Economic relationships and market trends of the rare earths

by Gary A. Campbell

This paper considers the market trends of the rare earths and how they are strongly influenced by the by-product/co-product nature of their mining and processing. The two main economic minerals for the rare earths are bastnasite and monazite. Monazite is primarily a by-product of mining ilmenite and rutile and is affected by changes in these markets as well as the presence of thorium. Bastnasite is a by-product of mining iron ore in China and a stand-alone product in the USA. The paper will use conceptional relationships and empirical data to delineate the various by-products/co-products relationships and how they determine observed market behavior.

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Rare earths is the common name given to a collection of chemically similar metals that are neither "rare" nor "earths". Rare earths are important material inputs into the petroleum cracking, iron & steel, lighter flint, permanent magnet, and ceramic & glass industries. Increasingly, rare earths are being used in new and developing "high tech" applications as well. The rare earths formally consist of the lanthanide series: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium plus the closely associated elements of yttrium and scandium. As commercial products, the rare earths consist of the lanthanide series (minus promethium which does not exist naturally in a stable isotope), yttrium, and thorium (always associated in the commercial phosphate ore – monazite). Scandium is not mined, processed, or used with the other rare earths commercially.

The chemical similarities of the rare earths make them unique. Geological conditions that concentrate one of the elements will concentrate the others as well so there are no ore sources for individual rare earth elements; they are always found together. However, geological processes have tended to concentrate the light rare earths (the first seven lanthanides) differently than the heavy rare earths (the last seven lanthanides plus yttrium) plus there are substantial variations in crustal abundance of each individual element. The rare earths' chemical similarities makes element separation difficult and expensive. The advantage of this similarity is that the substitution of one rare earth for another in a use is often posssible. It is also possible in some applications to use lower-grade mixtures of elements (even original ore percentage) in place of higher purity compounds. Historically, most rare earth usage and value has been in lower-grade mixtures and compounds, avoiding the difficult separation process. This is changing with the growing need for high purity compounds in high tech applications. The importance of lower-value rare earth products and the relatively low concentration of lanthanides in minerals have made by-product sources of rare earths the major commercial source (with one very important exception). Rare earths are by-products associated with heavy sand sources of titanium and zirconium, placer mining of tin in southeast Asia, and iron mining in China. There is one large principal mine of rare earths in California.

The net result of these chemical and geological conditions economically is a tangled web of commercial relationships among the rare earths and the other products associated with their mining and processing. Conceptionally, mineral production relationships can be broken into three economic behavioral categories: main product, co-product, and by-product. The simplest case is main product production. There is only one product considered to have any substantial impact on the output level decision. Therefore, there is no need to consider relationships with other products in the decision-making process. This is the category for the rare earth mine in California. A more complex case is the co-product situation. Here, two or more products are jointly considered in determining the appropriate production levels. This is an important economic category for rare earth processing and separation. A by-product is a material that is recovered as a secondary product associated with the primary economic products and has little or no influence on the primary output level. This is a common situation for the mining of rare earths minerals. The purpose of this paper is to organize and analyze these mining and processing relationships of the rare earths based on these categories in order to gain useful insights into the economic behavior of the rare earths industry and market. Of particular interest is the impact of the current economic change-over from low-grade bulk products to the high-purity compounds needed in high tech applications.

Rare earths production

There are five commercial mineral sources for rare earth concentrates: bastnasite, monazite, xenotime, loparite, and ion absorption clays. Bastnasite is the primary source used for rare earths products today. This mineral consists on average largely of the light lanthanides, particularly cerium, lanthanum, neodymium and lesser amounts of praseodymium. Monazite has, in addition, small amounts of yttrium, samarium, and gadolinium. Loparite is rich in cerium, lanthanum, neodymium, praseodymium, and to a lesser degree, yttrium. The other lanthanides are present only in trace amounts of less than one percent on average in these minerals. Xenotime is mined in much smaller quantities. It is the primary source of yttrium and the heavy lanthanides – terbium, dysprosium, holmium, erbium, thulium, ytterium, and lutetium. The ion absorption clays produced in China are similar in rare earth products to xenotime. Loparite is a source of rare earths in the CIS.

There are two large sources of bastnasite today. One is the surface mine at Mountain Pass, California operated by Molycorp of the USA. This mine is unique in that it is the only significant commercial main product source for rare earths. It is an important source of rare earths that has accounted for as much as 50–70 per cent of annual rare earth values in recent years. A potentially larger source of bastnasite has become available as an associated product of iron ore mining at Bayan Obo in the Nei Mongol Autonomous region of China. This mining region produces a variety of commercial mineral sources of rare earths but bastnasite dominates.

