x-ray energy transmitted as it passes through the sample material.

When a particle is exposed to a DE-XRT sensor, its signal is registered by x-ray scintillators, as illustrated in Figure 2. Scintillator crystals usually consist of Sodium Iodine (NaI) or Cesium Iodine (CsI), with dimensions of 0.2 to 0.1 mm in width, and 0.6 to 0.1 mm in length with a 3 mm beam thickness [5, 19]. Photodiodes are often made of silicon doped up with phosphorus (P) and act as a signal amplifier [20].
While DE-XRT implies dual or two x-ray sources, in reality there is only one x-ray energy source. This source, however, produces a spectrum of energy which is segregated into low or high energy intensity levels through the use of the scintillators and the filter metal (0.6 mm Cu sheet).

The attenuated energy is then captured as pixel data and sent for post-processing via an integrated software. The software receives this information as an electromagnetic spectrum energy disturbance in which the signal intensity $I$ is given by Equation 1 [21, 22].

Equation 1

$$ I = \frac{I_{\text{det},n}}{I_{0,n}} = e^{-\mu_{m,n}(\lambda)pd} $$

Where,

$I_{\text{det},n}$: detected signal intensity
$n$: number of particles
$I_{0,n}$: initial signal without disruption
$e$: Euler number
$\mu_m$: mass absorption coefficient
$\lambda$: wave length
$\rho$: object density
$d$: irradiated object thickness

2. MATERIALS AND METHODS

Laboratory-scale DE-XRT SBS equipment was used to perform multiple sorting simulations on 42 sample particles. Complementary validation of detected particles was conducted through multi-element, petrographic, and specific mass analyses that were subsequently performed on the separated samples. The specific mass analysis was performed using a gas helium (He) multi-pycnometer to ascertain if the particles detected by the SBS equipment were of high equivalent specific mass, since these particles were also higher in xenotime mineralization.

2.1 SAMPLES

The samples studied were taken from the Madeira deposit. The total sample mass is represented by 42 particles of size ranges between 10 and 5 cm (longest axis). Observation of the samples under a microscope indicated the presence of pegmatite rocks, which are rich in xenotime with gagarinite-(Y) and fluocerite-(Ce, La)
inclusions, core albite-enriched granite (CAG), border albite-enriched granite (BAG), and albite rock (waste).

More information about these identifications and their relevance to REE concentration may be found in [7-10]. For the purposes of this study, the REE contents are ranked from richest to lowest as xenotime, CAG, BAG, and waste.

It is important to note that the investigated material does not represent the Madeira deposit in its totality. Therefore, this should be characterized as an exploratory study as it would be illogical to infer that the sample material demonstrates statistical representativity of a mining operation at the madeira deposit.

2.2 SENSOR-BASED SORTING TESTS

2.2.1 OVERALL METHOD

The sorting equipment used for this study was a COMEX Lab-sorter MSX-400-VL-XR: multichannel scanning system [23]. While other sensor analysis systems exist on the equipment [24], only the DE-XRT sensor was used. Actual mechanical separation of the particles was not performed, enabling the simultaneous simulation of many different sorting thresholds to be analyzed.

The following equipment operation parameters were constantly maintained: supply voltage of the x-ray source, belt speed of (0.5 m/s), and linear scan angle (75 degrees). The particles were presented to the DE-XRT sensor by the conveyor belt in a random order. Images were analyzed by the DE-XRT sensor through a dynamic pixel scale. Multiple scans of each sample were made to ensure that the results were repeatable.

The system was operated by a control unit, which was housed in an industrial computer. Operators set separation criteria through software calibration of scanned images. Operator calibrations were tested multiple times to determine the most ideal threshold settings for each simulated sorting of the material.

All sorting tests were replicated four times to ensure repeatability, which occurred without error, obviating the need to analyze the averages of the results in this case.

2.2.2 DE-XRT CALIBRATION METHOD

The DE-XRT sensor calibration is exemplified below in Figure 3, which shows two radiographic images (1 and 2), referring to higher and lower energy intensity values (variable I in Equation 1) for the particles scanned.
Figure 3. Calibration image obtained by x-ray sensor of the investigated material.

The image treatment by the software allows using a false color scale, which shows high density particle volumes in yellow, intermediate density particle volumes in red, and low-density particle volumes in blue.

