AN ECONOMIC EVALUATION OF THE RARE EARTH INDUSTRY

by

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ABSTRACT

This study analyzes the rare earth industry to determine what degree of vertical integration is necessary, desired, and required for a company to enter and maintain a profitable position within the rare earth industry. The analysis developed in this study was based on a market survey and investment evaluation. The market survey included an analysis of the historical and current rare earth industry in order to evaluate and forecast the future supply/demand and market potential of rare earths. The investment evaluation was based on the development of a base case model which represented the rare earth industry from the mining stage to the sale of high-purity end products. An economic evaluation was conducted on the base case rare earth model using the discounted cash flow rate of return (DCFROR) and net present value (NPV) methods.

It was concluded that: 1) The high-purity, separated rare earths and metallurgical additives had a higher growth potential than the growth potential of concentrates and intermediate compounds. 2) A low operating cost primary rare earth mine with a substantial reserve base is not necessarily advantageous; whereas, a rare earth chemical processing plant is an essential element for entering and maintaining a profitable position in the rare earth industry.

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CHAPTER 1

INTRODUCTION

The rare earths are a transition subgroup of the periodic table and comprise the 15 elements having atomic numbers 57 (lanthanum) to 71 (lutetium). The close similarity of their chemical properties and the tedious methods known for separating them made these elements expensive and scarce. Hence, until recently, very little industrial application of the elements was developed. Through continued research and development by both government and industry, new separation techniques were developed. World-wide interest increased when less expensive rare earths became commercially available. In the last few years, extensive research has greatly expanded rare earth applications and markets to the point where the future in fields such as metallurgy (high-strength low-alloy) and electronics (phosphors) appears rather bright.

Companies today are interested in diversification through attractive investment opportunities. Hence, the purpose of this thesis is to analyze the rare earth industry and evaluate the profitability potential in this industry.

The methodology consists of a rare earth market analysis, development of an industry model including capital and operating costs, and an economic evaluation with an associated sensitivity analysis. The market analysis includes a study of the historical and current industry with emphasis on the period from 1960 to the present. A discussion and analysis of the resources, reserves, and capacity utilization is presented with respect to the three dominant minerals: bastnaesite, monazite, and xenotime, which are major suppliers of rare earths. A technology section is provided to acquaint the reader with the complex solvent extraction and ion exchange processes used to separate the elements and produce high-quality compounds. The processing technique is an important point to consider because several elements may need to be extracted before the desired element(s) can be produced, thus increasing costs. A supply/demand analysis is conducted with respect to the major market applications in order to forecast the future market potential of rare earths.

This study will entail the development of a base case model (including capital and operating costs) to represent the rare earth industry from mining the deposit to marketing the end products. The model is divided into various systems including mining/milling, chemical processing, and mining/milling/chemical processing (which represents total vertical integration).

Finally, an economic evaluation is conducted to determine the profitability in entering the rare earth industry. In addition, a sensitivity analysis will be presented to illustrate the sensitivity of the model's rate of return to changes in revenue, capital, and operating costs.

CHAPTER 2

THE LANTHANIDES

Description and Properties

The rare earths, also known as lanthanides, are a series of 15 chemically similar elements with atomic numbers 57 through 71. Yttrium and thorium (atomic numbers 39 and 90) are generally included in discussions regarding rare earths because of the close association with the lanthanide elements. Yttrium, in particular, has many chemical properties similar to the lanthanide series.

The first seven members of the lanthanide series (La through Eu) are often referred to as the cerium subgroup, because cerium is their most naturally abundant member. The remaining eight elements (Gd through Lu) together with yttrium are called the yttrium subgroup. In a similar manner, yttrium is the most naturally abundant element for this subgroup. The two subgroups are also referred to, respectively, as the "light" and "heavy" rare earth elements.

The chemical properties of the lanthanide elements are dominantly influenced by their electron configuration. As shown in Table 1, the tripositive state is characteristic of the rare-earth elements.

Table 1

Rare Earths and Yttrium Valences and Oxides

Element	Atomic Number	Valence	Oxide	
(La) Lanthanum	57	3	La_2O_3	
(Ce) Cerium	58	3, 4	CeO_2	Cerium
(Pr) Praseodymium	59	3, 4	Pr_6O_{11}	Group-
(Nd) Neodymium	60	3	Nd_2O_3	"Light
(Pm) Promethium	61	3	Pm_2O_3	Rare Earths"
(Sm) Samarium	62	2, 3	Sm_2O_3	
(Eu) Europium	63	2, 3	Eu_2O_3	
(Gd) Gadolinium	64	3	Gd_2O_3	
(Tb) Terbium	65	3, 4	Tb_4O_7	
(Dy) Dysprosium	66	3	Dy_2O_3	Yttrium
(Ho) Holmium	67	3	Ho_2O_3	Group-
(Er) Erbium	68	3	Er_2O_3	"Heavy
(Tm) Thulium	69	3	Tm_2O_3	Rare Earths"
(Yb) Ytterbium	70	2, 3	Yb_2O_3	
(Lu) Lutetium	71	3	Lu_2O_3	
(Y) Yttrium	39	3	Y_2O_3	

Source: Spedding and Daane, 1961.

Consequently, the separation and purification of the individual lanthanides presents a formidable problem, as will be discussed in a later section.

An exhaustive review of the physical and chemical properties of the rare-earth elements and compounds is beyond the scope of this dissertation. However, a brief description of the physico-chemical properties of the lanthanides is presented in Appendix A.

Industrial History

The rare earths were first recognized as elements around 1750, but were not studied in detail until the turn of the century. The term "earths" came from the early chemical term for oxide, since the rare earths were discovered as oxides; in addition, the source material was relatively rare, thus the reason for the name.

Because of similar chemical properties, the rare earths were not amenable to separation and identification by the more conventional techniques then available to chemists. Despite active study, it took until 1908 for the last of the naturally occurring lanthanides to be identified. The last lanthanide, promethium, was identified in 1946, after the element had been synthesized by uranium fission. Its occurrence in nature is questionable.

The first commercial use of a rare earth mineral, monazite, occurred in 1884. Thorium extracted from monazite was used in the manufacture of incandescent mantles for gas lighting. Ceria was needed to make the mantle glow properly. This application peaked in 1912, being superseded by the advent of electric lighting. Because of the small quantities used, gas mantle production accounted for very minor consumption of rare earths.

A larger commercial rare earth application was developed in 1903 by taking advantage of the pyrophoric properties of mischmetal, a naturally occurring mixture of lanthanide metals. Mischmetal was first used in making superior lighter flints. It was considered more advantageous from a cost standpoint to commercially utilize rare earths in natural mixtures rather than in their separated form, particularly since the available techniques required to separate the rare earths were extremely laborious and expensive.