Monazite and xenotime (which are found together) are by-products at all of their commercial sources. The largest source of these minerals is as by-products of heavy sands mining for ilmenite and rutile (titanium ores). Australia is the primary location for this type of mining, but it also occurs in Green Cove Springs (Florida), Brazil, and India. These minerals are commercially recovered as by-products of tin placer mining in southeast Asia as well – Malaysia being the largest producer. Monazite-xenotime is also a by-product of the Bayan Obo mine in China. Thorium is always an associated product in monazite concentrates (7.2 per cent thorium oxide on average).

The original percent of rare earths in mined ores are quite modest. Mountain Pass ore is 9 per cent rare earths oxides for example.

Milling techniques are used to create a concentrate that is 50–60 per cent rare earths oxides although China does make available a less concentrated product of 30 per cent . Bastnasite concentrate (60 per cent rare earths oxides) can be leached with hydrochloric acid and roasted to achieve a 85 per cent rare earths oxide content. At this stage, the material can be separated into a cerium-enriched concentrate and a lanthanum (cerium-poor) concentrate. It is also possible to recover europium oxide as a separate product at this stage. The remaining elements in the lanthanum concentrate (lanthanum, neodymium, praseodymium, and small amounts of the other rare earths) can be separated from each other to the desired level of purity by using solvent extraction procedures. Monazite-xenotime concentrates are 55 per cent rare earth oxides with thoria present. The concentrates are upgraded with a caustic solution of sodium hydroxide followed by an acid leach. The thorium can be separated from the rare earths during the leach step. The rare earths elements can then be separated and purified to the desired levels with solvent extraction as with bastnasite concentrates. Purity of individual element oxides reach 96 per cent to 99.9999 per cent depending on the element and its enduse.

A large variety of commercial materials can be obtained from the concentrates of bastnasite, monasite, and xenotime from various points throughout the processing stage. These materials range from low-purity mixed compounds (chlorides, fluorides, oxides, etc.) and metal (mischmetal) to high-purity individual element oxides and metals. These products can be separated into three categories based on the stage of processing at which they become available.[1] One category consists of the concentrates and mixtures that retain the natural lanthanide ratio of the ore. Another category is made up of the low-purity concentrates and compounds that have had their natural lanthanide ratios altered by non-solvent extraction methods. The third category consists of the elements and compounds obtained through solvent extraction. Traditionally, the majority of use of rare earths has been in low-value materials from the first two categories that need a limited amount of processing: petroleum cracking catalysts, mischmetal, polishing powders, etc.. Today, such products account for 75 per cent , by weight, of rare earths materials consumed but only 25 per cent of the value generated.[2] While these materials are inexpensive and require little extra processing, they tend to be a relatively inefficient way to make use of the variety of elements in the raw material. More recently, there has been a trend toward more specialized use of individual rare earths elements necessitating the higher levels of separation, purity, and cost found in the third category products.

Rare earths mining relationships

Without the complications of a by-product relationship, the production behavior from the Mountain Pass mine is solely responsive to conditions in the rare earths market. Annual data on capacity utilization show that Mountain Pass, in general, has excess capacity relative to its annual production.[3] Typically, this means a mineral producer is readily willing to change its output in response to demand changes for its product without requiring much of a price change. This appears to be the case for Molycorp. A regression model using annual bastnasite output from the mine for the last thirty years shows that, indeed, more than 70 per cent of the variations in annual bastnasite production can be explained by annual US consumption (a proxy for demand changes if supply is relatively stable) of rare earths.[4] Observed real prices for bastnasite concentrate had little impact, statistically, on production or consumption which is consistent with a producer with excess capacity.

The other mining sources of rare earths are as by-products to existing mining operations. The market behavior exhibited by any by-product depends to a large extent on the interaction of three factors: the costs that must be met in order for by-product production to be feasible, the limiting factors on short-run and long-run supply availability of the by-product, and the demand for the by-product. The interaction of these three factors for individual by-products vary greatly and requires that each case be considered separately.

