

# Recycling of Rare Earth Elements Contained on Fluorescent Lamps by Hydrometallurgical Processing

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## ABSTRACT

Fluorescent lamps have in their constitution a mixture of halophosphates, usually calcium phosphate, and of phosphors formed by rare earth elements (yttrium, europium, lanthanum, cerium, terbium and gadolinium). Despite multiple industrial plants of fluorescent lamps recycling already exist, most of them are still not capable of recovering rare earths, due to the high complexity and cost of the available processes.

This work is focused in the optimization of the solubilization of rare earths coming from spent fluorescent lamps, using a process that includes 3 individual hydrochloric acid leaching steps, and a heat-treatment before the last leaching step. The leachate was chemically analysed, and the solid residue was characterized structural and morphologically to evaluate the evolution of samples along the process.

The separation of the process in various steps allowed the sequential solubilisation of phosphors. In the first step, a 2 M HCl solution at 25°C for 1 h, was capable of solubilizing almost 100% of the calcium phosphate, and less than 15% of yttrium and europium. In the second step, a 2 M HCl solution at 60°C for 1 h, solubilized more than 90% of YOX and around 25% of gadolinium. Heat-treatment at a temperature higher than 200°C increases the solubilization of La, Ce and Tb. After a heat-treatment at 200°C and leaching with a 6 M HCl solution at 90°C for 9 h, more than 90% of the rare earth elements were solubilized.

**Keywords:** Fluorescent lamps; Rare earth elements; Recycling; Leaching; Heat-treatment.

## 1. INTRODUCTION

Rare earth elements (REEs) were classified by the International Union for Pure and Applied Chemistry (IUPAC) as a group of 17 elements, that include the 15 lanthanides, scandium and yttrium, because of their similar physical and chemical properties [1].

Despite the name, most REEs are not rare, with some existing in a relatively high amount in the Earth's crust. In 2017, the U.S. Geological Survey estimated that the global rare earth reserves were approximately 120 000 thousand metric tons [2]. The reasons for the classification of these elements as rare are two-fold, the first is related to the fact that most processes to separate REEs are complex, making their refining more difficult than for other metals [3], while the second is due to the localization of most know deposits in only a handful of countries [2].

To aggravate the problem, China was able to monopolize this market, being responsible for 85% of all REE production, and is also the major manufacturer of products that incorporate these elements, with fluorescent lamps being one example [4]. The current REE market makes the establishment of new rare earth mining operations extremely complicated, due to the high amounts of capital required [5].

However, some REEs are rarer than others, with demand for each element being driven by technological advancements. Currently, dysprosium, europium and terbium are some of the REEs in lower supply.

The imbalances inside this category of materials is attributed to the mined ores containing a larger amount of light REEs in comparison to heavy REEs, resulting in the oversupply of the first [1].

REEs are present in a variety of areas, such as: permanent magnets; petroleum refining and automotive catalysts; metallurgical additives and alloys; glass polishing; ceramics; lighting applications; and battery alloys [6].

The importance of REEs, lead the European Commission to incorporate them in the Raw Material Initiative, which highlights the importance of both primary and secondary production to support current demand. Because of the long life-cycle of most rare earth products, recycling needs to be considered as a long-term investment with great importance to achieve a more balanced market [7].

## 2. FLUORESCENT LAMP RECYCLING

Fluorescent lamps are primarily composed of glass, followed by plastic, and with only a small concentration of metals. The amount of glass in a lamp constitutes at its minimum 50% of the lamp. Compared with the amounts of these materials, the quantity of phosphors corresponds only to a small fraction [31].

The exact amount of rare earth phosphors in a fluorescent lamp will vary between each lamp category. Compact fluorescent lamps (CFLs) can have between 1.5 g to 1.125 g of phosphors in a single lamp, 60 % of each composed by rare earth oxides (REOs). The amount of phosphors in linear fluorescent lamps (LFLs) can range from 3 mg/cm<sup>2</sup> to 4 mg/cm<sup>2</sup>, with different percentage of REOs depending on lamp efficiency [5].

The most common rare earth phosphors are the red phosphor Y<sub>2</sub>O<sub>3</sub>:Eu<sup>3+</sup> (YOX), the green phosphors LaPO<sub>4</sub>:Ce<sup>3+</sup>,Tb<sup>3+</sup> (LAP) and CeMgAl<sub>11</sub>O<sub>19</sub>:Tb<sup>3+</sup> (CAT), and the blue phosphors BaMgAl<sub>10</sub>O<sub>17</sub>:Eu<sup>2+</sup> (BAM) and (Sr,Ca,Ba,Mg)<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>Cl:Eu<sup>2+</sup> [8].

