

Peng Cen, Wenyuan Wu\* and Xue Bian

# A novel process for recovery of rare earth and fluorine from bastnaesite concentrates. Part I: calcification roasting decomposition

DOI 10.1515/gps-2016-0031

Received March 4, 2016; accepted April 14, 2016; previously published online June 8, 2016

**Abstract:** Environmental pollution and valuable resource waste exist commonly in current metallurgical processes of bastnaesite concentrates. A novel associated process of calcification roasting, mineral beneficiation and acid leaching was proposed. This paper focused on the prior calcification roasting decomposition procedure. By studying the influence of roasting conditions on cerium oxidation, the optimum technology conditions were obtained: operated at 650°C for 60 min with 20% calcium hydroxide. After roasting, the leaching rate of rare earths can reach 98.84%. Bastnaesite can be sufficiently decomposed at lower temperature with calcium hydroxide added and the emission rate of fluorine decreased by over 98% compared with that during the roasting without additives. After the roasting, the main existence form of fluorine turned calcium fluoride, which made it possible for resource utilization and environmental protection. Particle sizes and scanning electron microscope and energy dispersive spectrometer analyses indicated that rare earth oxides gathered in particles of >48  $\mu\text{m}$ , while generated calcium fluoride with fluffy cotton morphology distributed evenly.

**Keywords:** bastnaesite; calcification roasting; calcium fluoride; fluorine; rare earth.

## 1 Introduction

Rare earths are a set of elements composed of 15 lanthanides (La to Lu, atomic number from 57 to 71), scandium (atomic number 21) and yttrium (atomic number 39) [1–4]. Different kinds of rare earth minerals are distributed in about 34 countries or districts. Among them, bastnaesite

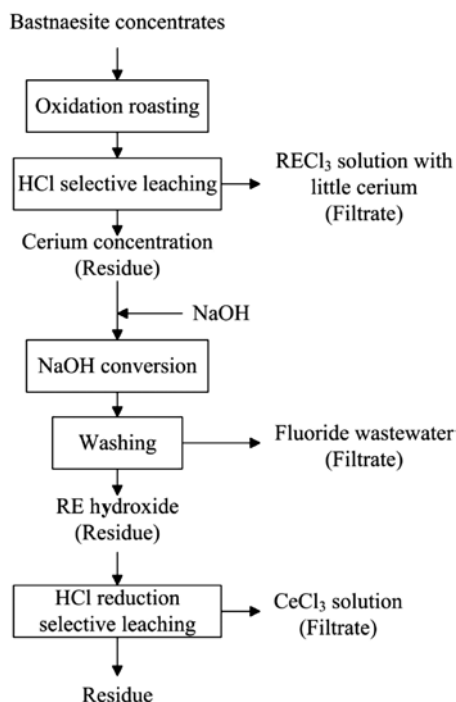
( $\text{RECO}_3\text{F}$ ), monazite ( $\text{REPO}_4$ ) and xenotime ( $\text{YPO}_4$ ) are the major minerals operated in industrial scale currently [5]. Seventy percent of the total rare earth oxides (TREO) in the world are manufactured from bastnaesite ores [6]. Mountain Pass in the United States, Bayan Obo polymetallic deposits and Weishan and Liangshan deposits in China are the world's major bastnaesite ore reserves [7, 8]. Rare earth deposits in Mianning, Liangshan (China), are a kind of typical bastnaesite ores with 80% of the rare earth oxides (REO) concentrated in bastnaesite, and the light rare earth elements such as lanthanum, cerium, praseodymium and neodymium account for more than 98% of the reserves [9]. Some associated minerals like barite ( $\text{BaSO}_4$ ), calcite ( $\text{CaCO}_3$ ) and fluorite ( $\text{CaF}_2$ ) also exist in the ores, bringing comprehensive utilization value [10].

After a series of beneficiation processes, rare earth minerals can be extensively enriched with plenty of gangue minerals removed. Next, a process that mainly consists of decomposition, leaching and solvent extraction is still necessary for most ores. After years of development, a series of production processes have been formed for bastnaesite concentrates in China. A process of oxidation roasting, sulfuric acid leaching and double salt precipitation separation was ever applied to obtain ceria of high purity [11]. However, high production cost was caused by large consumption of mineral resources and chemical materials, and plenty of waste emissions brought about serious environment pollution [12]. Caustic decomposition combined with acid leaching was another mature technology, although it was never widely employed due to the higher requirements for concentrates grade and more cost [13–15]. The present chief process of bastnaesite concentrates in industry (Figure 1) involves oxidation roasting, hydrochloric acid leaching and caustic conversion [12, 16, 17]. Washing is required after caustic conversion. This produces a large amount of wastewater containing fluorine and alkali and causes serious environmental pollution and resource waste [18].