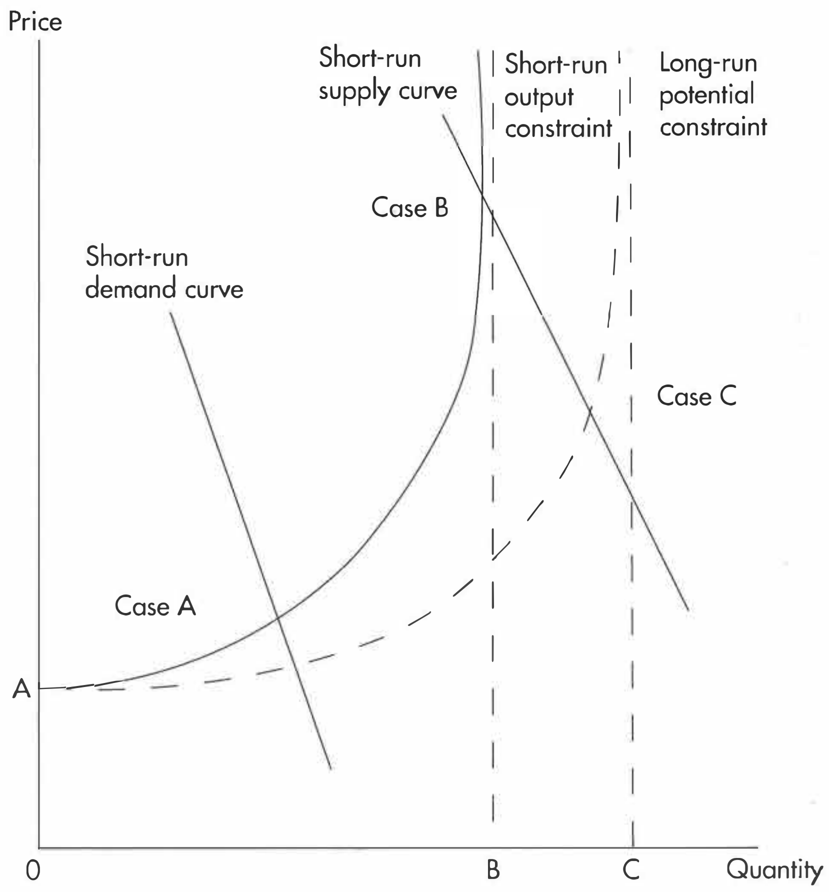
There are two factors that need to be considered in determining the costs that must be met by a by-product price in order for production to occur. Is it necessary (technically or economically) to separate the by-product from the primary product(s) before the primary product(s) are marketable? If it is, the separation costs do not have to be covered by the by-product price because the separation is a necessary cost of doing business in the primary product industry. If it is not, the separation costs must be covered in the by-product price since a joint product can be sold instead. Any additional processing of the by-product needed after separation to have a marketable product must be covered by the by-product price.

The potential supply of a by-product at a given time is dependent on the actual production levels of the primary product(s). This full potential is seldom realized in the short-run because the mining and processing techniques are established to maximize the efficient recovery of the primary product(s) and not necessarily that of the by-products. Existing processing capacity for the by-product is often limited by past demand as well. Subsequently, there may be no apparent link between primary production levels and by-product production levels if by-product output is significantly below theoretical potential. If by-product output levels are closer to potential levels, a link will be more observable.

The demand for a by-product also plays a vital role in dictating observed market behavior. It is the interaction of supply and demand that determines the market price for a by-product, and the market price in conjunction with required processing costs establishes what types of by-product production are economically viable. In the long-run, the strength or weakness of the market demand relative to supply as reflected in the market price determines the future availability of the by-product. A strong demand will lead to an increased use of the potential supply of the by-product through capacity increases, more efficient processing, and new sources while a weak demand will bring about capacity decreases and less efficient recovery.

This economic model of a by-product metal market offers three possible reference cases for observed market behavior (see Figure 1). Case A is when demand is less than the available short-run, full-capacity by-product supply. There can be substantial changes in the by-product

Figure 1. By-product reference cases



output independent of the main product output and with relatively small price changes by taking advantage of the excess capacity. In Case B, demand is at full-capacity by-product production as restricted by short-run constraints. In the short-run, by-product price changes have little effect on available by-product supply, and by-product output depends on the existing production capacity. Existing by-product production capacity is being used fully but additional raw material is still available. In the long-run, by-product capacity and technology can change in response to by-product price signals to take advantage of the additional raw material available from the main output. In Case C, demand is at full-capacity as restricted by the primary production. By-product production is limited solely by main product output and is not responsive to by-product price either in the short-run or the long-run (unless it becomes valuable enough to no longer be a by-product). All the available by-product is being utilized.

The heavy sands of Australia are the world's primary by-product source of monazite. Ilmenite output is the best indicator of main product production from Australian heavy sands mining. The percent of rutile recovered from a mined unit of heavy sands has been declining over the years considered (1969–1994) so rutile output is not consistent enough to serve as a good historic indicator like ilmenite. Since historically Australia has exported its rare earth concentrates for processing, annual US imports of monazite-xenotime is used as an available crude proxy variable to measure processing demand for Australian concentrates. U.S. imports were down to zero by 1991. France has been a historically important importer of monazite-xenotime from Australia as well and shows a similar import pattern. Regression analysis shows that annual Australian ilmenite output and annual US imports of monazite-xenotime are significant, positively-correlated variables with annual Australian monazite-xenotime output that account for 70 per cent of the observed annual variation.[5] Price, itself, has little explanatory power. This result is consistent with by-product behavior on the boundary to Case C where the by-product supply curve is approaching full capacity. The primary output of ilmenite is somewhat relevant to the supply of monazite, but monazite supplies are still responsive to demand changes.

Malaysia is the largest producer of rare earths as a by-product of tin placer mining. The empirical data are limited and inconsistent but still give some general indications about production relationships. In recent years tin mining output has declined steadily and significantly as material substitution has reduced the derived demand for tin. Only export data is available before 1984 so the regression model is for the years 1984–1994. The Malaysian production of rare earths has a significant and position relationship with tin production that explains 76 per cent of the annual observed variation over that time period.[6] This behavior is consistent with a Case C scenerio. If so, rare earths output from Malaysia should be directly affected by the reduction of tin mining.