Some fluorescent lamps also contain the broad-band white emitter (Sr,Ca)<sub>10</sub>(PO<sub>4</sub>)<sub>6</sub>(Cl,F)<sub>2</sub>:Sb<sup>3+</sup>,Mn<sup>2+</sup> (halophosphate), that is mixed with YOX to obtain better colour-rendering. This phosphor has no REE in its constitution, and so, its intrinsic value is lower compared to REE bearing phosphors [8].

All gas-discharge lamps, including fluorescent lamps, require some concentration of mercury for the equipment to function. Legislation limits the amount of mercury in lamps, establishing a maximum value between 2.5 to 3.5 mg depending on the output of the lamps. Most current lamps use between 1.5 to 2.5 mg. However, in collection it is possible to find lamps with mercury content as high as 5 mg [9].

In general terms, secondary production of rare earth elements can be divided in 4 stages: collection; dismantling; separation; and processing. Three approaches can be considered for processing phosphors, the first being the reuse of the phosphor mixture for the manufacture of newer lamps, the second is based on the separation of the different phosphor compounds present in the lamp phosphor mixture, and the last approach aims to recover each individual rare earth element [8]. In the second approach, the complete dissolution of the phosphors is not required, and physicochemical separation methods are suitable to separate phosphors. The third approach is more complex, with the recovery of individual REEs being almost exclusive to hydrometallurgical methods, the most important being acid leaching, alkali fusion and solvent extraction [8].

The behaviour of each phosphor when leached with an acid solution is significantly different, with halophosphate being easily solubilized by cold diluted acids, followed by YOX, that can be dissolved

with strong acids at higher temperature ( $T \leq 90^{\circ}\text{C}$ ). Green and blue phosphors are more resistant to attack, normally requiring high temperature ( $T \geq 100^{\circ}\text{C}$ ) sulphuric acid, or molten inorganic salts [8]. The main aim of this work is to find optimal conditions for the recovery of the REEs present in fluorescent lamps utilizing primarily acid leaching.

### 3. EXPERIMENTAL

#### 3.1. *Preparation of the waste phosphor samples*

The waste phosphor used as samples in this work was provided by the Company Ambicare Industrial, S.A. that has a license to treat luminescent discharge lamps. To study procedures suitable for the recovery of REEs, Ambicare provided wet phosphor sludge (30 %wt water) to IST, that was then prepared for the following tests as described by Fonseca; J [54]. Summarizing, the sludge was continually divided in a lab sampler until the weight of the fractions reached 450 g. In this work, further divisions of these initial fractions were carried on a 16-position rotating divider (Microscal Spinning Riffler) to maintain the homogeneity between samples.

#### 3.2. *Particle size determination*

To determine the phosphor powder granulometry, samples were dry sieved using the standard sieve series established by the ISO 3310-1. In total nine sieves were used, starting with an aperture of 0.71 mm, with the aperture of the remaining sieves decreasing by the square root of 2 until the last sieve, with an aperture of 0.045 mm. The sieves were electromagnetically agitated (Retsch AS200) for periods of 15 min, until significant changes to the weight of powder in a single sieve stopped being observed. Since the %wt of phosphor collected in the meshless sieve was superior to 10 %, then the fraction of material found in the meshless and 0.045 mm aperture sieves was mixed and characterized by laser diffraction granulometry (Cilas 1064), to obtain more details of the fine fraction (phosphor particles smaller than 0.063 mm).