2.2.3 SORTING METHOD

The images illustrated in Figure 4, represent the results of a sequence of simulated sorting tests. The pixels registered with the attenuated energy levels in a relative color scale, making the range of image values unique to the sample set Figure 4-f).

First, the particles were all placed on the conveyor belt together, scanned, and the selection criteria of the equipment was set to its highest threshold (Figure 4-a). The sorting calibration algorithm identified the first particle to be separated by a red box (middle left of Figure 4-a). This particle was considered concentration 1. Then, the previously identified particle was removed, and the remaining particles were rescanned (Figure 4-b). A new calibration threshold was established for the remaining particles, which in this case identified three particles (near the top left). These particles were considered concentration 2. Finally, the process was repeated (Figures 4-c through 4-e), identifying additional particles and creating new concentrations in each case until only one particle remained without being categorized to a threshold.
(the blue particle without a red boundary located in the lower left corner of Figure 4-e).

Figure 4. Detection sequence from high (a) to low (e) calibrated thresholds with color scale (f).

The process as illustrated in figure 4, above, was repeated four times to ensure that the equipment selected the same particles every time and that there was no bias due to the position of particles on the conveyor belt relative to the sensor. Figure 4-f shows the false color scale used to display the equivalent relative density characteristics of the particles.

Only 22 samples were used for calibration purposes, the remaining samples were subsequently sorted based on the calibration.

2.3 MULTIELEMENT CHEMICAL ANALYSIS

After the sorting tests were completed, multi element chemical analyses of the samples were performed by Actlabs – Activation Laboratories LTD, a laboratory located in Canada. The multi element chemical analysis tests were performed using mass spectroscopy with inductively coupled plasma (ICP-MS), and were repeated thrice for each sample.

2.4 PETROGRAPHIC ANALYSIS

Petrographic description of some of the samples by thin sections was done by the Instituto de Geociências (IGEO) from UFRGS. This was done to evaluate the presence of xenotime and classify the minerals as either xenotime, BAG, CAG or
albite rock. The petrographic analysis also aimed to evaluate Thorium and Uranium contents pertaining to the detection results.

2.5 GAS MULTI-PYCNOmeter ANALYSIS

Gas multi-pycnometer analysis verifies the specific mass of a material using the Archimedes principle [25]. A MUP-5DC model multi-pycnometer was used with Helium gas. The material used in the multi-pycnometer was taken from samples of each concentration (samples removed from the conveyor belt after each calibration), which were prepared to between 5 mm and 1 cm particle size.

3. RESULTS

3.1 DE-XRT IMAGE ANALYSIS

DE-XRT image analysis of the scanned particles using built-in software revealed that the equipment was capable of characterizing the samples into one of three classification zones, denoted by the two red lines (Figure 5). These zones were defined by the operator and represent strong statistical differences between one another. Zone 1 matches the xenotime sample and corresponds to the threshold set in Figure 6-a. Zone 2 represents the complete gambit of BAG and CAG samples and corresponds to the threshold values of figures 6-b through 6-e. Zone 3 corresponds to the albite-rock sample and corresponds to the particle that is not identified by a red box in any of the figures 6-a through 6-e.

![Figure 5. Percent of attenuated X-ray energy (relative) vs. percent of sample area (in pixels) for the calibration samples. Samples were labeled as LI, LII, LIII, LIV, LV, LVI and numbered 1 through 6 with duplicate samples given by ()](image)

3.2 MULTI-ELEMENTAL ANALYSIS

Results from the multi-elemental analyses are shown in Table 1. From Table I, aptitude of the sensor for REE particle detection is demonstrated, since effectively
100% of the light rare earth elements (LREE) and HREE contained in those samples is indicated by the sensor. In addition, as each concentration generally shows a smaller increase in REE concentration than its predecessor (the exception being for the La and Ce for concentrations C2 and C3), the results indicate that higher thresholds are effective at selecting the particles richest in REE.

Table 1. Percent metallurgical recovery of REE detected by the DE-XRT sensors.