Other applications began to emerge in the 1920's when it was discovered that certain rare earth oxides produced colored glass with special properties. Cerium oxide was first used as a glass polishing medium in the 1930's; subsequently, the value of rare earths as decolorizer in glass was discovered in the 1940's. A number of metallurgical applications were developed during the 1950-1960 period. Rare earth petroleum catalysts were introduced in the early 1960's.

Prior to 1960, industrial development and usage evolved slowly. The rare earth market was small, and growth was modest when compared to market size. However, since 1960, the introduction and development of new applications has accelerated market growth. In particular, the discovery that europium and yttrium oxides, which were used in color TV phosphors to improve color fidelity, significantly stimulated the demand for these two oxides.

Monazite, a rare earth mineral, was the principal source of rare earth oxide (REO). Monazite, however, was a by-product of heavy mineral sands and tin operations. Consequently, the discovery of bastnaesite, another rare earth mineral, in 1949 at Mountain Pass, California was of significant importance. As a result of this enormous primary bastnaesite deposit being brought into production by Molycorp in 1952, the rare earth industry, and particularly Molycorp, promoted the use of rare earths in those applications requiring large tonnages.

The mutual growth of the rare earth industry and the Mountain Pass operations was no coincidence. It was the commercial availability of rare earths on a scale first made possible by the capacity of the Mountain Pass operations that spurred research and development efforts toward new applications for rare earths.

Resource Base

The rare earth elements are relatively abundant in the earth's crust when compared to copper, cobalt, lead, zinc, molybdenum, or tungsten. However, even the more common rare-earth elements tend to be dispersed in nature and are rarely found in primary concentrations of sufficient size and grade to constitute mineable deposits (Adams and Staatz, 1973). Hence, knowledge of the lanthanide distribution in minerals from various occurrences and environments is of considerable economic importance in the search for specific rare-earth elements.

Mineralogy

Lanthanides are essential constituents in more than 150 mineral species. Lanthanides occur in nature as silicates, carbonates, phosphates, fluorites, and sulfates. Minerals that are actual or potential sources of the rare earth elements are presented in Table 2 together with their chemical composition. It is generally common to find radioactive elements such as thorium, uranium, strontium, or plutonium associated with lanthanide minerals (Heinrich, 1958, p. 241).

Although rare earths are found in several mineral species, only three occur in quantities of economic significance: bastnaesite, monazite, and xenotime. Bastnaesite has surpassed monazite as the preferred rare earth mineral because of supply and processing advantages. Comparative assays of these lanthanide minerals are given in Table 3.

Bastnaesite

Bastnaesite, a fluocarbonate mineral, is the major raw material source for the light rare earths (cerium, lanthanum, neodymium,

Table 2

Common Rare-Earth and Thorium Minerals

Mineral	Composition	Mineral	Composition
Oxides:		Phosphates - continued:	
Cerianite	CeO_2	Florencite	$Ce,Al_3(PO_4)_2(OH)_6$
Thorianite	ThO_2	Monazite	$(Ce,La,Th,Y)PO_4$
Fluorides:		Rhabdophane	$(Ce,Y)PO_4 \cdot H_2O$
Fluocerite	$(Ce,La)F_3$	Weinschenkite	$YPO_4\ 2H_2O$
Fluorite, cerian		Xenotime	YPO_4
(yttrocerite)	CaF_2 + dominantly Ce subgroup	Multiple oxides containing	
Fluorite, yttrian		columbium (niobium),	
(yttrofluorite)	CaF_2 + dominantly Y subgroup	tantalum and titanium:	
Carbonates and fluocarbonates:		Brannerite	$(U,Ca,Fe,Th,Y)_3Ti_5O_{16}$
Ancylite	$(Ce,La)_4(Sr,Ca)_3(CO_3)_7(OH)_4 \cdot 3H_2O$	Eschynite-priorite series:	
Bastnasite	$CeFCO_3$	Eschynite	$(Ce,Ca,Fe,Th)(Ti,Nb)_2O_6$
Doverite	$CaY(CO_3)_2F$	Priorite	$(Y,Er,Ca,Fe,Th)(Ti,Nb)_2O_6$
Parisite	$2CeFCO_3 \cdot CaCO_3$	Euxenite-polycrase series:	
Synchisite	$CeFCO_3 \cdot CaCO_3$	Euxenite	$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$
Silicates:		Polycrase	$(Y,Ca,Ce,U,Th)(Ti,Nb,Ta)_2O_6$
Allanite	$(Ca,Ce,Th)_2(Al,Fe,Mg)_3 \cdot Si_3O_{12} \cdot (OH)$	Fergusonite-formanite	
Cenosite	$Ca_2(CeY)_2Si_4O_{12}CO_3H_2O$	series:	
Cerite	$(Ce,Ca)_2Si(O,OH)_5$	Fergusonite	$(Y,Er,U,Th)(Nb,Ta,Ti)O_4$
Gadolinite	$Be_2FeY_2Si_2O_{10}$	Formanite	$(Y,Er,U,Th)(Ta,Nb)O_4$
Huttonite	$ThSiO_4$	Loparite	$(Ce,Na,Ca)(Ti,Nb)_2O_6$
Stillwellite	$(Ce,La,Ca)BSiO_5$	Perovskite[2]	$CaTiO_3$
Thalenite	$Y_2Si_2O_7$	Pyrochlore-microlite	
Thorite	$ThSiO_4$	series:	
Thortveitite	$(Sc_2Y)_2Si_2O_7$	Betafite	$(U,Ca)(Nb,Ta,Ti)_3O_9 \cdot nH_2O$
Phosphates:		Microlite[3]	$(Na,Ca)_2Ta_2O_6(O,OH,F)$
Apatite[1]	$Ca_5(PO_4)_3F$	Pyrochlore	$NaCaNb_2O_6F$
Brockite	$(Ca,Th,Ce)PO_4 \cdot H_2O$	Samarskite	$(Y,Er,Ce,U,Fe,Th)(Nb,Ta)_2O_6$
		Yttrotantalite	$(Fe,Y,U,Ca)(Ta,Nb,Zr,Sn)O_4$

[1] May contain rare-earth elements.

[2] Cerian varieties known.

[3] Cerian and thorian varieties known.