In recent years, a series of clean metallurgy processes with effective use of rare earths and fluorine have been developed. Zhu proposed an ammonium chloride roasting method to chloridize rare earths using hydrogen chloride gas obtained from  $\text{NH}_4\text{Cl}$  decomposition [19]. The

\*Corresponding author: Wenyuan Wu, School of Metallurgy, Northeastern University, NO. 3-11 Wenhua Road, Shenyang 110819, China, e-mail: neuwuwy@sina.cn

Peng Cen and Xue Bian: School of Metallurgy, Northeastern University, NO. 3-11 Wenhua Road, Shenyang 110819, China



**Figure 1:** The flow sheet of process involves oxidation roasting, hydrochloric acid leaching and caustic conversion.

chlorination rate was high with good chlorination selectivity. Chloride products can be directly dissolved in water. Mild reaction conditions without acid and alkali made this method perform well in the colloidal rare earth extraction production from black weathered slime of Panxi (China) rare earth ores. Wu declared that bastnaesite can be decomposed into rare-earth oxyfluoride (REOF),  $\text{Ce}_3\text{O}_4\text{F}_3$  and  $\text{Ce}_6\text{O}_{11}$  by small amount of nitrate after roasting for 2 h at  $430^\circ\text{C}$ , and the emission rate of fluorine was reduced by 60% compared with the usual [20]. Liu found that adding sodium carbonate may turn fluorine into sodium fluoride and thus produce hydrogen fluoride gas rarely during roasting [21]. The generated sodium fluoride can be recycled by washing. One of the shortcomings was the high cost. In the last decades, studies on cleaner rare earth hydrometallurgy have been carried on [17]. Among them, Wang developed an environmentally friendly process consisting of oxidation roasting, sulfuric acid leaching and solvent extraction with HEH (EHP) (2-ethylhexylphosphonic mono-2-ethylhexyl ester). The cerium, fluorine and thorium in the leach liquor were separated and recovered

in the form of  $\text{CeO}_2$ , synthetic cryolite and  $\text{ThO}_2$ , respectively [22, 23]. Economical value was increased with environmental problems reduced.

Based on the strengths and weaknesses of the mentioned processes, we proposed an innovative process of bastnaesite concentrates decomposition and separation to establish a clean metallurgy process with efficient comprehensive utilization of rare earth elements and fluorine. This paper involves the first part of calcification roasting. Calcium hydroxide was used as the additive to turn fluorine into calcium fluoride, an important resource in the fluorine chemical industry. This could increase the economical value of bastnaesite resources. And more importantly, recovery of fluorine in the form of calcium fluoride can efficiently reduce the amount of waste containing fluorine and thus protect the environment.

## 2 Materials and methods

### 2.1 Materials

Bastnaesite concentrates used as raw materials in the experiments were obtained from Mianning in Sichuan Province of China. The chemical compositions measured by X-ray fluorescence (XRF) are given in Table 1. A variety of rare earth elements exist in the ores, and TREO are approximately 70% among which lanthanum and cerium account for about 60%. The X-ray diffraction (XRD) pattern (Figure 2) reveals that the main mineral phases are bastnaesite ( $\text{REFCO}_3$ ) with minor components of parisite ( $\text{CaCe}_2(\text{CO}_3)_3\text{F}_2$ ), barite ( $\text{BaSO}_4$ ) and fluorite ( $\text{CaF}_2$ ) and less quartz ( $\text{SiO}_2$ ), calcite ( $\text{CaCO}_3$ ) and hematite ( $\text{Fe}_2\text{O}_3$ ). The concentrates were obtained after desliming and dressing process, making a coarse granularity with particles of  $>38\ \mu\text{m}$  accounting for more than 95%. Other reagents used in the experiments were all analytically pure and supplied by Sinopharm, China.

### 2.2 Methods and analyses

The roasting experiments were performed in a box-type resistance furnace under air atmosphere. A sheathed K-type thermocouple was inserted into the furnace chamber to monitor the temperature in real time. Powder ore sample of 1 g was put into a nickel crucible and laid on the test point. The sample was roasted at  $400\text{--}800^\circ\text{C}$  for different times, ruled by CKW 3100 temperature controller. After roasting, the products were properly kept in a jar for test.

The decomposition rate was determined by roasting conditions (amount of calcium hydroxide, roasting temperature and time). They can be analyzed based on the variable valences of cerium.

**Table 1:** Chemical compositions of bastnaesite concentrate.

Elements	$\text{CeO}_2$	$\text{La}_2\text{O}_3$	$\text{Nd}_2\text{O}_3$	BaO	CaO	$\text{SO}_3$	$\text{Pr}_6\text{O}_{11}$	$\text{Fe}_2\text{O}_3$	$\text{SiO}_2$	F
Content/wt. %	30.22	30.83	6.65	3.51	3.28	2.70	2.21	1.01	0.67	8.20

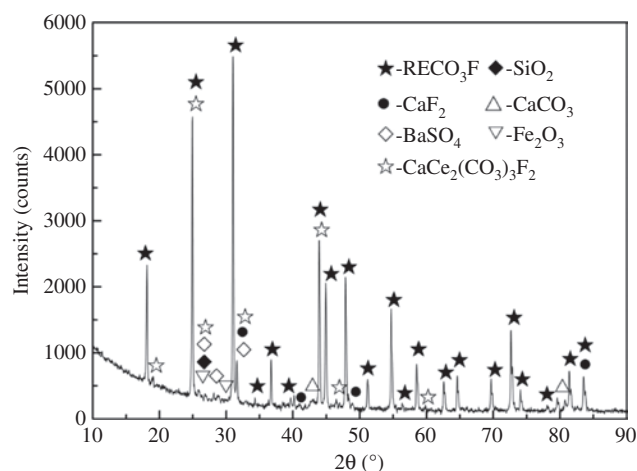


Figure 2: X-ray diffraction pattern of bastnaesite concentrates.