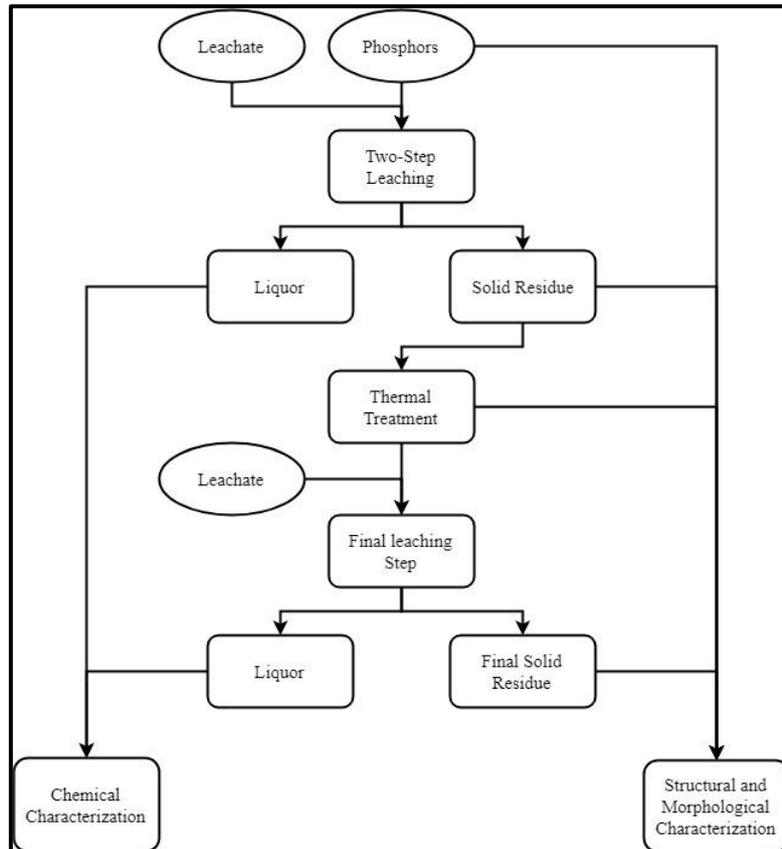
#### 3.3. *Hydrometallurgical processing*

The procedure followed during this work consist of a multi-step leaching coupled with a heat-treatment step. To increase the selectivity of the process, the procedure will start with two leaching steps, the first to remove calcium and the second yttrium. The solid material that did not react will pass through a calcination step before being leached again to recuperate the remaining REEs.

Hydrochloric acid (HCl 37 %wt Sigma-Aldrich) diluted in water was the solution used for all leaching steps, with a liquid/solid ratio of 10 L/kg, unless it is specified otherwise. All reagents present during the leaching tests and analytical procedures were of pro analyses grade. After every leaching operation, the resulting aqueous solution would be filtered, and the solid residue washed with demineralized water and dried at  $55^{\circ}\text{C}$  for a period superior to 12 h.

The leaching tests were carried out in an air heated oven, or in a chemical reactor, when the weight of the prepared phosphors was superior to 20 g. For the smaller samples, 200 mL glass round flasks were introduced in the oven, which provided temperature control ( $\pm 2^{\circ}\text{C}$ ) and orbital shaking ( $120 \text{ min}^{-1}$ ). As for the chemical reactor, heating was performed with an electromantle, agitated by a paddle impeller connected with an overhead stirrer. The heat-treatment was performed in ceramic crucibles, introduced

in a temperature-controlled oven (Prolabo). Figure 1 shows the flowchart of the followed experimental procedure.



**Figure 1 - Experimental procedure flowchart.**

To follow the evolution of reactions over time, whenever necessary, small aliquots of 3 mL were extracted from the pulp, centrifuged for 2 min at  $2000 \text{ min}^{-1}$ , with 2 mL of the dissolved product being diluted and stored for analyses in volumetric flasks.

A small fraction of residue was digested with sulphuric acid ( $\text{H}_2\text{SO}_4$  commercial, 98 %wt) for 1 hour at  $200^\circ\text{C}$ , to determine the initial composition of the phosphor mixture.

### 3.4. Material Characterization

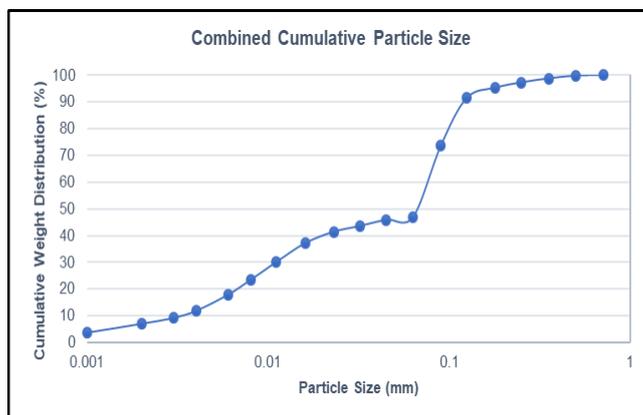
Inductively coupled plasma – atomic emission spectrometry (ICP-AES, Horiba Jobin-Yvon Ultima) was used to characterize the collected dissolved product, while X-ray diffraction (PANalytical XPERT-PRO diffractometer) and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM/EDS, JEOL JSM 7001F microscope, 15kV) were utilized to characterize the structure and morphology of selected solid residues.