Source: Adams and Staatz, 1973, p. 550

Table 3

Comparative Analysis of Rare Earth Minerals

(Percent of Total REO)

	Bastnaesite California Percent	Monazite Australia Percent	Xenotime Malaysia Percent	Phosphate Rock Florida Percent
La_2O_3	32.0	20.2	0.5	25.4
CeO_2	49.0	45.3	5.0	20.3
Pr_6O_{11}	4.4	5.4	0.7	5.1
Nd_2O_3	13.5	18.3	2.2	11.9
Sm_2O_3	0.5	4.6	1.9	5.3
Eu_2O_3	0.1	0.05	0.2	0.7
Gd_2O_3	0.3	2.0	4.0	2.4
Tb_4O_7	———	———	1.0	0.9
Dy_2O_3			8.7	2.8
Ho_2O_3			2.1	0.7
Er_2O_3	0.1	2.0	5.4	3.6
Tm_2O_3			0.9	0.3
Yb_2O_3			6.2	1.4
Lu_2O_3	———	———	0.4	0.5
Y_2O_3	0.1	2.1	60.8	18.7
	100.0	100.0	100.0	100.0

Source: Moore, 1979; Parker and Baroch, 1971.

praseodymium, gadolinium, samarium, and europium). The mineral has been found in vein deposits, contact metamorphic zones, pegmatites, most importantly in carbonatites and related veins, and as a rare accessory mineral in igneous rocks. Bastnaesite is usually the desired source as it contains less than one percent of radioactive elements (Heinrich, 1958). Currently, bastnaesite is mined as a primary source.

Monazite

Monazite, a rare-earth phosphate, is a major source for the light rare earths, yttrium, and thorium. Thorium is usually present in substitution for the rare earth metals, varying in content between 3 and 9 percent thoria. Monazite has been found as an accessory mineral in igneous and metamorphic rocks, vein deposits, and placer deposits. Currently, monazite is produced as a by-product of beach sand and tin operations.

Xenotime

Xenotime, also a rare-earth phosphate, is a major source of yttrium and the heavy rare earths. Xenotime has been found as an accessory mineral in igneous rocks, with monazite in metamorphic rocks, and most commonly in placer deposits. Currently, xenotime is produced as a by-product of tin operations.

Leach Liquors

Although leach liquors from phosphate rock is not currently a rare earth source, the future potential is significant and, therefore, deserves mention. The rare earth content of apatite, the principal mineral constituent of phosphate rock, is only 0.01 to 0.1 percent by weight of the apatite. However, the potential for recovery of substantial quantities of rare earth elements becomes appreciable because of the enormous tonnages of phosphate rock processed each year. It has been estimated that the potential annual recoverable rare earths from Florida phosphate is approximately 13,000 tons of mixed rare earth oxides (Pincock, Allen, & Holt, Inc., personal communication, 1980), slightly less than half of the world's current REO production.

Resources - Reserves

The rare earth industry is based largely on three main mineral sources: bastnaesite, monazite, and xenotime. In regard to the light rare earths, bastnaesite is the principal rare earth source, with monazite the second most significant. Xenotime is the main source for yttrium and the heavy rare earths. These minerals are extracted from deposits in the United States, Brazil, Russia, Malaysia, India, and Australia. An assessment of world rare earth and yttrium resources has been compiled by the U.S. Geological Survey and U.S. Bureau of Mines. A summary of the reserve estimate is presented in Table 4.

Table 4

Assessment of World Rare Earth Elements and Yttrium Reserves

	REO Reserves (1,000 ST)	Yttrium Reserves (S. Tons)
North America:		
United States	5,000	3,500
Canada	250	2,400
South America:		
Brazil	350	2,500
Europe:		
Finland, Norway, Sweden	60	200
Africa:		
Malagasy Republic	20	--
Republic of South Africa	5	--
Egypt	10	--
Malawi	15	--
Other	20	--
Asia:		
Malaysia	30	600
India	1,000	20,000
Republic of Korea	50	1,000
Sri Lanka	10	200
Other	10	200
Australia	400	6,000
U.S.S.R.	500	1,600
World Total	7,730	38,200

Source: Moore, 1979, p. 6, 7

Rare earths occur in a variety of geological environments. The more favorable types of environments from an economic viewpoint are carbonatites and heavy mineral beach sands.

Carbonatites are igneous assemblages of essentially carbonate minerals found in the form of intrusions and complexes along major rift zones cutting old stable continental shield areas. The two most significant commercial carbonatite deposits are Molycorp's Mountain Pass deposit in California and RTZ's Palabora deposit in South Africa. The deposit at Mountain Pass supplies nearly all of the world's bastnaesite, while Palabora is more concerned with copper production although rare earth concentrates have been produced in the past. The Mountain Pass deposit contains an estimated five million tons of rare-earth oxide (REO), probably 80 to 90 percent of the U.S. reserve and the bulk of world reserves. Interest in the carbonatites of East Africa (namely Tanzania, Malawi, and Burundi) and Scandinavia (particularly southern Norway) has in the past been noted as a likely source of rare earths. Sporadic production from Malawi and Burundi has been reported; however, there was severe competition from Molycorp's Mountain Pass operation. The African operation's major disadvantages were high operational costs, lengthy transportation distances, and political problems.

Most economic exploitable monazite deposits occur as placer deposits where monazite is produced as a byproduct from heavy mineral sands which are processed for ilmenite, rutile, and zircon. Australia and Malaysia are major sources of monazite, which is recovered as a byproduct from placer deposits and tin mine tailings, respectively. Brazil and India are major producers of monazite from beach sands; however, the Brazilian and Indian governments have restrictions on the export of concentrate prior to the removal of thorium. Thailand, a minor monazite producer, recently resumed rare earth oxide (REO) exports after a two-and-a-half year export ban by the Thai government.

A rare vein deposit of primary monazite was mined at Steenkampskraal in the northern part of the Cape Province of the Republic of South Africa. This unique vein deposit was a major source of monazite during the 1953-1963 period (Overstreet, 1967).

Sporadic domestic production of monazite from beach placers occurred in the southeastern United States. Fluvial placer deposits in the northwestern United States have been noted to contain monazite.

Xenotime has been produced, together with monazite, from placer deposits. However, a majority of xenotime is exclusively produced as a byproduct from uranium and tin processing. Currently, xenotime is supplied mainly from Malaysia as a byproduct of tin production.

Very little exists in the literature about China as a potential source of rare earths. However, recent issues of World Mining (Argall, October 1979 and January 1980) indicate that resources on the order of one billion tons of ore grading from 1.0 to 6.0 percent with high grade areas containing 10 percent rare earths exist in the Bayan Obo iron ore mine in China's Nei Monggol Autonomous Region, 95 miles north of Baotou.

Geological descriptions of the Bayan Obo mine indicate that it is a rare, one-of-a-kind deposit. Rare earth mineral types such as bastnaesite, monazite, beiyinite, oborite, and tantalian aeschynite, have been reported. Locally pyrite, chalcopyrite, galena, sphalerite, and molybdenite are also present. Thorium-poor monazite has been reported; however, radioactive material does exist within other mineral matrices (Lee, 1970).