Cerium in raw ores is known as trivalent [Ce (III)]. In the heating process, part of the mineral can be decomposed and cerium can be oxidized into tetravalent [Ce (IV)], while that in the undecomposed mineral remains trivalent. As a result, the oxidation rate of cerium, defined as the following equation (1), can represent the decomposition ratio of ores to some extent. In the definition, Ce (IV) and TCe are, respectively, the content of tetravalent cerium and total cerium in roasted ore sample. They both can be determined by cerium sulfate method with ammonium ferrous sulfate solution as reducing agent and sodium diphenylamine sulfonate indicating final reduction point.

$$\eta = [\text{Ce (IV)} / \text{TCe}] \times 100\% \quad (1)$$

The elements contents in the ores were tested quantitatively through XRF and inductively coupled plasma spectrometry optical emission spectroscopy (ICP-OES) analyses. Laser particle size analyses were put into use to define the mineral particle size distribution. XRD analyses combined with scanning electron microscope and energy dispersive spectrometer (SEM-EDS) analyses made it possible to gain further insight into mineral morphology and the phase transformation in the decomposition reactions.

Elemental composition was mainly measured using a LEEMAN (China) Prodigy XP ICP-OES. Argon with a purity of 99.999% was used to form the plasma. Standard solutions for calibration were prepared by suitable dilution of the stock solutions (1000 µg/ml, Sinopharm, China). The dissolution of samples was conducted by using acid digestion in a high concentration of nitric acid. Plasma parameters were adjusted as follows: RF power 1.1 kW, nebulizer pressure 34 psi, coolant gas flow rate 18 l/min and sample uptake rate of 1.4 ml/min.

A PANalytical (Netherlands) X'Pert Pro X-ray diffractometer with Cu K $\alpha$  radiation was used. After fine grinding, the samples were loaded into a cell and flattened. Then they were put on the sample stage in the equipment. The scanning was performed with  $2\theta$  from  $10^\circ$  to  $90^\circ$ , and the speed was  $4^\circ/\text{min}$  with the step of  $0.033^\circ$ . The data processing was operated using HighScore Plus 2.0.

SEM-EDS analyses were conducted on a Zeiss (Germany) Ultra Plus SEM equipped with a X-Max 50 EDS. The accelerating voltage was set at 15 kV. The samples for analyses were prepared through a series of steps. Carbon conductive tape was first stuck on a cylindrical copper block, and the samples were sprinkled on the tape. Then the samples were gold coated using a sputter coater.

## 3 Results and discussion

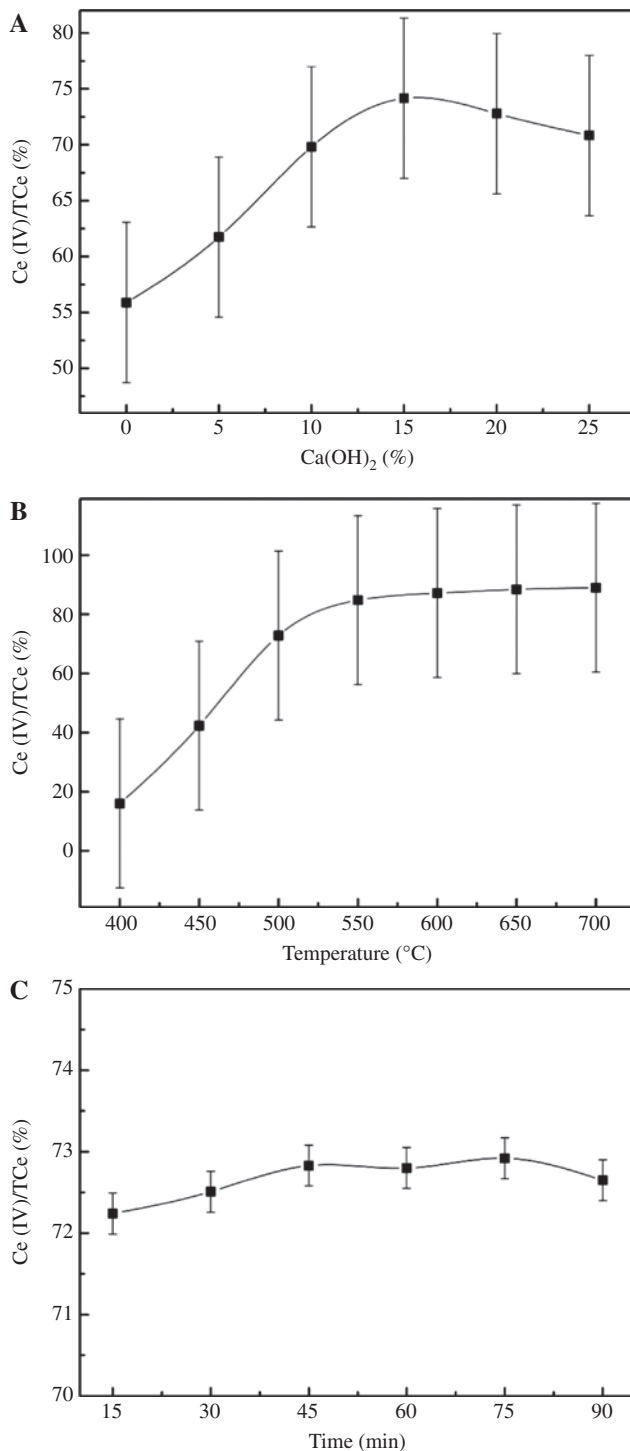
### 3.1 The influences of roasting conditions on bastnaesite decomposition