## 4. RESULTS

### 4.1. Particle size

The sample used to characterize the particle size of the lamp phosphors weighed 18.3 g. Since, more than 15% of the particles have a size smaller than  $45 \mu\text{m}$ , material with a particle size inferior to  $63 \mu\text{m}$  was further characterized by laser diffraction granulometry.

The assembly of the two techniques creates a small discontinuity in the intersection of the results, seen in the cumulative particle size distribution in Figure 2. However, this assembly can still be viewed as an approximate representation of the particle size of the phosphor powder before the hydrometallurgical recovery is initiated.



**Figure 2 - Cumulative particle size distribution obtained by assembling the results from dry sieving and laser diffraction granulometry.**

#### 4.2. Hydrometallurgical recovery

A sample from a final solid residue was digested with sulfuric acid to determine the composition of the initial sample, which is shown in Table 1.

**Table 1 - Weight fraction of REEs, Al, Ca and Hg present in the phosphor initial sample.**

Element (wt%)	Y	La	Ce	Eu	Gd	Tb	Ca	Al	Hg
Initial Sample	13.95	1.50	0.98	0.83	0.33	0.43	13.92	2.17	0.03

To optimize the first leaching step, reactions were carried out for 6 h, simultaneous testing two different HCl concentrations, 2 M and 4 M, and reaction temperatures, 25°C and 60°C. The literature agrees that the previous conditions are only able to attack YOX and halophosphate, as such the ICP-AEC analyses of the obtained solutions will be focused on the evolution of calcium and yttrium during leaching. The results are expressed in Table 2.

As expected, an increase in efficiency can be observed when the acid is more concentrated and when the temperature increases. Also, none of the conditions was able to effectively attack the green and blue phosphors, with the extraction of Tb, Ce and La reaching only a maximum of 14%, 11% and 1% in the more aggressive conditions. Excluding Y and Eu, only Gd also reached higher yields.

**Table 2 - Yield of Ca, Y, Eu and Gd during the first leaching step.**

Element (wt%)	Ca				Y				Eu				Gd			
	0.5	1	3	6	0.5	1	3	6	0.5	1	3	6	0.5	1	3	6
2 M HCl @ 25 °C	76	85	93	74	4	6	22	29	-	-	-	38	-	3	-	5
2 M HCl @ 60 °C	83	86	81	78	25	57	93	110	-	-	-	98	-	11	-	47
4 M HCl @ 60 °C	86	86	87	83	75	90	93	87	-	-	-	88	-	21	-	81

A solution of 2 M HCl concentration reacting with the phosphors at 25°C for 1 h allows the process to have selectivity between YOX and halophosphate, therefore, for the remaining tests, these parameters will be chosen for the first leaching step.

After removing most of the halophosphate during the first leaching step, the second will focus in solubilizing Y and Eu. The previous tests showed that a 2 M HCl solution reacting for 3 h at 60°C can solubilize almost all Y and Eu. The yield of Y, Eu and Gd can be observed in Table 3.

**Table 3 - Yield of Y, Eu and Gd during the second leaching step.**

<i>Element (wt%)</i>	<i>Y</i>			<i>Eu</i>			<i>Gd</i>		
<i>Time</i>	0.5	1	3	0.5	1	3	0.5	1	3
<i>2 M HCl @ 60 °C</i>	99	95	98	83	84	95	14	20	44

It is observable that removing the halophosphate in the first leaching step increases the solubilization speed of YOX and Gd. During this step, the yield of La, Ce and Tb was less than 1%, 6% and 8%, respectively. Selecting a hydrochloric acid concentration of 2 M reacting at 60°C for 1 h enables the separation of Y and Eu from Gd, while ensuring that only small amount of the latter is lost.

After recovering YOX during the second leaching step, the solid residue is heat-treated to increase the recovery efficiency of La, Ce and Tb. The chosen temperature for the tests were 100, 125, 150, 175, 200 and 225°C. These samples, plus one that was only dried, were then leached using 4 M of HCl at 90 °C for 6 h, to compare their effectiveness.