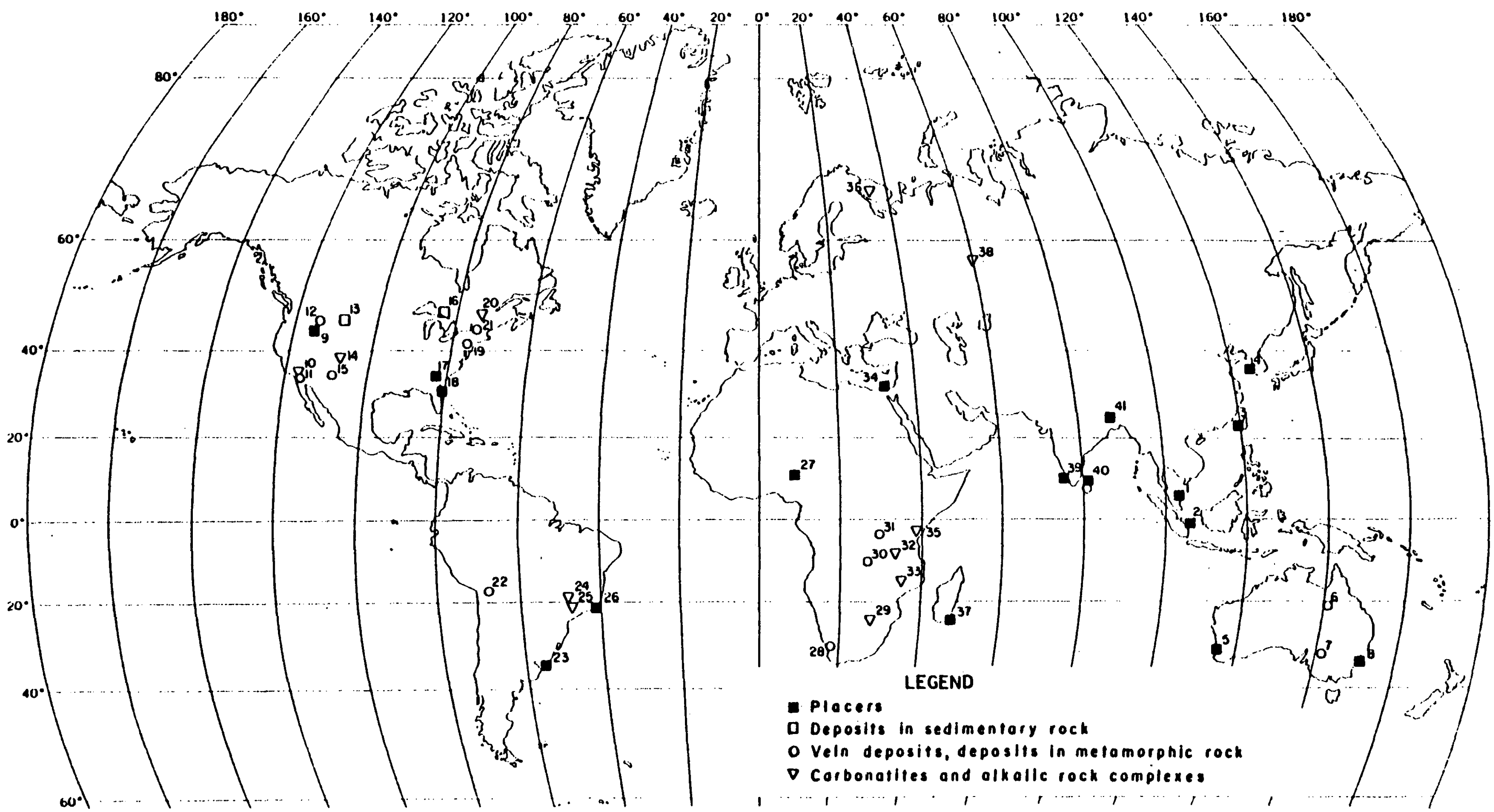
Some of the more important rare earth deposits of the world are shown in Figure 1 and listed in Table 5. The inventory is not complete and estimates of the quantity of rare earth minerals present are not available for all deposits. Hence, the 20-million-ton rare earth oxide resource total given in the table should be regarded as minimal. (The Bureau of Mines has estimated total world resources of rare earths to be about 47 million tons of REO).

The following are among the factors that could greatly influence the total resource figure:

1) The very large, unreported rare earth resources of the Communist countries, notably the U.S.S.R.;

2) The many important, unevaluated deposits, such as the thorite veins in the United States and the many carbonatite deposits in Africa;

Figure 1 -Location of the world's principal rare-earth deposits.



Source: Parker and Baroch, 1971

3) The extent to which large, low-grade deposits, such as the Blind River-Elliot Lake conglomerates in Canada or the Phosphoria Formation of the Western U.S. are considered; and

4) The reconcentration of sea beach deposits with time.

World reserves of rare earths are large and expected to be adequate for consumers for several decades at current rates of demand. Hence, there is little incentive at present to search for and develop new deposits. However, this situation could change rapidly depending on research, development and advanced industrial technology.

Table 5

Rare-Earth Deposits of the World and Their Potential Resources

Location	Deposit[3]	Type	Minerals	Remarks	Rare-earth oxide[1] resources, tons
North America: Canada	(16) Blind River-Elliot Lake	Conglomerate	Brannerite, monazite	Byproduct potential may be much larger than shown.	50,000
	(20) Oka	Carbonatite	Pyrochlore up to 9 percent RE_2O_3	Large byproduct potential	
United States	(10) Mountain Pass, Calif.	do	Bastnaesite	Large operation	5,000,000
	(11) Music Valley, Calif.	Metamorphic rocks	Xenotime, monazite	Insufficient data	
	(9) Idaho-Montana placers, includes Bear Valley, Idaho	Placer	Euxenite Uranothorite		36,000
			Monazite		4,500
	(12) Lemhi Pass, Idaho-Mont.	Vein	Thorite	Little data	
	(12) Mineral Hill district, Idaho-Mont.	do	Thorite, monazite, others	do	
	(13) Bald Mountain, Wyo.	Conglomerate	Monazite		15,000
	(14) Powderhorn and Wet Mountain areas, Colo.	Vein and carbonatite	Thorite, bastnaesite, xenotime	do	
	(15) Gallinas Mountains, N.M.	Vein	Bastnaesite	do	
	(17) Piedmont area, N.C. and S.C.	Stream placers	Monazite (minor xenotime)	Scattered deposits	600,000
	(18) Atlantic coast beaches	Beach placers	Monazite	Only Hilton Head Island, S.C. evaluated	60,000
	(21) Mineville, N.Y.	Magnetite deposit	Apatite, bastnaesite	Large rare-earth byproduct potential	
	(19) Dover, N.J.	do	Xenotime, doverite, bastnaesite	Little data	

See footnotes at end of table.

Source: Parker and Baroch, 1971.