The influences of roasting conditions on cerium oxidation rate ( $\eta$ ) were studied by several groups of single-factor experiments. The three factors including calcium hydroxide addition, roasting temperature and time were analyzed respectively with the other two remaining unchanged. As can be seen from Figure 3A, calcium hydroxide can effectively promote mineral decomposition. Cerium oxidation rate markedly increased from 55.88% to 69.82% when the amount of calcium hydroxide rose to 10%. After this, the change trend of oxidation rate slowed down with the addition of calcium hydroxide further increased. The rate even reduced when the amount exceeded 15%. This may be due to the excess calcium hydroxide that wrapped the minerals and restrained the oxygenation of cerium. The calculation according to chemical formula of calcium fluoride ( $\text{CaF}_2$ ) showed that the additional amount of 15.89% was essential to ensure that all fluorine in the minerals can turn into calcium fluoride. In conclusion, the amount of calcium hydroxide can be 20%. Figure 3B proved that temperature had the greatest impact on bastnaesite decomposition. The oxidation rate of cerium increased rapidly when temperature rose from  $400^\circ\text{C}$  to  $550^\circ\text{C}$ . Then the growth range diminished, and  $650^\circ\text{C}$  can be the appropriate temperature. After roasting for some time, cerium oxidation rates in the ores were measured. Figure 3C indicated that roasting time was not a decisive factor. It did not take a long time for bastnaesite decomposition and cerium oxidation. Nevertheless, some time of heat preservation was still required for crystal growth, and 60 min should be guaranteed. Overall, the bastnaesite decomposition process should be operated at  $650^\circ\text{C}$  for 60 min with 20% calcium hydroxide. Under this condition, a higher oxidation rate of 88.46% was achieved. Sulfuric acid solution of 6 mol/l was used to leach roasted ore at  $60\text{--}80^\circ\text{C}$ , and the leaching rate of rare earth can reach 98.84%. The difference between cerium oxidation rate and leaching rate was attributed to the existence of  $\text{Ce}_2\text{O}_3$ .

### 3.2 Comparison in the absence and presence of calcium hydroxide

#### 3.2.1 Emission rate of fluorine

The effects of calcium hydroxide on fluorine emission in the roasting process were studied by contrast experiments. Two kinds of ore samples were prepared as follows:



**Figure 3:** The influences of roasting conditions on bastnaesite decomposition.

Source of error bars: standard deviation of data. (A) Roasted at 500°C for 60 min; (B) roasted for 60 min with 20% Ca(OH)<sub>2</sub>; (C) roasted at 500°C with 20% Ca(OH)<sub>2</sub>.

sample 1 (S1): mixtures of bastnaesite concentrates and 20% calcium hydroxide, sample 2 (S2): bastnaesite concentrates. After roasting at different temperatures, mass

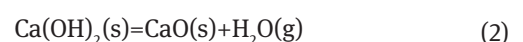
**Table 2:** Emission rate of fluorine in roasting process.

Results	Sample		
	S1	S1(650°C)	S1(750°C)
a. S1: Bastnaesite concentrates and calcium hydroxide (20%)			
m/g	12.000	10.081	10.074
F/%	6.80	8.08	8.07
ΔF/%	–	0.24	0.37
	Sample		
	S2	S2 (650°C)	S2 (750°C)
b. S2: Bastnaesite concentrates			
m/g	10.000	8.120	7.831
F/%	8.16	8.14	7.45
ΔF/%	–	18.99	28.55

and fluorine content of the ores were measured and are shown in Table 2. It can be seen that emission rate of fluorine in the two samples both increased when temperature was raised, while the promotion in S2 was more apparent. At the same temperature, fluorine escaped less from S1 with calcium hydroxide added. Compared with S2, the emission rate of fluorine in S1 reduced by 98.74% at 650°C and that was 98.70% at 750°C. Calcium hydroxide effectively inhibited the escape of fluorine.