<table>
<thead>
<tr>
<th>Detection Stages</th>
<th>HREE</th>
<th>Light rare Earth elements - LREE</th>
<th>Heavy rare Earth elements - HREE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Feed</td>
<td>100</td>
<td>100 100 100 100 100 100</td>
<td>100 100 100 100 100 100</td>
</tr>
<tr>
<td>Concentration 1 (C1)</td>
<td>69</td>
<td>52 54 58 62 64 65</td>
<td>65 67 68 69 70 70 69</td>
</tr>
<tr>
<td>Waste 1 (W1)</td>
<td>31</td>
<td>48 46 42 38 36 35</td>
<td>35 33 32 31 31 30 30 31</td>
</tr>
<tr>
<td>Concentration 2 (C2)</td>
<td>24</td>
<td>19 18 20 20 22 22</td>
<td>24 23 22 21 20 18 18 17</td>
</tr>
<tr>
<td>Waste 2 (W2)</td>
<td>7</td>
<td>30 27 23 18 15 13</td>
<td>11 11 11 10 11 12 12 14</td>
</tr>
<tr>
<td>Concentration 3 (C3)</td>
<td>5</td>
<td>20 19 16 12 10 9</td>
<td>8 7 7 7 7 8 8 9</td>
</tr>
<tr>
<td>Waste 3 (W3)</td>
<td>2</td>
<td>9 9 7 5 4 4</td>
<td>3 3 3 3 4 4 4 4 5</td>
</tr>
<tr>
<td>Concentration 4 (C4)</td>
<td>1</td>
<td>5 5 4 3 2 2</td>
<td>2 2 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Waste 4 (W4)</td>
<td>1</td>
<td>5 4 3 2 2 2</td>
<td>2 2 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Concentration 5 (C5)</td>
<td>1</td>
<td>4 4 3 2 2 2</td>
<td>2 2 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>Final Waste (W)</td>
<td>0</td>
<td>0 0 0 0 0 0</td>
<td>0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

Table 1 represents the multiple sorting concentration simulations. To obtain the true recovery for a concentration number, its recovery value must be added with all previous concentrations. For example, concentration 2, which contained 24 percent of the element Y on its own, would in reality contain concentration 1, which contained 69 % of Y, leaving only 7 % of Y remaining, which is given by the Y column of the Waste 2 row.

Metallurgical recovery represents the ratio (in percentage) of the REE mass value recovered in the concentrate (C1 through C5) to 100% of the same REE found in all feed [26]. Figure 6 illustrates Table 1 to express the behavior of the metallurgical recovery of the elements of interest in each of the concentrations, labeled as C1 through C5, and the final waste (W).
Figure 6. Metallurgical recovery of the five simulated concentrations (C1-C5) and waste (W).

Considering the difference between C1, which falls under zone 1, and all other concentrations C2 through C5, figure 6 further confirms the ability of the sensor to select the particles richest in REE. With the exception of elements La and Ce, the threshold for separating concentration C2 was also effective at separating particles with the next highest REE concentrations after those of C1. However, C4 and C5 yielded similar results in terms of their REE composition despite having different calibration thresholds. This suggests that there are some limitations to the accuracy of the equipment for separating particles of nearly the same REE concentration. Results from the specific mass tests by the helium multi-pycnometer also confirm this issue.

A metallurgical accumulated recovery evaluation quantifies the percentage of LREE and HREE for every calibration setting. Accordingly, C2 represents the result of the best suggested calibration setting for HREE recovery, although further economic evaluation would be needed to confirm its viability. Table 2 presents the content values (grades), accumulated content (accumulated grade), metallurgical recovery, and accumulated mass recovery for every simulated concentration. The outcome also shows that the third stage allows a metallurgical recovery of 94% for LREE and 96% for HREE, which were recovered along with a total of approximately 66% of the mass of the samples tested. Here it is important to note that the sample mass was not representative of the mining operations and heavily biased CAG and BAG representation. Thus, the mass recovered for a true ROM of the deposit would likely be much less than 66%, in effect rejecting considerably more than 34% of the mass, thus resulting in much better overall effectiveness of the sorting operation.
Table 2 Accumulated content, metallurgical recovery and accumulated mass recovery in the studied concentrations.