Table 5

Rare-Earth Deposits of the World and Their Potential Resources (Continued)

Location	Deposit[3]	Type	Minerals	Remarks	Rare-earth oxide resources,[1] tons
South America:					
Brazil	(26) Atlantic coast	Beach placers	Monazite		180,000
	Others	Stream placers	Monazite		
	(25) Morro do Ferro	Alkalic complex	Allanite, bastnaesite		300,000
	(24) Araxa	Alkalic complex	Unknown		90,000
Uruguay	(23) Atlantida	Beach placer	Monazite	1 area sampled	288
Bolivia	(22) Llallagua area	Vein	Monazite in tin deposits	Not evaluated	
Europe: U.S.S.R.	(36) Kola area	Alkalic rocks and carbonatite	Apatite, loparite, others	Large, estimated 60,000,000 tons apatite (1933)	
	(38) Kyshtym area (Vishnevye Mt.)	Alkalic rocks and placers	Cerite, bastnaesite, allanite, apatite	Apatite contains rare-earth oxides	
Africa:					
Nigeria	(27) Plateau Province	Tin placers	Monazite, thorite	Small annual production	
United Arab Republic (Egypt)	(34) Nile delta	Stream placers	Monazite		120,000
Burundi	(31) Karonge mine	Vein	Bastnaesite		
Malawi	(33) Kangankunde Hill	Carbonatite	Monazite	Inferred for 100 feet of depth	10,800
Kenya	(35) Mrima (Jombo)	Alkalic complex and carbonatite	Monazite, pyrochlore	Probably large deposit	

See footnotes at end of table.

Source: Parker and Baroch, 1971.

Table 5

Rare-Earth Deposits of the World and Their Potential Resources (Continued)

Location	Deposit[3]	Type	Minerals	Remarks	Rare-earth oxide[1] resources, tons
Tanzania	(32) Panda Hill (Mbeya)	Carbonatite	Pyrochlore, apatite	Large deposit	
Republic of South Africa	(29) Glenover	do	Monazite	Not evaluated	
	(28) Steenkampskraal	Vein	do	Mined out (?)	9,000
Zaire (Kinshasa)	(30) Shinkolobwe	do	do	do	
Malagasy Republic	(37) Ft. Dauphin area	Placer	do	Indicated	60,000
Asia:					
India	(39) Chiefly Kerala State	Beach placer	do	5,000,000 tons[2]	3,000,000[2]
	(41) Bihar and West Bengal	Alluvial placers	do	Large potential	
Ceylon	(40) West and northeast coasts	Beach placers	do	1 northeast deposit	6,000
Malaysia	(1) Various	Placers	do	Tin mining byproduct	
Indonesia	(2) Various	do	do	Small production	
Taiwan	(3) Coastal areas	Beach placers	do		6,000
Korea	(4) Various	Placers	do	Partly evaluated	54,900
Australasia:					
Australia	(5,8) Various	Beach placers	do	Byproduct of Ti-Zr	480,000
	(6) Mary Kathleen mine	Metamorphic	Allanite, stillwellite, others	Not evaluated	
	(7) Radium Hill	Vein	Brannerite	do	
China	(42) Bayan Obo	Carbonatite	Bastnaesite, monazite	Byproduct of iron ore mine	10,000,000
Total					20,082,488

[1]Monazite assumed to contain 60 percent rare-earth oxides; euxenite assumed to contain 15 percent rare-earth oxides.
[2]Estimated total for all deposits in India.
[3]Numbers refer to locations on Figure 1.

Source: Parker and Baroch, 1971.

CHAPTER 3

TECHNOLOGY

A chapter on the mining, milling, and chemical processing of rare earths is provided to aid in the foundation of cost estimating which will be undertaken in a later chapter.

Mining

Rare earths are currently mined exclusively via surface methods. Underground rare-earth mines have existed, but are generally rare because of the high operating costs.

Bastnaesite

Although bastnaesite occurs in several deposits around the world, the largest and most thoroughly exploited deposit is located near Mountain Pass, California. Hence, this installation will provide the base used to describe the beneficiation techniques employed to upgrade bastnaesite.

The Mt. Pass orebody is currently mined by open-pit methods. The average strip ratio is estimated to be 0.19 to 1. Mining and milling averages over the last five years, computed subsequent to the 1974 expansion, include: 330,000 tpy milled ore, 7 percent REO mill head grade, 70 percent overall recovery, and production of 16,000 tpy of REO. Ore reserves are estimated at 5 million tons containing 7 percent REO. Probable ore is estimated at 40 million tons ranging in grades from 5 to 15 percent.

The mining, milling, and chemical plant are operated on a relatively small scale. Actual mining requires only three to four 35-ton trucks used in conjunction with two to three wheeled front end loaders with 7-cy. buckets. Mining at Mt. Pass is accomplished via a bulldozer pushing broken ore from the upper benches to a level where the ore is loaded into the 35-ton end-dump trucks. The close proximity of the crushing plants to the orebody allows a mine crew of eight men to produce 1,800 tons per shift, one shift per day.

The mill has a designed yearly throughput capacity of 600,000 tons of ore and a designed annual output capacity of approximately 60 million pounds of rare earth oxides. The chemical plant has an annual capacity to process 30 million pounds of REO per year. Currently, Molycorp sells one-third of the REO concentrates, retaining the remainder for separation and production of higher purity products.

Monazite and Related Minerals

Monazite and xenotime are rarely mined as primary products. The majority of monazite is produced as a byproduct of heavy mineral sands production, while xenotime is produced from the processing of tin tailings. Monazite was mined underground in Africa; however, the operations proved uneconomic. Grades of particular monazite deposits range from 0.05 to 0.10 percent with grades reported as high as 2.0 percent (Overstreet, 1967).

Operating costs are regarded to be relatively low since both monazite and xenotime are produced as byproducts.

Processing

The major domestic processors include such companies as the Davison Chemical Division of W. R. Grace & Co., Transelco Division of Ferro Corporation, Ronson Metals Corporation, Reactive Metals and Alloys Corporation (Remacor), and Molycorp of Union Oil Company of California, which is currently the only vertically integrated company, from mining ore to the processing of high purity rare earth elements.

Major foreign processors include Rhone-Poulenc of France, Th. Goldschmidt AG of West Germany, and an assortment of companies from Japan, United Kingdom, Brazil, India, Malaysia, and USSR. Appendix B contains a list of major international processors of rare earths.

The major nondomestic processor of REO is Rhone-Poulenc at La Rochelle, France, where intermediate compounds to high-purity rare-earth elements are produced from monazite and/or bastnaesite concentrates. The bastnaesite concentrates are purchased from Molycorp, whereas, the monazite concentrates are imported from Australia and Malaysia. Rhone-Poulenc is highly diversified within the rare earths industry to minimize risks because of the differential demand for the lanthanides. Rhone-Poulenc's processing technology is highly advanced and cost efficient as they are the only processor who produces all the rare earth elements in high-purity states.