### 3.2.2 Major mineral phase transformation

Figure 4 shows the XRD patterns of S2 roasted at 650°C and 750°C. The mineral (REFCO<sub>3</sub>) could be largely decomposed at 650°C while REOF still existed. Meanwhile, REO and barite (BaSO<sub>4</sub>) became major phases. When the temperature reached 750°C, bastnaesite concentrates were almost completely decomposed into REO, and fluorite (CaF<sub>2</sub>) emerged in the XRD pattern (Figure 4B). The XRD pattern of S1 roasted at 650°C is shown in Figure 5. In contrast to S2, rare earth ores in S1 were completely decomposed at 650°C. In Figures 4B and 5, CaF<sub>2</sub> was easily identified, and the crystal form and intensity were both different with that in raw ores. That meant new CaF<sub>2</sub> was generated during roasting. It can be concluded that proper amount of calcium hydroxide can promote the decomposition of bastnaesite and lower reaction temperature. Due to the addition of calcium hydroxide, calcium fluoride became prominent minerals. At the same time, a large amount of calcium oxide existed in the roasted ores. A range of reactions may happen as equations (2)–(6) in the calcification roasting process.



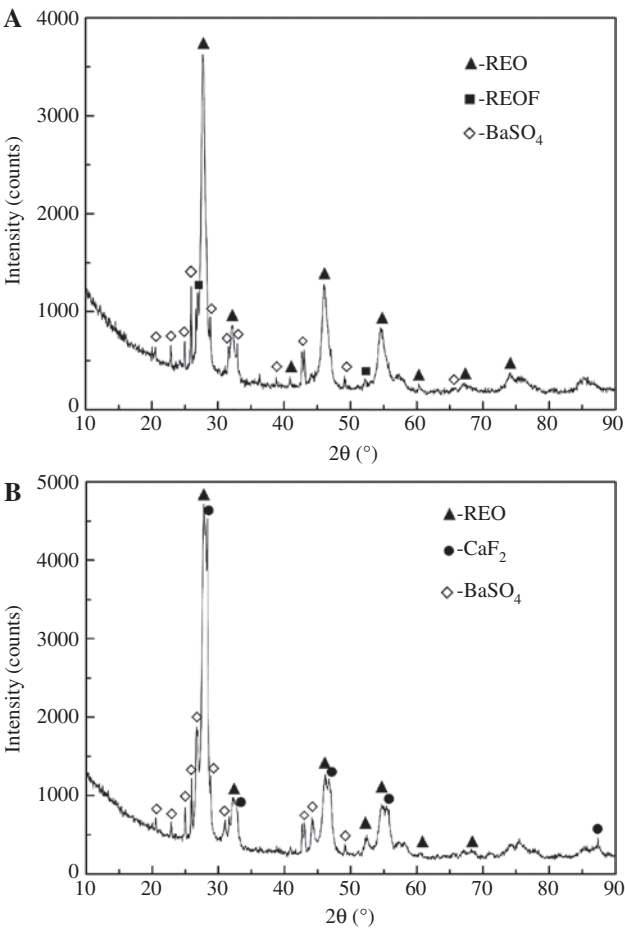
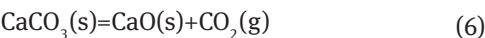
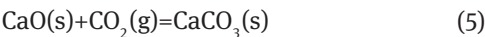
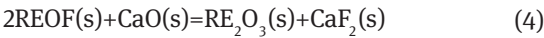


Figure 4: X-ray diffraction pattern of S2 roasted at 650°C and 750°C.



3.3 Particle size analyses of calcification roasted ores

In order to obtain major phase composition distribution in different particle sizes, bastnaesite concentrates (S2)

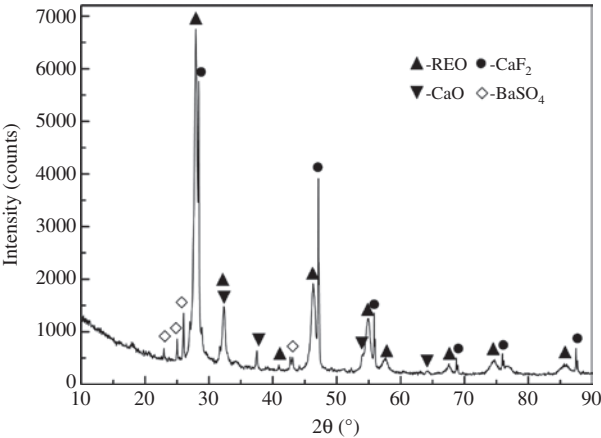


Figure 5: X-ray diffraction pattern of S1 roasted at 650°C.

and roasted ores of S1 at 650°C were griddled and measured by XRF and ICP. Mineral particle size distributions are first listed in Table 3. Particles of >48 μm accounted for more than 98% (weight distribution) in bastnaesite concentrates, while that in roasted ore dropped to 87.16% as a consequence of the use of fine-particle calcium hydroxide.

Table 4 shows the main chemical composition of minerals in different sizes. Rare earth elements and fluorine had a higher proportion in large particles of concentrates, while the content of barium increased with the shrink of particle sizes. The distribution of calcium was uniform. In contrast, the contents of calcium and fluorine were higher in small particles of roasted ores, and barium proportion changed just a little. Rare earth elements had the similar variation rule as that in the concentrates.

Elemental distribution in multi-granularity roasted ores, reported in Table 5, can be calculated from Tables 3b and 4b. About 97.32% of the rare earths and 92.84% of the barium in the ores were concentrated in large particles of >48 μm, in which a little more than 50% of calcium and fluorine gathered. Combined with previous XRD patterns, REO and barium sulfate (BaSO<sub>4</sub>) can be determined mainly in large particles, while calcium fluoride (CaF<sub>2</sub>) distributed evenly in different size particles. As a result, it is practicable to separate the roasted ore with 48 μm as boundaries and study them, respectively.