<table>
<thead>
<tr>
<th>Content (ppm)</th>
<th>Accumulated Content (ppm)</th>
<th>Metallurgical Accumulated Recovery</th>
<th>Accumulated Mass Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>LREE</td>
<td>HREE</td>
<td>LREE*</td>
<td>HREE*</td>
</tr>
<tr>
<td>C1</td>
<td>9,024.3</td>
<td>107,490.0</td>
<td>9,024.3</td>
</tr>
<tr>
<td>C2</td>
<td>883.2</td>
<td>9,895.8</td>
<td>9,907.5</td>
</tr>
<tr>
<td>C3</td>
<td>160.2</td>
<td>622.5</td>
<td>10,067.8</td>
</tr>
<tr>
<td>C4</td>
<td>98.3</td>
<td>368.2</td>
<td>10,166.0</td>
</tr>
<tr>
<td>C5</td>
<td>154.7</td>
<td>700.4</td>
<td>10,320.7</td>
</tr>
</tbody>
</table>

*LREE: Light rare Earth elements; ** HREE: Heavy rare Earth elements.

Figure 7 shows the behavior of the accumulated metallurgical recovery for the simulated concentrations C1 to C5 (data shown in Table 2). The curve on the graph emphasizes a low mass recovery in the first stage, but the average level of HREE and LREE is superior to 60% (LREE) and 67% (HREE). C3 increases the REE content between 94% and 96% for LREE and HREE, respectively. However, should the recoveries of C3 not be high enough, C4 effectively showed a recovery of ~98% in 86% of the mass. Therefore, it should be noted the SBS equipment serves to separate into a product and a waste stream so that the REE remaining in the feed material is essentially unaltered.

The average contents shown from the multi elemental chemical analysis corroborate with the literature that characterizes the Madeira deposit [27-30], which substantiates that HREE are more present than LREE.

When considering the characteristics of the simulated concentrations, their REE contents differ on a logarithmic scale but follow similar patterns across the

Figure 7. Metallurgical recovery in function of the recovered mass.
different elements analyzed. Figure 8 shows the REE grades in the minerals separated for each simulated concentration.

Figure 8. Distribution of the LREE and HREE contents in each concentration.

In figure 8, C1 differs greatly from C2, which also differs greatly from C3, C4 and C5. There is very little difference in the REE contents of C3, C4 and C5 between themselves. This implies that the samples contained in these concentrations are very mineralogically similar.

Taking an exploratory interpretation of the cumulative contents of each concentration, which are shown in Table 3, the capacity of the DE-XRT sensor to selectively detect REE particles can be evaluated. It is noted that REE detection is possibly affiliated with the presence of minerals rich in Sn, Ta, Nb and Zr (metallic ores), as well as Th and U (thorite)[31].

Table 3. Metallurgical recovery, mass recovery, and contents of the LREE, HREE, Th and U.

<table>
<thead>
<tr>
<th>Origin</th>
<th>LREE (ppm)</th>
<th>HREE (ppm)</th>
<th>Ores (ppm)</th>
<th>Th+U (ppm)</th>
<th>Metallurgical Recovery LREE (%)</th>
<th>Metallurgical Recovery HREE (%)</th>
<th>Simple Mass Recovery</th>
<th>Accumulated Mass Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>514.8</td>
<td>5,113.6</td>
<td>7,695.8</td>
<td>965.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C1</td>
<td>9,024.3</td>
<td>107,496</td>
<td>3,787.0</td>
<td>2,327.0</td>
<td>1.6%</td>
<td>7.9%</td>
<td>3.3%</td>
<td>3.3%</td>
</tr>
<tr>
<td>C2</td>
<td>883.2</td>
<td>9,895.8</td>
<td>7,612.1</td>
<td>1,319.7</td>
<td>11.2%</td>
<td>15.5%</td>
<td>11.6%</td>
<td>14.6%</td>
</tr>
<tr>
<td>C3</td>
<td>160.2</td>
<td>622.5</td>
<td>8,884.3</td>
<td>1,004.9</td>
<td>59.1%</td>
<td>53.3%</td>
<td>51.2%</td>
<td>65.8%</td>
</tr>
<tr>
<td>C4</td>
<td>98.3</td>
<td>368.16</td>
<td>6,859.9</td>
<td>586.2</td>
<td>18.0%</td>
<td>12.3%</td>
<td>20.2%</td>
<td>86.0%</td>
</tr>
<tr>
<td>C5</td>
<td>154.7</td>
<td>700.36</td>
<td>6,974.4</td>
<td>960.7</td>
<td>9.9%</td>
<td>10.9%</td>
<td>11.0%</td>
<td>97.0%</td>
</tr>
<tr>
<td>W</td>
<td>7.2</td>
<td>34.17</td>
<td>307.4</td>
<td>29.5</td>
<td>0.1%</td>
<td>0.1%</td>
<td>3.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

The mass recovery of the combined concentration of C1 and C2 represents a good metallurgical recovery, with over 70% of the LREE and HREE, and a low metallurgical recovery of ores rich in Sn, Ta, Nb, Zr, Th and U. Data of the
metallurgical accumulated recovery of the LREE, HREE, metallic ores and thorite are evidenced in Figure 9.