The results didn't show differences between samples heat-treated at the same temperature for 1h or 3h, therefore, Table 4 will only show the results of a single heat-treatment duration for each sample.

**Table 4 -Yield of La, Ce, Tb and Gd for the different heat-treatments, during the standard last leaching.**

<i>Element (wt%)</i>	<i>La</i>			<i>Ce</i>			<i>Tb</i>			<i>Gd</i>		
<i>Time (h)</i>	1	3	6	1	3	6	1	3	6	1	3	6
<i>Dried</i>	2	10	28	10	22	40	12	-	40	72	-	102
<i>100 °C</i>	3	10	29	11	23	42	13	-	44	75	-	99
<i>125 °C</i>	3	10	27	11	23	42	13	-	43	78	-	100
<i>150 °C</i>	5	16	33	9	25	33	11	-	37	-	-	91
<i>175 °C</i>	6	17	34	10	28	33	12	-	37	-	-	92
<i>200 °C</i>	5	19	37	10	28	53	14	-	56	80	-	94
<i>225 °C</i>	6	33	49	12	44	68	16	-	73	83	-	99

The yield of Ce, Tb and Gd during the last leaching after 1 h of reaction is almost identical to the values observed after 6 h of reaction during the first leaching step using 4 M of HCl at 60°C. As for La, instead of identical, the yield during the last leaching is superior.

Increasing the heat-treatment temperature doesn't show noticeable increases of the yield of La, Ce, Tb and Gd for 1 h of leaching. This could indicate that by removing the halophosphate and YOX during previous steps, facilitates the solubilization of the remaining phosphors. As leaching time advances, in the case of Ce and Tb, from drying to heat-treatments at 175°C, the yield of both elements remains identical. For heat-treatments above 200 °C changes start to appear, and after 6 h of leaching, the yield of Ce and Tb increase with heat-treatment temperature.

As for the recovery of La, the results for drying and the heat-treatments at 100°C and 125°C are similar for the leaching tests of 6 h, only starting to increase for heat-treatments above 150°C. Variations in the

temperature of the heat-treatment don't seem to affect the behaviour of Gd during the last leaching step. For all the previous REEs, the best results were obtained for the heat-treatment at 225°C.

To optimize the last leaching step, a larger fraction of material was heat-treated at 200°C for 1 h, and then divided in 4 samples, which results can be seen in Table 5.

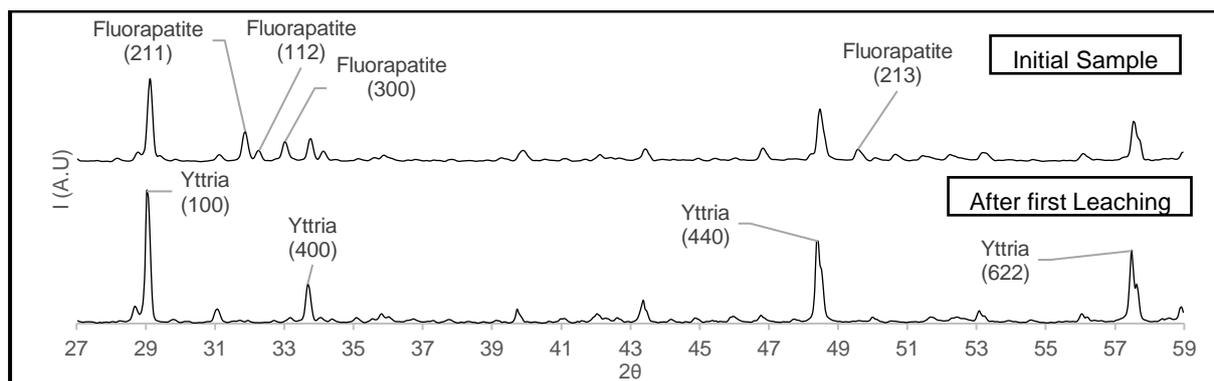
**Table 5 - Yield of Ca, Y, Eu and Gd during the first leaching step.**

Element (wt%) Time (h)	La				Ce				Tb				Gd			
	1	3	6	9	1	3	6	9	1	3	6	9	1	3	6	9
4 M HCl @ 90 °C	5	19	37	49	10	28	53	67	14	-	56	72	80	-	94	99
5 M HCl @ 90 °C	8	35	68	77	14	50	88	99	18	-	100	104	87	-	112	97
6 M HCl @ 90 °C	12	48	76	97	19	65	99	116	24	-	106	130	95	-	94	98
6 M HCl @ 90 °C (5 L/kg)	7	26	38	46	14	41	55	66	17	-	59	67	75	-	91	93