Table 3: Mineral particle size distribution.

a. Bastnaesite concentrates					b. Roasted ores of S1				
Size/μm	>74	74~48	48~38	<38	Size/μm	>74	74~48	48~38	<38
Content/wt.%	88.47	10.28	0.95	0.30	Content/wt.%	70.93	16.23	7.76	5.08



**Table 4:** Particles composition distribution.

Size ( $\mu\text{m}$ )	Element			
	$\Sigma\text{RE}$	Ca	F	Ba
<b>a. Bastnaesite concentrates</b>				
>74	63.16	1.51	8.36	8.02
74~48	55.58	1.57	7.23	16.62
48~38	47.64	1.52	6.21	24.69
<38	36.10	2.33	5.23	28.83
<b>b. Roasted ores of S1</b>				
>74	48.84	4.80	3.66	3.50
74~48	50.92	12.6	8.01	5.49
48~38	9.04	30.5	26.51	2.57
<38	9.42	32.9	31.51	1.12

**Table 5:** Elemental distribution.

Element	Size ( $\mu\text{m}$ )			
	>74	74~48	48~38	<38
$\Sigma\text{RE}$	78.58	18.74	1.59	1.09
Ca	35.86	21.52	25.00	17.62
F	34.39	17.20	27.25	21.16
Ba	68.32	24.52	5.51	1.65

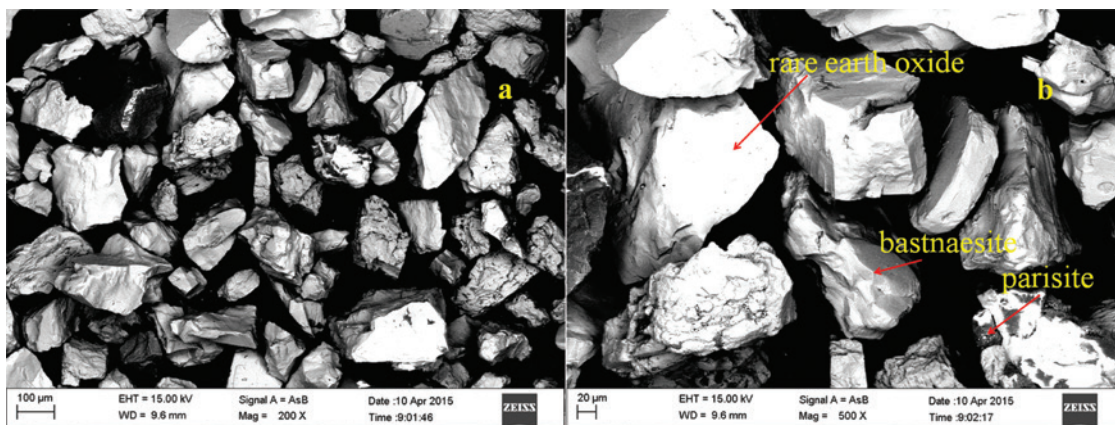
### 3.4 Morphology and phase composition of calcification roasted ores

To observe surface morphology of the main phases, SEM-EDS analysis results of bastnaesite concentrates and roasted ores of S1 at 650°C are presented in Figures 6 and 7 and Table 6. As shown in Figure 6A, particle sizes were relatively uniform with larger grains occupying the majority.

This agreed with the particle size distribution results mentioned in section 3.3. Bastnaesite and parisite were easily detected due to the large amount. Some REO or oxyfluorides (REOF) also arose along with calcium fluoride, which indicated that rare earth carbonates can be partly oxidized in nature.

Changes in granularity and phase composition were brought about by calcification roasting. More fine particles appeared in the SEM images of roasted ores. A number of REO, calcium oxides, calcium fluorides and calcium carbonates took the place of bastnaesite and parisite. Seen from Figure 7A, pure REO existed in roasted ores. Due to the emission of carbon dioxide generated during roasting, the surface was loose and uneven. Calcium oxide and carbonate were embedded in the ambient calcium fluoride, which displayed a kind of fluffy cotton morphology. A few of the REO attached to calcium fluoride can also be found in the field.

Seen from the results above, original ores and calcium oxide particles should be regarded as the reaction cores. In the roasting process, fluorine escaped and diffused from rare earth ores and met the surrounding calcium oxides. Then calcium fluorides were generated in the interface resulting in the phenomena in Figure 7B and C. The calcium fluorides with loose structure like calcium oxide can be identified as new reaction products. It was easy for most of them to fall off from REO particles, beneficial to separation. A lot of calcium oxide and fluoride with some REO and barium sulfate concentrated in particles of <48  $\mu\text{m}$  without calcium hydroxide. In roasted ores, calcium fluoride distribution had little to do with particle sizes, while REO concentrated in the particles of >48  $\mu\text{m}$ . The generated calcium fluoride showed completely different fluffy cotton morphology,