Concentrates of the rare-earth elements must be processed by chemical methods to recover usable compounds and to separate the rare earth elements from other elements forming the mineral compound and from associated impurities. Monazite requires the removal of the phosphate anion and the separation of rare earth elements from thorium. Sometimes a small quantity of uranium is present and must be separated and possibly recovered. Xenotime also requires removal of the phosphate anion. Bastnaesite is comparatively simple to decompose; however, fluorine must be removed, and intimately associated mineral impurities tend to dissolve along with the rare earth elements (Parker and Baroch, 1971).

Many processes have been developed, most of which are designed for certain minerals or mineral combinations requiring specific chemical separation. Furthermore, every processor has process variations, short cuts, or techniques which are regarded as proprietary information. Hence, much of the technology for processing the rare earth concentrates into intermediate and finished products is covered by existing patents. The patents are reported to be more extensive for the production of high-purity oxides and metals. It would behoove a company desiring entry into the rare earth industry to review existing patent coverage to consider the possibility of negotiating licensing contracts or developing new technology.

Separation of the Rare Earth Elements

For some uses, such as the production of certain types of ferrocerium or mischmetal, the lanthanides can be used as they occur in monazite and bastnaesite without separation into the individual elements. In other uses, such as the production of certain glass-polishing or opacifying compounds, only a broad separation into the light and heavy subgroups is sufficient. However, the use of certain lanthanides for their specific properties requires the separation and processing of high-purity metals and compounds.

Several separation and purification methods are available; however, the two most commonly used methods in industry include ion exchange and solvent extraction (also known as liquid-liquid extraction).

The solvent extraction method has cost advantages because of the high degree of automation which requires only a few skilled operators, and the technique can be used for group or individual element separations. Disadvantages of the ion-exchange method include the large volume of costly resins and chelating agents used during the process, their difficult recovery, and the requirement of close technical control. Nevertheless, ion-exchange methods are still used in pilot plant productions to satisfy demands for small tonnages of rare earths which do not justify the capital investment in equipment for the solvent extraction process.

Solvent extraction batteries are assembled from standardized equipment, and it is therefore possible to modify the separation schemes to satisfy special needs. Operating costs are low for large units and high for small capacity installations because the same number of workers are necessary to operate a battery whatever its size.

The raw material source, bastnaesite or monazite, is not necessarily a major factor in the REO concentrate preparation. However, the desired end-product is the controlling factor when designing the chemical processing plant. Essentially, a different circuit is required for each desired rare earth product, especially when producing high-purity metals and oxides. If raw material other than bastnaesite or monazite were used, the type of processing would require careful scrutiny. Rare earths exist in several minerals; however, not all are amenable to the same processing techniques (Parker and Baroch, 1971).

The bastnaesite ore at Molycorp's Mt. Pass operation is beneficiated to a 60 percent REO concentrate using hot froth flotation methods. Molycorp has various options at this point. First, they can produce and market unleached bastnaesite (60 percent REO). Second, they can leach the concentrate with hydrochloric acid to remove calcite, producing 70 percent REO concentrate, which can also be marketed. Finally, the leached concentrate can be calcined to remove CO_2 resulting in a marketable 85 percent contained REO. Prior to further refinement, the REO concentrate undergoes processing to remove a majority of associated source material. Figure 2 is a simplified diagram of the sequential procedure to process bastnaesite ore.

The process continues by dissolving the 85 percent REO with hydrochloric acid to form rare earth chloride in solution. Undissolved cerium is thickened, filtered, and sent to the cerium circuit to undergo further processing to produce a marketable cerium concentrate. The liquid filtrate goes to the europium circuit where, via solvent extraction methods, europium is separated from lanthanum. Samarium and gadolinium remain with europium until the europium purification stage where europium is separated, forming europium oxide. Sodium carbonate is added to the europium-free solution to produce gadolinium-samarium carbonate. Raffinate from the solvent extraction circuit, which is free of europium-gadolinium-samarium, is processed through the lanthanum circuit to remove any remaining lead or cerium, thereby producing a lanthanum hydrate or carbonate. (Molycorp recently added six solvent extraction circuits at Mt. Pass to increase production of high-purity samarium, gadolinium, cerium, lanthanum, neodymium, and praseodymium.)