An associated product of monazite mining is thorium which is present in all monazite concentrates. Data are limited on the thorium market because of the important role that nuclear uses play in its consumption. Indications are, however, that thorium is readily available to meet current demands and that the presence of thorium in monazite concentrates will not serve to increase the output need of monazite. There are exceptions like Brazil and India that do mine and process monazite in order to obtain thorium for use in their nuclear programs. The impact of this on the rare earths market is small. More important impacts are the environmental problems associated with the handling and disposing of thorium in the typical processing of monazite concentrates. The importance of these problems were illustrated in 1991 when Davison Specialty Chemical, the major US consumer of monazite (for petroleum cracking catalysts), and Rhone-Poulenc of France, the world's largest monazite refiner switched to thorium-free feeds because of the cost and lack of sites for disposing of the excess thorium (Metals & Minerals Annual Review, various years). Such switches were possible with the large increase in production of bastnasite by China.

The by-product production of bastnasite from the iron ore mining in China is quite new with little readily available data so little meaningful analysis can be done. It is known to be a large source of competitive material, and China is rapidly becoming a key supplier of rare earths products, particularly because of its large supply of thorium-free bastnasite. This source of rare earths is being used to replace monazite ores from regions like Australia. At this point, there is no reason to assume that typical by-product behavior will not be observed at the Chinese operations. The importance of iron ore to a developing economy like China's will likely insure the availabilty of significant amounts of by-product rare earths minerals.

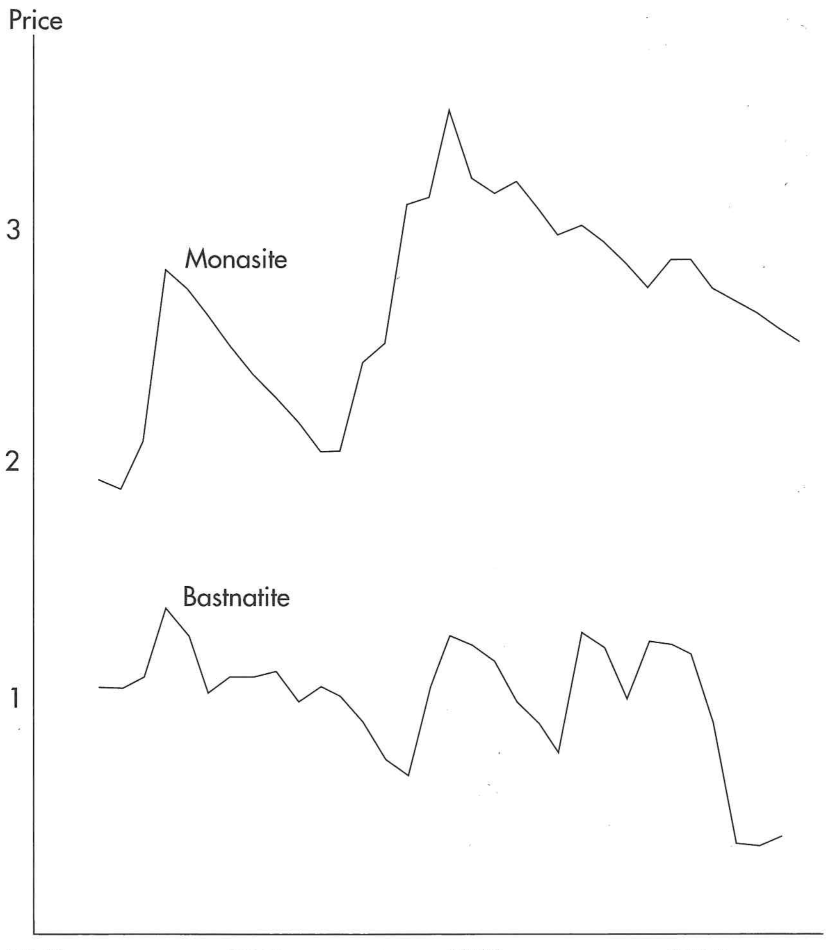
It is apparent that while much of the potential sources of rare earths minerals are by-product in nature there is little problem of restricted availability. The main product production in California of bastnasite is typically below full production capacity. Since 1976 full capacity has been reached only once. The output of monazite-xenotime from heavy sands mining of ilmenite (primarily in Australia) is shown historically to be somewhat dependent on the level of ilmenite production, but data evidence also shows that concentrate output does respond to changes in demand needs indicating that supply potential has not been reached. In addition, annual ilmenite production in Australia has been increasing in recent years which increases the potential supply of raw earths minerals available for recovery while demand has decreased for monazite concentrates because of its thorium component. Tin placer mining output in southeast Asia has been decreasing precipitously and this has reduced the production of monazite. This decrease in output has corresponded with the substitution of new bastnasite production from China for monazite and has presented no supply problems. By-product supplies of rare earths minerals from iron ore mining in China should continue to be an important source in the future as mineral production grows in this large and fast-growing economy. The net result is that rare earths minerals should be readily available for consumptive needs under current mining conditions even with any foreseeeable increase in demand, especially if that increase in demand is for low-volume, high-purity uses in high tech applications.