![Figure 9. Accumulated metallurgical recovery of the LREE, HREE, metals (Sn, Ta, Nb and Zr), Th and U in each concentration (C1 through C5) and waste (W).](image)

The distinction between samples rich in REE and those rich in metallic elements, Th and U can be found in Bastos Neto, et al. (2014), where they state the deposit mineralization consists of cassiterite (SnO₂), pyrochlore with columbite (Nb₂O₅, Ta₂O₅) and zircon (ZrSiO₄), and that pyrochlore associated with zircon contains U and Pb, and these might be associated with thorite ((Th,U)SiO₄). Thus, it can be inferred that the metallurgical recovery of the metallic elements (Sn, Ta, Nb and Zr) occurs in conjunction with Th and U recovery. At concentration C3, as is shown in Figure 9 above, recoveries of the metallic ores as well as Th and U jump by over 50%. These findings confirm the possibility of effective separation of REEs from metallic elements, Th and U through SBS of these ores.

### 3.3 PETROGRAPHIC ANALYSIS

As previously mentioned, xenotime (YPO₄) is the primary host mineral of REE ore in the Madeira mine. It was found in a considerably larger quantity in the first two concentrations (C1 and C2). This information is aligned with the higher quantity of HREE found in their chemical analyses. Xenotime is dispersed in the rock as phenocrysts, which are prematurely formed minerals with sizes between 0.5 to 2 cm, and that, by having more time to crystallize, present a contrasting size to the rest of the rock matrix. These phenocrysts occur as isolated crystals, clusters, and/or interbred with other minerals. The figures 10-a and 10-b show the xenotime presence in the rock structure and low presence of thorite. These figures were created from material in concentrations C1 and C2 was used for figure 10-c).
Figure 10. Thin sections from the sample minerals for xenotime (xtm) identification in natural transmitted light.

The xenotime inclusions are regular – being composed of feldspar, cryolite or mica, gagarinite-(Y), fluocerite-(Ce, La), pyrochlore and thorite (Figure 11-a). Polylithionite is common with oxide filled cleavage. In the matrix, albite is dominant in correlation to the microcline, dominating the quartz.

For concentrations C3 to C5, the pattern texture of granite albite from Madeira is observed along with variations that later affected it, such as hydrothermal events or percolation of corrosive fluids loaded in fluorine. The texture is equigranular: composed of a matrix with an average particle size that is quartz-feldspathic with predominant albite in correlation to the microcline, that, by its turn, predominates the quartz.

Phenocrysts of the feldspar were commonly changed to white clays and corroded, indicating hydrothermal events. The later quartz includes matrix minerals. Polylithionite is common, making it possible to see biotite alteration. Cryolite is abundant as an actor disseminating and corroding the matrix minerals. Zircon and columbitized pyrochlore are common (Figure 1-b). Riebeckite and biotite have variable abundancy, from non-existence and up to 5% of abundance. Fluorite occurs inside the altered micas by fluids that originated by percolating preferentially in the mica cleavage and precipitating the fluorite in these weak points.
Figure 11. Samples from concentrations C3, C4 and C5 (a, b, c) in natural light (a, c), transmitted (b) and waste (d).

The W or waste sample is basically composed of albitite (Figure 11-d). It is a medium equigranular rock with feldspar crystals without any preferential orientation. This mineralogy is considered waste at the Madeira mine.

3.4 SPECIFIC MASS

The x-ray energy transmission data of the studied material are inversely proportional to the bulk density of the particles when correlated to the specific mass, considering that higher cumulative color values by sample area (in pixel units) represent lower specific mass.

Specific mass data shows that the DE-XRT sensor allowed for the removal of samples from high to low density. Table 4 was based on gas multi-pycnometer analysis of material from each concentration, where each stage mass (C1 through C5 and waste W) presented a coherent specific mass value.

Table 4. Specific mass values of the concentrations (C1 through C5 and waste W) by gas multi-pycnometer.