Despite some results being superior to 100% due to experimental errors, a clear increase in the recovery of La, Ce, Tb and Gd can be seen when the acid is more concentrated. Leaching with 6 M of HCl after heat-treatment at 200°C can yield more than 90% of the previous elements, meaning the full procedure is able to recover more than 90% of each REEs present in fluorescent lamps. Reducing in half the L/S ratio showed the same results as leaching with 4 M and 10 L/kg.

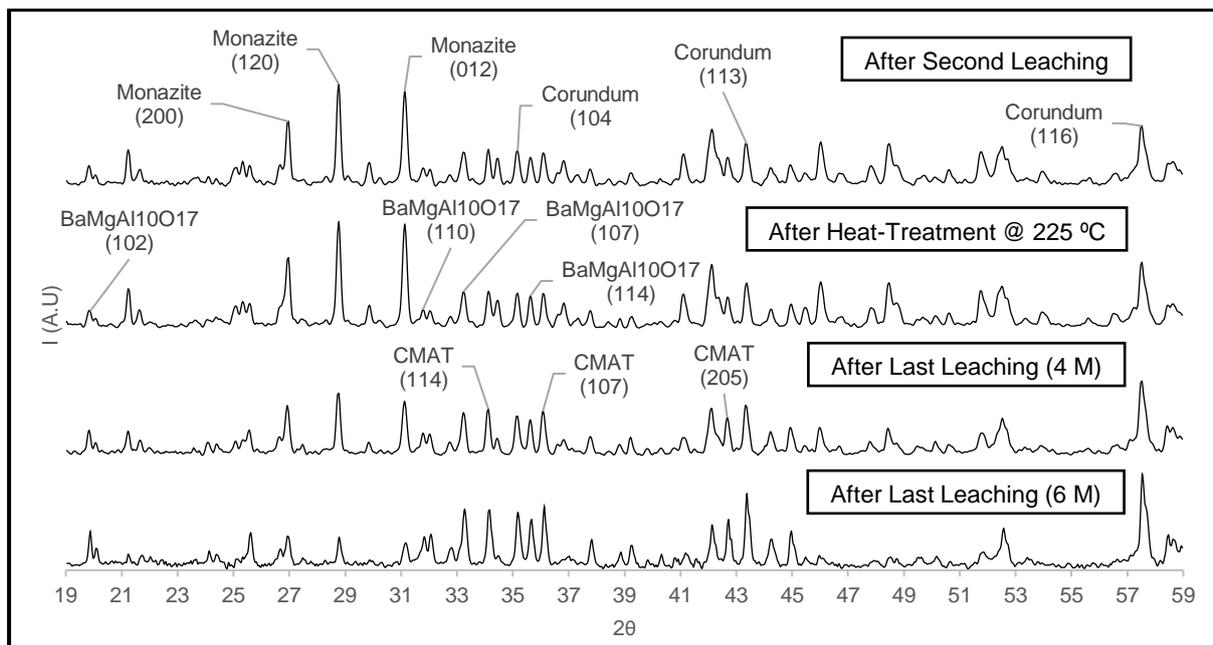
#### 4.3. XRD Characterization

Based on the results of the ICP-AEC, solid samples were selected to determine the structure of the phosphors and the changes that occurred during the various steps, especially during the heat-treatment. Figure 3 shows the diffraction patterns of the initial sample and the solid residue obtained after the first leaching step.



**Figure 3 - Diffraction patterns of the initial sample and the solid residue after the first and second leaching step.**

The peaks with the highest intensity are attributed to yttria, with the remaining structures producing smaller intensity peaks that are more difficult to identify. As seen in the chemical analyses, during the first leaching step almost all halophosphate is solubilized, confirmed by the disappearance of the peaks corresponding to fluorapatite. The peaks corresponding to yttrium will disappear after the second leaching as seen in Figure 4.