Rare earths processing relationships

With so many available options for the commercial use of rare earths materials, economic interactions among the various products can be quite complex, but some useful indicators can be established. The underlying economic relationship between the different marketable products recovered from the concentrates is that of co-product. The processor's goal is to maximize total profits over the co-products which jointly determine the level of output. Changing output levels may have, however, different impacts on the individual co-product's profitability as their market needs and conditions can be quite different. Expanding production to increase the output of a product that has a strong demand can lead to excess supplies of co-products with weaker demands. This is a significant issue in the case where the product desired consists of a scarce element and relatively large amounts of the more common elements must be produced as well. Oversupply of the common elements could readily occur. Conversely, scarce element products could be underproduced to prevent oversupply of the common element products. The historic trends of real prices (corrected for inflation) can be used as an indicator of which situation might exist for a particular product. A significantly downward real price trend would be indicative of oversupply relative to demand situation. A significantly upward real price trend would be indicative of the underproduced situation.

Rare earths concentrates are low-value material that are bought by processors as raw material for their operations. The largest region of monazite-xenotime production, Australia, has not historically been a processor of rare earths and has sold its concentrates on world markets. Other monazite-xenotime producers have localized processing for specific purposes but also provide concentrates for exportation. Rhone-Poulenc has been the main processor of exported monazite-xenotime concentrates, historically, but has moved to bastnasite concentrates from China to avoid thorium. Rhone-Poulenc offers a wide range of commercial products in all categories. Molycorp uses its own bastnasite concentrates to provide a wide range of products in all categories as well as selling it to producers of specific products. Japan has several companies that produce high-purity products from imported concentrates. While China has been a major supplier of concentrates, its companies are also developing their own capacity to produce

Figure 2. Bastnasite and monasite real prices (USD)



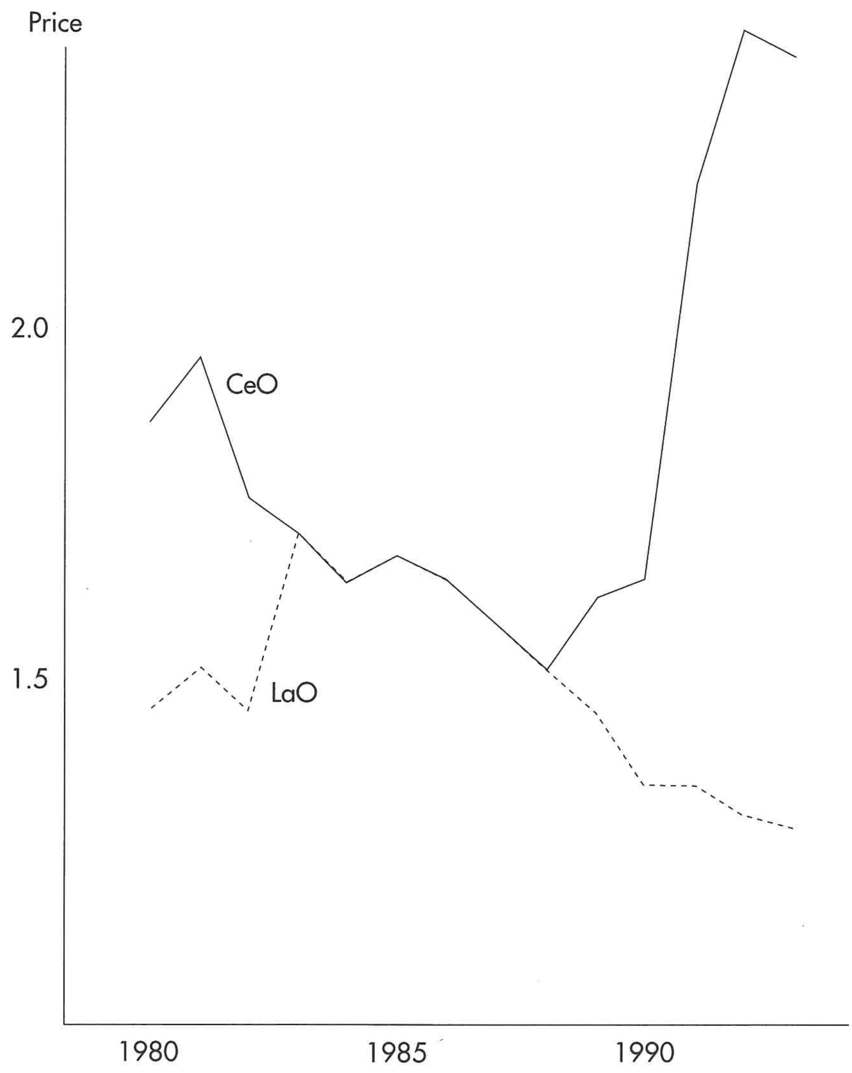
high-purity products as illustrated by the joint venture with Advance Material Resources Ltd of Canada. Other processors specialize in more narrow product ranges – Davison Specialty Chemical in catalysts and Reactive Metals and Alloys in mischmetal of the USA for example.