**Figure 6:** SEM image of bastnaesite concentrates.

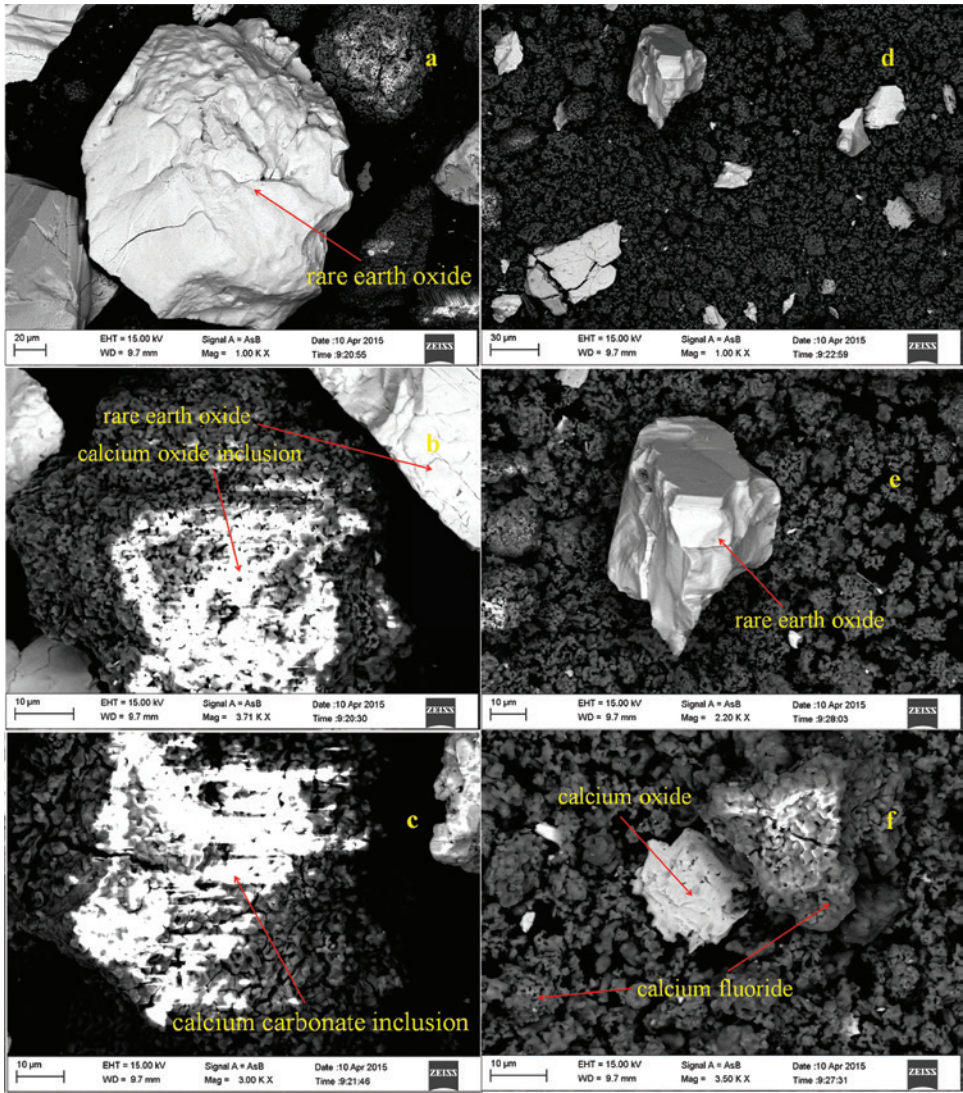


Figure 7: SEM image of calcification roasted ore. (A, B, C) >48 μm; (D, E, F) <48 μm.

Table 6: EDS analysis.

No.	Phase	La		Ce		Ca		F		C		O		Ba		S	
		wt.%	at%	wt.%	at%	wt.%	at%	wt.%	at%	wt.%	at%	wt.%	at%	wt.%	at%	wt.%	at%
1	Bastnaesite	20.94	4.35	24.29	5.01	—	—	8.73	13.27	13.39	32.18	24.08	43.45	2.18	0.46	—	—
	Parisite	15.23	2.61	15.57	2.64	5.62	3.34	10.68	13.37	13.35	26.41	34.15	50.74	—	—	—	—
	REO/REOF	22.28	5.53	27.39	6.74	3.22	2.78	12.51	22.72	—	—	28.14	60.67	—	—	—	—
2	REO(a)	30.29	11.43	37.47	14.02	—	—	—	—	—	—	21.56	70.64	—	—	—	—
	REO(b)	32.23	12.76	37.64	14.78	0.41	0.56	1.46	4.21	—	—	18.61	63.98	—	—	—	—
	CaO	—	—	—	—	65.86	46.51	24.71	36.82	—	—	9.43	16.68	—	—	—	—
	CaCO <sub>3</sub>	—	—	—	—	39.50	19.47	—	—	14.24	23.41	46.27	57.12	—	—	—	—
3	REO	23.93	7.74	31.55	10.12	9.13	—	8.12	19.20	—	—	17.70	49.70	—	—	—	—
	CaO	—	—	—	—	4.55	6.10	—	—	—	—	12.01	40.40	67.26	26.35	16.18	27.15
	CaF <sub>2</sub> (f1)	—	—	—	—	32.08	30.97	67.92	69.03	—	—	—	—	—	—	—	—
	CaF <sub>2</sub> (f2)	—	—	—	—	59.50	41.05	40.50	58.95	—	—	—	—	—	—	—	—