**Figure 4 - Diffraction patterns of the remaining experimental steps.**

In these diffraction patterns it is possible to observe the green and blue phosphors that remain after the two-step leaching. In the case of green phosphors both LAP and CAT were identified due to the peaks corresponding to monazite and magnesium cerium terbium aluminium oxide, respectively. While the monazite peaks observed in the diffraction pattern correspond to cerium phosphate, the peaks of lanthanum phosphate (LAP) are very similar, except for the peak at  $31.127^\circ$  in  $\text{CePO}_4$ , that is replaced by two peaks, one at  $30.895^\circ$  and the other at  $31.016^\circ$  in  $\text{LaPO}_4$ . Since these peaks are all very close it is possible that the used step isn't enough to distinguish between both. As for the blue phosphors, BAM was identified due to the peaks corresponding to barium magnesium aluminium oxide. None of the observed crystalline structures has gadolinium in its composition, but its absence is most likely because of the low amount present in the phosphor mixture, as determined by the chemical analyses. The diffraction patterns also show the existence of alumina in the phosphor mixture, a compound that can sometimes be found in the phosphor layer inside the lamp.

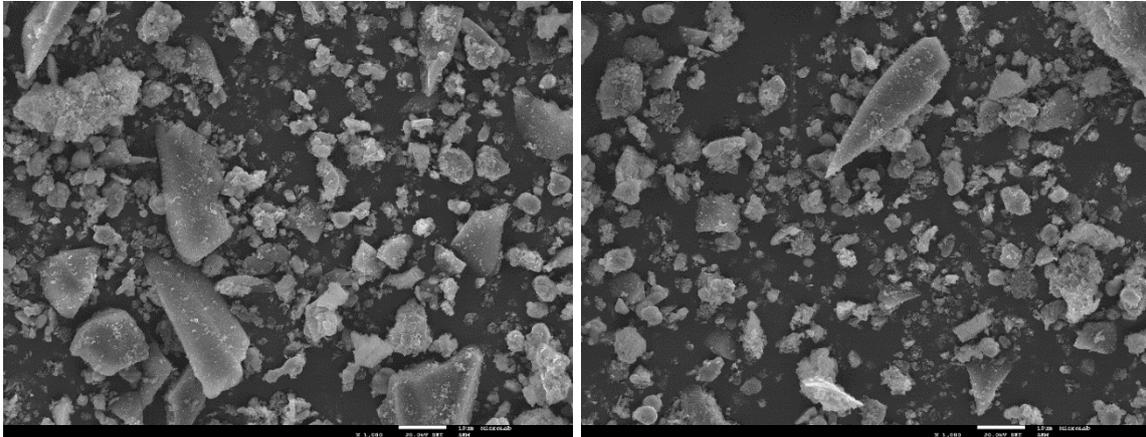
#### 4.4. SEM/EDS Characterization

SEM/EDS was also used to observe morphological changes to samples during the heat-treatment that allow solubilizing a higher amount of REEs through the last leaching. The analysed solid samples came from the tests with the optimal conditions.

EDS spectra showed that the phosphor mixture includes glass impurities, obtained on the crushing of fluorescent lamps. Alumina was also identified, indicating that some of the recycled lamps had this compound in the phosphor layer. Halophosphate particles are only found in the initial sample, and show a broad range of geometries, from spherical and rectangular, to more complex shapes and even sharper looking particles.

Particles of YOx, LAP,  $\text{GdMgB}_5\text{O}_{10}:\text{Ce}^{3+}, \text{Tb}^{3+}$  and CAT were found in the studied samples. In the initial sample, these compounds were very difficult to find, since their particle size was much smaller than halophosphate. BAM, one of the phosphors identified in XRD, didn't appear in any of the taken spectra.

Comparing SEM images obtained at heat-treatments of various temperatures, it seems that increasing the temperature, deagglomerates the particles, that also appear more irregular, being possible to observe less spherical particles. These reasons have the ability of increasing the solubility of the particles, allowing to recover larger amounts of rare earths even in less aggressive conditions. In Figure 5 is possible to observe the differences between a phosphor mixture before and after heat-treatment at 225°C.



**Figure 5 - SEM images of the initial sample and solid residues: left – second leaching step; right - Heat-treatment @ 225°C (Scale: While line corresponds to 10 µm).**

## 5. CONCLUSIONS

The proposed hydrometallurgical procedure starts with a leaching step that uses 2 M of hydrochloric acid as the leachante solution to react with the initial phosphor mixture for 1 h at 25°C. This step primarily attacks the halophosphate, solubilizing more than 90% of Ca from the mixture.