The processing capacity for rare earths, especially high-purity products for high tech applications, is concentrated among a few firms with cooperative agreements being common. This is typical for minor metals. This degree of concentration will affect market behavior and pricing. The strength of the impact will depend on factors like percent of market share, user sensitivity to price changes, the likelihood of entry by new producers, and the ability and willingness of new producers to coordinate their activities. Typically, these factors have tended to effectively reduce the long-run impact of market concentration in the mineral industries as market forces counter the supplier concentration. This article does not consider the issue in any empirical depth for rare earths processing. In the rare earths processing case, though, as the demand for high-purity products grows and becomes dependable, the appearance of new producers to take advantage of this demand is likely to occur, especially with the excess production of concentrates available in China and Australia. An increase in new capacity (or its threat) may well moderate any long-run impacts of the current degree of concentration.

The real price trends of monazite and bastnasite are shown in Figure 2. The real price for monazite concentrate has been fairly erratic in the short-run while following a fairly constant price trend during 1963 to 1991, largely due to its by-product nature. The thorium disposal problem for monazite concentrates and the growth in Chinese bastnasite concentrates has significant reduced demand since 1991. A new constant long-term price trend may be developing, but it is too early to tell yet. Over the same time period of 1963–1995, the real price of bastnasite concentrates has had two price adjustments upward followed by a prolonged price decline due to a stable nominal price that loses value with inflation. There has been such a downward trend in real price since the last peak in 1979. This strong negative relationship between price and time is indicative of excess capacity and production. This situation has been created by the growth in Chinese by-product production and by Molycorp's main product bastnasite production that is used primarily as a raw material for its processing needs and not necessarily as a marketable product in itself.

The economic relationships for processors who take concentrates and convert them into a specific category of low-purity mixtures and compounds are basic and uncomplicated. The mixture's value depends on the price of the concentrate, cost of the processing, and the demand for the final product. A simple main product model is adequate for analytical purposes. For example, a regression model shows that Molycorp's real prices for bastnasite concentrates and mischmetal have very similar trends.[7] A more

Figure 3. Low-purity oxide real prices (USD)



complex case is that of the multi-product processor. Good case studies of this situation are Molycorp using its bastnasite concentrates, Rhone-Poulenc importing monazite-xenotime concentrates until 1991 and bastnasite concentrates since then, and the heavy element prices posted by Research Chemical before its purchase by Rhone-Poulenc.

Today, Molycorp posts prices for a variety of products in all three product categories ranging from concentrates to low-purity compounds to high-purity oxides. With bastnasite concentrates, the bulk of the rare earths elements is going to consist on average of cerium and lanthanum (over 80 per cent) with appreciable amounts of neodymium and praseodymium (16 per cent). The other elements make up the remaining four percent. For low-purity concentrates and mixtures, the element make-up of the raw material is not an economic factor, and the posted price for these types of products tend to move in a similar pattern as the price of the original bastnasite concentrate as shown for mischmetal. So like the nominal price for bastnasite concentrates, these prices have tended to be very stable with periodical adjustments upward in response to long-run inflation and other cost increases like energy. The real prices, accordingly, are moving downward, in general, suggesting excess supply. There are occasionally price increases for a particular product when its demand increases due to a market change in its use. Such changes are uncommon.

As processing and separation of elements continues, however, co-products are extracted, and the desire to produce one product will necessitate the production of others. As a result, higher-purity products present a more complex joint-product economic situation. Bastnasite concentrate is first separated into cerium-enriched and lanthanum (everything else) concentrates. Low-purity cerium oxide compounds are an important bulk product utilized in industries like glass polishing. The real price of cerium oxide has been rising since 1989 (Figure 3). The real price of lanthanum oxide concentrate has been moving downward since a peak in 1983. There is a significant negative correlation between the two price series. This result suggests the possibility that strong demand for one product can lead to oversupply of the other. Europium oxide can also be separated easily at this stage. Over the last 15 years, there has been a significant decrease in real price. This decrease is highly correlated with the price decrease of bastnasite, suggesting excess supply relative to consumption needs.