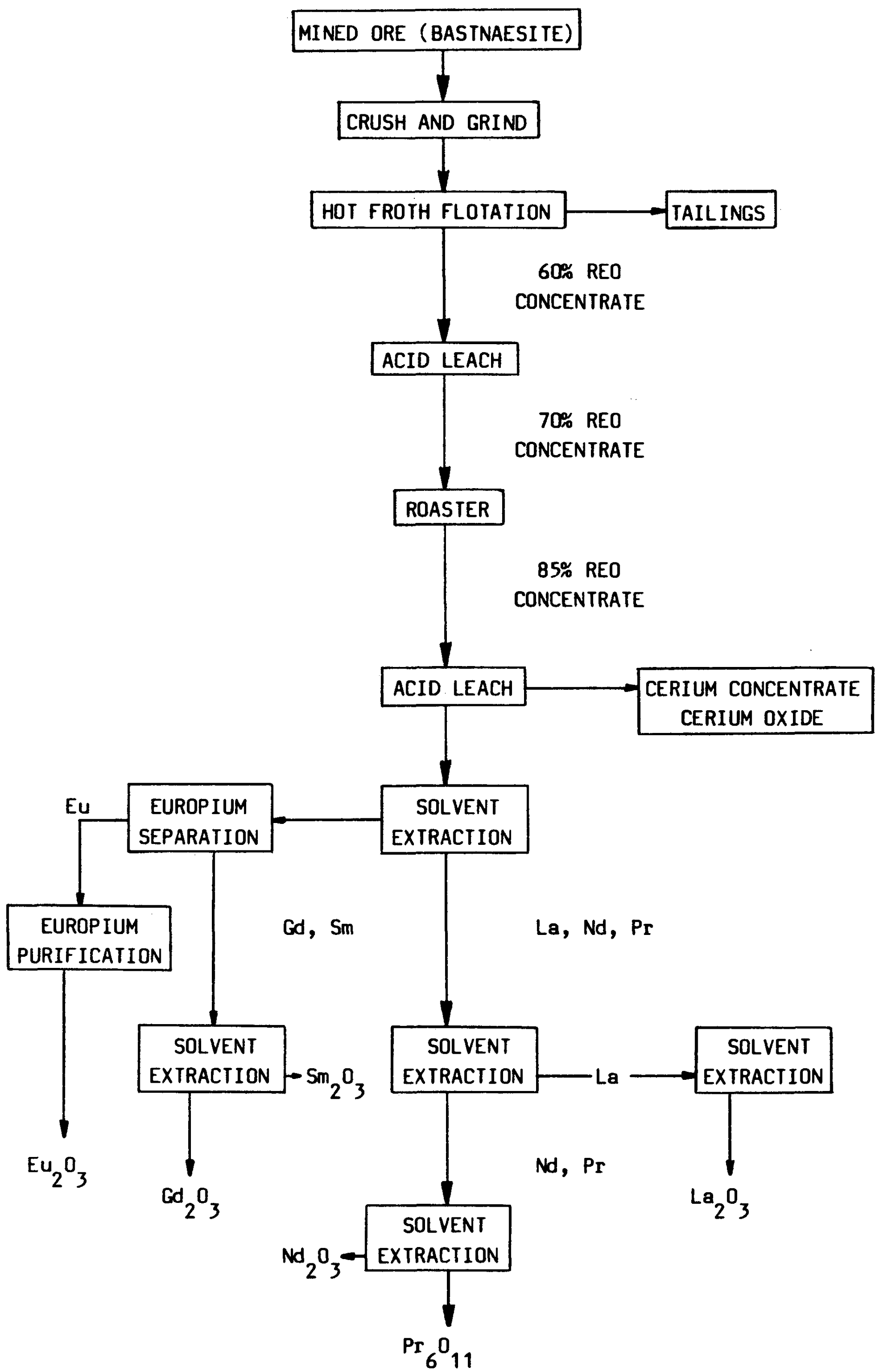


Figure 2. Rare earth production from bastnaesite ore.

Source: Petrick and others, 1973.

Monazite is derived as a byproduct from heavy mineral sands production. Figure 3 illustrates a simplified flowsheet of a heavy mineral sand separation plant.

Industrial processing of monazite concentrate is accomplished via the acid or alkaline (caustic) process. Proponents of the acid process claim that it is the more flexible of the two processes and is adaptable to a greater variety of concentrates of differing grades.

The caustic process, on the other hand, has two advantages: It removes the phosphate as readily marketable trisodium phosphate, and it presents fewer problems with corrosion than the acid process. However, reagent costs are higher for the caustic process than for the acid, and filtration problems increase when the concentrate contains less than 70 percent total oxides.

Acid Process

A generalized flowsheet of the acid process is shown in Figure 4. Finely ground concentrate is mixed with concentrated sulfuric acid and heated in gas-fired iron pots. After cooling and leaching, the rare earths and thorium are dissolved as sulfates in solution. Silica, rutile, ilmenite, zircon, and other insoluble minerals are separated from the solution by filtration. Sodium pyrophosphate is added to precipitate thorium from solution. Subsequently, the rare earth elements are either precipitated as a double sulfate salt by reacting with a sodium sulfate solution or as the rare earth oxalate by reacting with oxalic acid (Parker and Baroch, 1971).

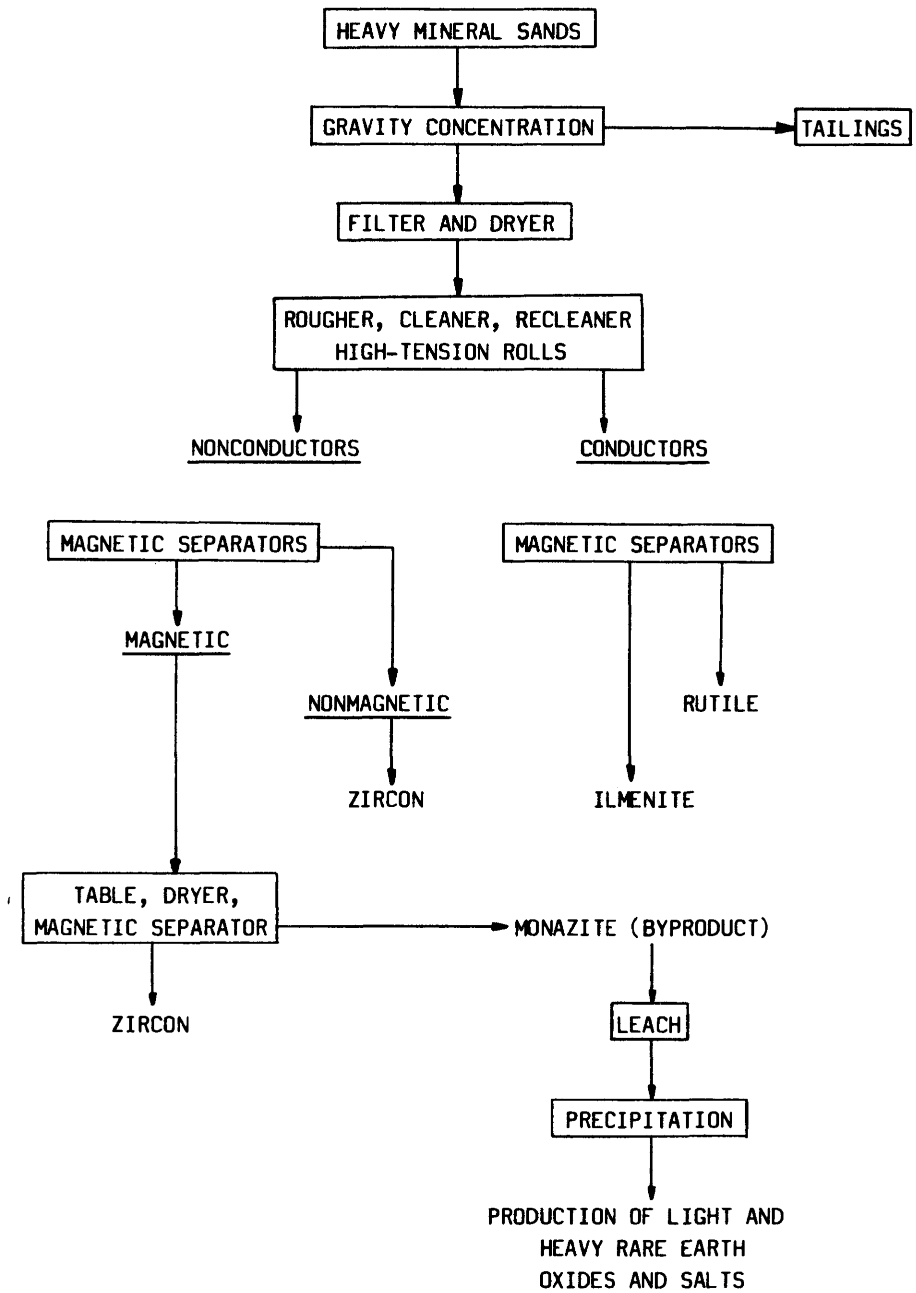


Figure 3. Flowsheet of heavy mineral sand separation plant.

Source: After Parker and Baroch, 1971, pg. 43.