<table>
<thead>
<tr>
<th>Stages</th>
<th>( \rho_{\text{medium}} ) (g/cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>3.01</td>
</tr>
<tr>
<td>C2</td>
<td>2.82</td>
</tr>
<tr>
<td>C3</td>
<td>2.66</td>
</tr>
<tr>
<td>C4</td>
<td>2.50</td>
</tr>
<tr>
<td>C5</td>
<td>2.54</td>
</tr>
<tr>
<td>W</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Figure 12-a shows the equivalent energy values in order of the color percentage by area of each particle measured in every pixel configuring attenuated energy curves of the x-ray sensor. The curves show that as the attenuation of the x-ray energy is higher, the projected values in the ordinated axis are lower. Its inverse is proportional to the attenuated energy increase. In this content, it is easily seen that the higher energy reflects the waste (W) mass.
Specific masses, from stages C4 and C5, present similar values. In C1, C2 and C3, a bigger difference of these energy levels can be seen. The specific mass values printed in Figure 12-b affirms the highest density at 3.01 g/cm³ in the C1 stage, presenting coherence with the energy attenuation from the x-ray. The same behavior can be noticed in the C2, C3, C4, C5 and W stages that have densities of 2.82, 2.66, 2.50, 2.54 and 2.0 g/cm³, respectively. Until this point, it is possible to clearly see that the attenuated energy of the REE ores depend directly on the specific mass of the particles.

In particular, the medium energy levels of the masses in stages C4 and C5 present practically the same density compared to the medium specific mass values and the attenuated energy levels, which justify a possible overlap or variation in the graphic curves above when analyzing its levels of attenuated energy. It is possible to infer that equipment configurations might be adjusted to avoid albrite rocks (W) in the process, or, simply, make the particles of the rare earth elements (C1 to C2) part of the process with the minor presence of other mineral ores.
CONCLUSION

The purpose of this work was to assess an SBS DE-XRT sensor for separating real xenotime hosted REE ores and evaluate the results of sorting based on the same sensor. The concentrates made by the sorter were analyzed by multi-elemental chemical analysis, petrographic analysis, and gas pycnometer.

The calibration images (Figure 3) allowed identification of different densities in the investigated groups using a hierarchic color scale. The calibration curve allowed the study to deduce the existence of three permissive detection zones, evaluated by the cumulative percentual quantification of the color concentration of each particle's area in pixels (Figure 5).

The multi-element chemical analysis results showed that the xenotime hosts significant quantities of both HREEs and LREEs. The first concentrations, C1 and C2, contained over 70% of the REE contents of the samples and only 15% (Figure 9 and Table 3) of the total mass of the sample. Results also showed that REE grades of each concentration followed a consistently decreasing trend across all elements for the first three concentrations (Figure 8). The first concentration (C1) contained less than 0.25% combined Th and U, and less than 0.4% metallic ((Sn, Ta, Nb and Zr) contents, showing that it is possible to separate REEs from all other product streams.

Comparing the chemical characterization data with the petrography, it was possible to infer that the rich xenotime rocks were readily detectable by the DE-XRT sensor. The petrography analysis also confirmed the pegmatite’s mineralogical matrix clasts, the characteristic presence of the metallic elements, and the character of the waste rock.

As for the gas multi-pycnometer, tests compared with the DE-XRT sensor data proved the detection capacity of the sensor for REE rich ores, showing that the higher attenuated energy level is the result of the clasts with the higher specific mass, rich in xenotime (Figure 12).

In conclusion, the DE-XRT sensor showed the ability to detect xenotime clasts, and sort them effectively into their own product stream from the grab samples provided for this study. Further work, including sorting tests that involve a more representative sample and an economic analysis of the potential product streams and equipment cost is required to further verify these findings and determine the suitability for the sensor to such a sorting processing for an industrial scale operation. These tests would need to address the issues of sample representation, machine operation without operator oversight, and the cost trade-off of the value stream added by SBS.
ACKNOWLEDGMENTS

The authors would like to thank CNPq, LAPROM and IGEO-UFRGS, Mineração Taboca and the Federal Institute of Amapá (IFAP). Their contributions and encouragement helped to develop, initiate, support and collaborate this research. The last institution, IFAP, specifically, helped support the graduation of the doctoral candidate throughout the process of this work.

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