The second leaching step uses the same acid concentration and reaction time, but with a higher temperature of 60°C. This step is aimed at recovering the REEs present in YOX, and the experimental results showed that more than 90% of the Y and Eu found in the solid residue obtained after the first leaching step were solubilized.

After the two-step leaching, the solid obtained on the second leaching is heat-treated. Temperatures ranging from 55°C to 225°C were tested, with the phosphor compounds LAP, CAT,  $\text{GdMgB}_5\text{O}_{10}:\text{Ce}^{3+},\text{Tb}^{3+}$  and BAM showing different behaviours with temperature, on the last leaching step using as reference parameters (4 M HCl at 90°C). The behaviour of  $\text{GdMgB}_5\text{O}_{10}:\text{Ce}^{3+},\text{Tb}^{3+}$ , seen by the yield of Gd, doesn't have notable changes with the variation of temperature, and in all prepared samples, almost 100% was solubilized after 6 h of leaching. The yield of CAT only increased in the samples heat-treated at 200°C and 225°C, with the latter producing the better results, 68% for Ce and 73% for Tb after 6 h of leaching. LAP was the most affected by heat-treatment, with the yield of La starting to improve after being heat-treated at 150°C, up until 225°C, when the yield of La reaches almost 50% after 6 h of leaching.

Two mechanisms that increase the yield of more resistant phosphors seem to happen after the first leaching procedure, the first being related to the sequential recovery of phosphors, and the second with the heat-treatment. In single step leaching the acid is consumed during leaching, starting with the most reactive materials until the least. By increasing the number of steps, the amount of acid available to

recover the pretended phosphors also increases, resulting in a noticeable improvement of leaching efficiency. The only observed changes after heat-treatment were detected by SEM. Samples without heat-treatment show small spherical phosphor particles, which are usually agglomerated. As the samples are heat-treated at increasing temperature, it seems the particles start to deagglomerate, and spherical particles become more irregular. These changes could increase the surface area of the particles, improving the reactivity of the remaining phosphors with hydrochloric acid.

Increasing the acid concentration from 4 M to 6 M during the last leaching step, allowed to recover more than 90% of La, Ce, Tb and Ce in samples heat-treated at a temperature above 200°C. Therefore, the process can achieve yields greater than 90% for every rare earth.

If phosphors being solubilized outside of their intended stream are considered as material loss, then the overall yield of some REEs will decrease. This is the case of Y, Eu and Gd, with the yield of these elements decreasing to 75%, 80% and 72% respectively. Also, small amounts of these REEs will be present in the liquor of other leaching steps, which could remain a problem during a posterior extraction or precipitation process.

## REFERENCES

- [1] P. Christmann, "A forward look into rare earth supply and demand: a role for sedimentary phosphate deposits," *Procedia Engineering*, vol. 83, pp. 19-26, 2014.
- [2] "Statista," [Online]. Available: <https://www.statista.com/statistics/277268/rare-earth-reserves-by-country/>. [Acedido em 25 February 2018].
- [3] United States Environmental Protection Agency, "Rare Earth Elements: A review of production, processing, recycling and associated environmental issues," 2012.
- [4] B. Zhou, Z. Li e C. Chen, "Global potencial of rare earth resources and rare earth demand from clean technologies," *Minerals*, vol. 7, p. 203, 2017.
- [5] U.S. Department of Energy, "Critical Materials Strategy," 2011.
- [6] "Statista," [Online]. Available: <https://www.statista.com/statistics/604190/distribution-of-rare-earth-element-consumption-worldwide-by-end-use/>. [Acedido em 26 February 2018].
- [7] D. Guyonnet, M. Planchon, A. Rollat, V. Escalon, J. Tuduri, N. Charles, S. Vaxelaire, D. Dubois e H. Fargier, "Material flow analyses applied to rare earth elements in Europe," *Journal of Cleaner Production*, vol. 107, pp. 215-228, 2015.
- [8] K. Binnemans e P. Jones, "Perspective for the recovery of rare earths from end-of-life fluorescent lamps," *Journal of Rare Earths*, vol. 32, pp. 195-200, 2014.
- [9] U. Kasser e D. Savi, "Risks of recycling energy saving lamps," Swiss Lighting Recycling Foundation, Zurich, 2013.
- [10] J. Fonseca, "Caraterização e Processos Físico-Químicos de Recuperação de Terras Raras em Resíduos," 2017.