1. Bastnaesite concentrate, 2. roasted ore (>48 μm), 3. roasted ore (<48 μm).  
(Pr, Nd and other rare earth elements are omitted).



and most dropped from REO. It is workable to separate REO and calcium fluorides through beneficiation. Through calcification roasting decomposition, fluorine in bastnaesite concentrates can be recovered in the form of calcium fluoride. This is an environmentally friendly way to increase the economical value. Next, thermodynamics and dynamics analyses are necessary to study the reaction mechanism. Clearer mineral-embedded characteristics and surface properties are required to serve the following beneficiation process.

**Acknowledgments:** The authors would like to acknowledge the Ministry of Science and Technology of the People's Republic of China for funding this work in National Basic Research Program (973Program, 2012CBA01205).

## References

- [1] Chen Z. J. *Rare Earths* 2011, 29, 1–6.
- [2] Smythe DM, Lombard A, Coetzee LL. *Miner. Eng.* 2013, 52, 52–61.
- [3] Yang X, Lin A, Li X, Wu Y, Zhou W, Chen Z. *Environ. Dev.* 2013, 8, 131–136.
- [4] Jaireth S, Hoatson DM, Mieztis Y. *Ore Geol. Rev.* 2014, 62, 72–128.
- [5] Jordens A, Sheridan RS, Rowson NA, Waters KE. *Miner. Eng.* 2014, 62, 9–18.
- [6] Bhushan SK, Kumar A. *J. Geological Soc. India* 2013, 81, 41–60.
- [7] Zhou F, Wang LX, Xu ZH, Liu QX, Deng MJ, Chi R. *Miner. Eng.* 2014, 64, 139–145.
- [8] Ozbayoglu G, Atalay MU. *J. Alloy. Compd.* 2000, 303–304, 520–523.
- [9] Cheng JZ, Che LP. *Chin. Rare Earths* 2010, 31, 65–69 (In Chinese).
- [10] Chi RA, Wang DZ, Eds., *Rare Earth Mineral Processing*, 1st ed., Science Press: Beijing, 2014 (In Chinese).
- [11] Xu GX, Ed., *Rare Earths*, 2nd ed., Metallurgical Industry Press: Beijing, 1995 (In Chinese).
- [12] Wu WY, Bian X, Eds., *Metallurgy Technology of Rare Earth*, 1st ed., Science Press: Beijing, 2012 (In Chinese).
- [13] Han XY, Li LC, Chang S. *Chin. Rare Earths* 1985, 6, 39–43 (In Chinese).
- [14] Yao YD, Li HM, Li Y. *Multipurp. Util. Miner. Resour.* 1999, 1, 1–6 (In Chinese).
- [15] Zhao SL, Zhang XS, Yang DJ, Liu XY. *J. Sichuan Univ.* 2002, 39, 926–932 (In Chinese).
- [16] Li LC, Ge XF, Li LS. *Chin. Rare Earths* 1999, 20, 52–55 (In Chinese).
- [17] Huang XW, Long ZQ, Wang LS, Feng ZY. *Rare Met.* 2015, 34, 215–222.
- [18] Li LC, Lin Y, Liang YG. *Sichuan Rare Earth* 2009, 4, 10–12 (In Chinese).
- [19] Zhu GC, Shi WZ, Chi R. *J. Chin. Rare Earth Soc.* 2002, 20, 136–142 (In Chinese).
- [20] Wu WY, Chen J, Sun SC, Tu GF. *J. Northeast. Univ.* 2004, 25, 378–381 (In Chinese).
- [21] Liu ZG, Yang QS, Liu LS. *Chin. Rare Earths* 2004, 25, 20–25 (In Chinese).
- [22] Wang LS, Wang CM, Yu Y, Huang XW, Long ZQ, Hou YK, Cui DL. *J. Hazard Mater.* 2012, 209–210, 77–83.
- [23] Wang LS, Yu Y, Huang XW, Long ZQ, Cui DL. *Chem Eng J.* 2013, 215–216, 162–167.

## Bionotes



Peng Cen

Peng Cen studied nonferrous metallurgy at School of Metallurgy, Northeastern University (NEU), China, where he obtained a Masters degree in 2014. Since 2014, he has been pursuing a Doctors degree in NEU, under the supervision of Prof. Wenyuan Wu and Dr. Xue Bian, working on green comprehensive utilization of rare earth resources.



Wenyuan Wu

Wenyuan Wu is a professor and doctoral supervisor at School of Metallurgy, Northeastern University, China. Most of his research has been focused on the area of comprehensive utilization of rare earth resources and clean metallurgy. The green preparation technology of rare earth materials is also included in his main research direction.



Xue Bian

Xue Bian obtained his Doctors degree from School of Metallurgy, Northeastern University (NEU; 2008). Currently, he is an associate professor at NEU. His research activities have been focused on the development of rare metal metallurgical technology and application, comprehensive utilization of rare earth resources and clean metallurgy, and green preparation technology of rare earth materials.