The lanthanum oxide concentrate is also used by Molycorp as the feed for the solvent extraction process needed to produce higher purity products (even cerium oxide which still makes up 12 per cent of the material). High-purity products are very small (by weight) relative to bulk needs and has little impact on overall rare earths mining output. High-purity production can be restricted by the capacity to do solvent extraction, and existing facilities are currently concentrated among only s few key producers. As demand has grown for high-purity products, the capacity to produce them has increased and will continue to increase as seen today in China. Solvent extraction, itself, presents an interesting economic question in that the technical process creates a range of purified products whose quantity depends on the percent availability of the elements in the feed material. There need not be any correlation between how much is produced of each element product based on its percentage and chemical situation in the feed material and the industrial demand for the products. Accordingly, short-term adjustments to market needs may not be easy to make. One of the elements that is commercial available in bastnasite concentrates, samarium, has shown strong changes in demand over the last decades and makes an excellent case study on how production responds to market needs.

Figure 4. Samarium real prices (USD)

The increase in demand for samarium was for use in samarium-cobalt permanent magnets. The real price for samarium tripled within three years (Figure 4). There is an important joint-product problem of providing samarium. Samarium makes up less than one percent of bastnasite, less than three percent of monazite, and just over one percent of xenotime. Any significant increase in samarium production would have a sizeable impact on the supplies of more common elements. Therefore, the natural market response to increase output in response to rising demand would have to be tempered to protect the other element markets (hence the large price increase). One of the advantages of using rare earths is that their chemical similarities often allow for substitution among the elements. It is often possible, therefore, to substitute a more common product in ample supply for scarcer material which is why low-purity products make up such a large portion of rare earths use. In this particular case, supplies of cobalt were also a concern so industry had a strong incentive to find a new mixture for permanent magnets. The result has been the development of the now favored neodymium-iron-boron permanent magnet. Neodymium is a much more common element in bastnasite (12 per cent) and monazite (18 per cent) and creates less of a joint-product problem. Price responses were quick. The real price of samarium dropped by one-third immediately and continues to drop sharply. The real price of various neodymium products have strengthen but the larger availability of neodymium has kept price increases moderate so far. Meanwhile, all the other light, high-purity element oxides have shown strong downward trends in their real prices that are significantly correlated with the decreasing real price of bastnasite (Table 1). This trend would be expected in a period of increasing supply without a corresponding increase in demand.

Table 1. Molycorp correlation matrix (1982–94)

	Year	Bast	Ce	La	Pr	Eu	Gd
Year	1.000	-.964	-.764	-.801	-.974	-.933	-.966
Bast	-.964	1.000	.761	.769	.941	.932	.947
Ce	-.764	.761	1.000	.764	.880	.789	.815
La	-.801	.769	.764	1.000	.846	.889	.848
Pr	-.974	.941	.880	.846	1.000	.952	.973
Eu	-.933	.932	.789	.889	.952	1.000	.963
Gd	-.966	.947	.815	.848	.973	.963	1.000

Rhone-Poulenc used monazite concentrates until 1991 with a very small amount of xenotime concentrates (one percent) for its process feed. More recently, it has used bastnasite concentrates from China. Real price movements for Rhone-Poulenc's lighter rare earth elements over the last fifteen years have mainly decreased over time with the exceptions of samarium and lanthanum (Table 2). These results are quite similar with those of Molycorp except for the case of lanthanum.

Research Chemical, until its purchase by Rhone-Poulenc in 1990, was a provider of heavy element rare earths (and the lighter ones as well). Rhone-Poulenc has been listing prices for the heavy elements since 1988 as well. Over more than 15 years of data for real prices posted by Research Chemical, the real prices of yttrium, lutetium, ytterbium, terbium, and thulium had significant downward trends, and the real price of erbium was significant upward (Table 3). Yttrium, being by far the most available of the heavy elements, seems to suffer from oversupply over the long-run in order to provide the other desired heavy elements (as well as being recovered from monazite). Lutelium ytterbium, terbium, and thulium also seemed to be in oversupply relative to demand while erbium was undersupplied. Holmium's and dysprosium's real prices showed no significant trends, suggesting changing demand patterns. As a general observation, the higher the percent of the element in the feed material, the more negative the price trend seemed to be. The real prices posted by Rhone-Poulenc for heavy elements have moved sharply downward in the short

Table 2. Rhone – Poulenc price correlation matrix (1977–94)

	Year	Mona	Ce	La	Pr	Eu	Gd	Sm	Y
Year	1.000	-.569	-.617	.600	-.957	-.878	-.974	.209	-.887
Mona	-.569	1.000	.815	-.571	.565	.822	.608	.504	.792
Ce	-.617	.815	1.000	-.810	.709	.750	.712	.484	.728
La	.600	-.571	-.810	1.000	-.740	-.676	-.758	-.297	-.739
Pr	-.957	.565	.709	-.740	1.000	.860	.986	-.103	.862
Eu	-.878	.822	.750	-.676	.860	1.000	.897	.225	.969
Gd	-.974	.608	.712	-.758	.986	.897	1.000	-.091	.915
Sm	.209	.504	.484	-.297	-.103	.225	-.091	1.000	.143
Y	-.887	.792	.728	-.739	.862	.969	.915	.143	1.000

Table 3. Research chemical price correlation matrix (1973–88)

	Year	Y	Dy	Ho	Lu	Tm	Tb	Er	Tb
Year	1.000	-.681	-.243	.216	-.966	-.738	-.942	.579	-.758
Y	-.681	1.000	.613	-.147	.818	.622	.842	-8.957E-3	.539
Dy	-.243	.613	1.000	-.499	.364	.041	.440	.292	.034
Ho	.216	-.147	-.499	1.000	-.203	.422	-.261	.341	.255
Lu	-.966	.818	.364	-.203	1.000	.747	.993	-.406	.758
Tm	-.738	.622	.041	.422	.747	1.000	.8714	-.144	.769
Tb	-.942	.842	.440	-.261	.993	.714	1.000	-.333	.721
Er	.579	-8.957E-3	.292	.341	-.406	-.144	-.333	1.000	-.232
Tb	-.758	.539	.034	.255	.758	.769	.721	-.232	1.000

history of their posting, possibly in response to Rhone-Poulenc's larger production operations in general which supply more of these elements without a corresponding increase in demand (Table 4).

Evidence shows that the production of individual, purified elements does not adjust well to changes in market demand. Historic real prices show that most elements have significantly negative trends that indicate a persistent over-production relative to demand. A few key elements are strongly demanded and are typically under-produced leading to a significantly increasing price. It is hard to alter the amount of production of a particular element because of the co-product nature of rare earths and the different crustal abundance of each element. Often, the most effective way to adjust is to substitute a more common element for a scarcer one. This is effective in reducing the demand for the scarce element and increasing the use of the common one. The recent case of samarium and neodymium is an example.

Conclusion

The economics of the rare earths market is affected by the by-product nature of rare earths mining and by the co-product relationships of rare earths processing. As a production by-product, rare earths concentrates (particularly monazite) are dependent on the market trends of titanium and tin. With the increasing production of ilmenite in Australia and the rapid growth of iron ore production in China, the rare earths concentrate production trend has been toward oversupply and declining real prices. The decline of tin mining in Southeast Asia has had little impact on available supplies. The economics of processing rare earths concentrates into marketable products is affected by their co-product relationships which are based on crustal abundance and chemistry. Meeting a changing demand for one product affects the supply for others so adjustments must incorporate the impacts elsewhere. The recent trend toward high-purity products for high-tech purposes has increased the probability of market co-product imbalances. The result of these two conditions is a commercial market that is not easily able to adjust to changing consumption needs.

Due to the similarities of chemistry and properties of rare earths elements, adjustment problems can be overcomed by the use of abundant low-purity mixtures and compounds where the individual element make-up is not critical or through the substitution of a more common element for a scarcer one in higher-purity needs. This seems to be the most practical market adjustment mechanism directly controllable by the rare earths industry. The wide use of low-purity products and the samarium-neodymium case study show this sort of behavior. The concentration of high-purity production capacity among a few firms presents another potential market problem. However, there are no shortages of raw materials nor are any likely in the near future. The availability of excess concentrates provides opportunities for new processors to enter the market as seen in China. Australia with its large supply of monazite is another excellent site for new entries. Shortages or noncompetitive prices of rare earths products for high-tech needs should not be a significant long-run problem because of the correction mechanism and potential competition.

Table 4. Rhone-Poulenc price correlation matrix (1988–94)

	Year	Y	Dy	Ho	Lu	Tm	Yb
Year	1.000	-.941	-.871	-.972	-.929	-.802	-.727
Y	-.941	1.000	.944	.978	.957	.898	.769
Dy	-.871	.944	1.000	.952	.981	.946	.830
Ho	-.972	.978	.952	1.000	.985	.869	.764
Lu	-.929	.957	.981	.985	1.000	.883	.823
Tm	-.802	.898	.946	.869	.883	1.000	.769
Yb	-.727	.769	.830	.764	.823	.769	1.000

Notes

1. Kilbourn, 1988.
2. *Metals & Minerals Annual Review*, 1995.
3. U.S. Bureau of Mines, various years.
4. Equation 1: *US Bastnasite = f (US consumption).* Years: 1963–94; R-squared=0.72; tstat=8.84.
5. Equation 2: *Australian Production of Monazite & Xenotime = f (Australian Ilmenite Prod., US Imports).* Years: 1969–94; R-squared=0.60; t-stat=4.80; t-stat=4.37.
6. Equation 3: *Malaysian Production of Monazite & Xenotime = f (Malaysian Tin Production),* Years: 1984–1994; R-squared=0.76; t-stat=5.29.
7. Equation 4: *Mischmetal Price = f (US Bastnasite Price).* Years: 1980–1994; R-squared=0.79; t-stat= 6.97.

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