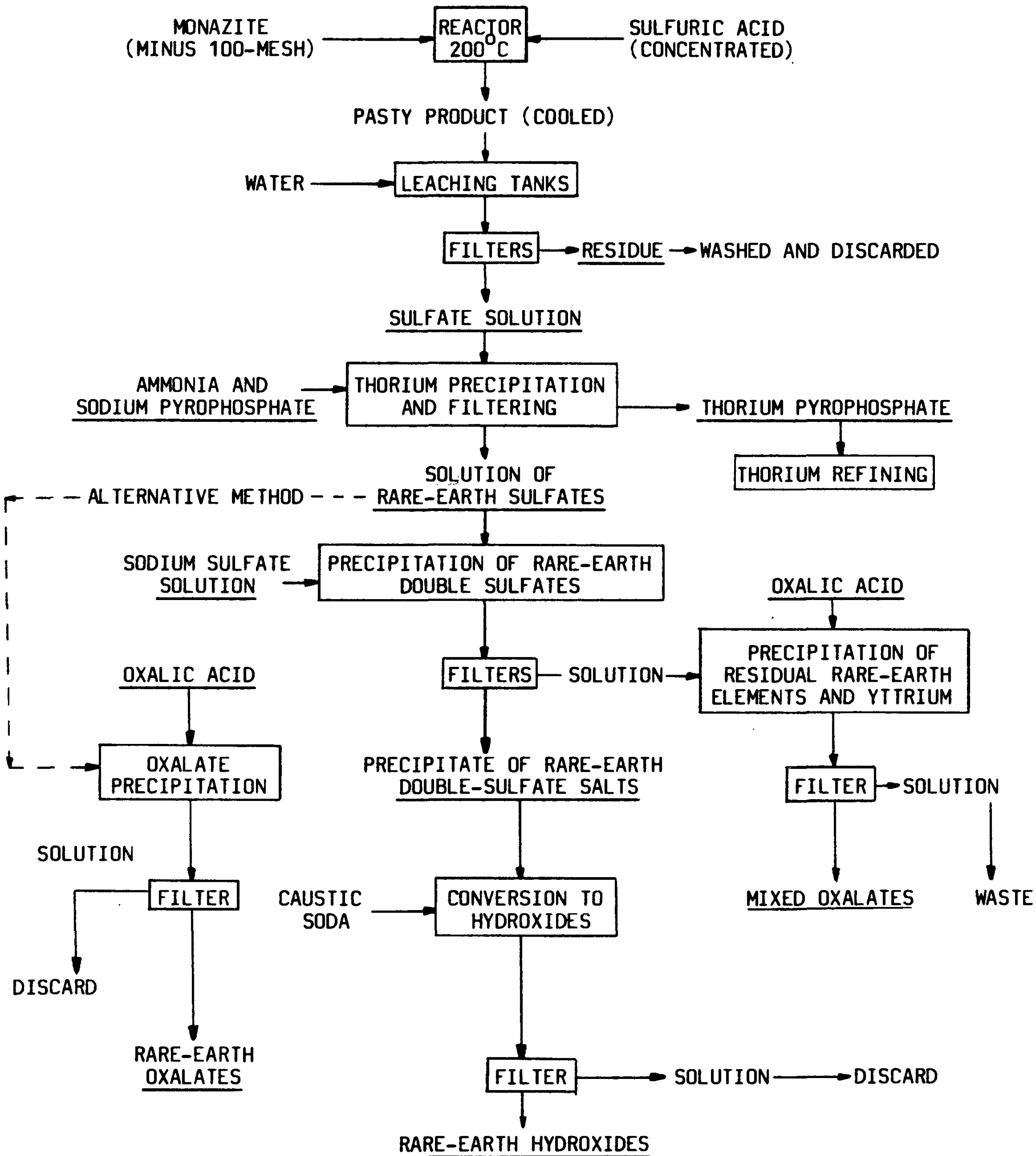


Figure 4. Generalized flowsheet of the acid process for treating monazite

Source: Parker and Baroch, 1971, pg. 46.

The double sulfate salt is stable, insoluble in water, and provides a good intermediate rare earth product, because it is easy to store or process further. The double sulfate can be hydrated by reacting with caustic soda making another convenient intermediate product. This product can then be processed to form other salts or treated with hydrochloric acid to form the chloride.

An alternative method in the acid process features the early removal of phosphate from the sulfate solution. Such a solution is more suitable for cleaner separations in the later stages (Poirier and Apgar, 1976).

Caustic Process

Finely ground concentrate is mixed with hot, concentrated sodium hydroxide. The reaction produces insoluble hydroxides of rare earth elements and thorium, leaving trisodium phosphate in solution to be recovered by crystallization from the filtrate. After dilution, filtration, and washing, the hydroxides are treated with hydrochloric acid. The rare earth hydroxide dissolves leaving slightly contaminated thorium hydrate which is recovered by a stronger acid solution. (If strong nitric acid is used, the thorium may be recovered by tributyl phosphate [TBP] solvent extraction.) The rare earth chlorides can be recovered by evaporation and the hydroxides reprecipitated, or the solution may pass directly to the individual rare-earth-element separation stage (Parker and Baroch, 1971).

Metal and Alloy Production

The preparation of high-purity rare-earth metals is difficult because the metals have high melting points that range from 800°C for cerium to 1,650°C for lutetium, and all are exceedingly reactive when molten (Poirier and Apgar, 1976). They have a strong affinity for oxygen, and a large amount of energy is necessary to decompose their compounds (Poirier and Apgar, 1976). Current processes for producing these metals involve either the electrolytic process or metallothermic reduction with active metals such as sodium, calcium, magnesium, or low-melting rare-earth elements.

Cerium, lanthanum, didymium, and mischmetal are produced, via the electrolytic process, from rare-earth chloride or oxide. Mischmetal, which is produced in the largest quantities, does not need to be of high purity for its major uses, in particular, steel alloying.

The oxide electrolytic process is a lower cost operation than the chloride process. Approximately 3 1/4 pounds of chloride are needed to produce one pound of rare earth metal. Molycorp sells rare earth chloride for 70¢ per pound (89¢ per pound if europium and samarium have been separated out). The table on the following page compares electrolytic processing costs (Source: Luyckx, personal communication, 1980):

	Oxide Process	Chloride Process
Raw Material	$1.00	$2.28
Electric Power	1.40	1.25
Labor	.35	.35
Total Cost	$2.75/lb mm	$3.88/lb mm

The current selling price of mischmetal is $4.50 per pound. Hence, the example illustrates the lower costs associated with mischmetal production via the oxide route.

Having presented a brief description of the various beneficiation techniques employed in processing rare earth minerals, this will provide the foundation for capital and operating cost estimates which will be conducted in a later chapter.

CHAPTER 4

MARKET APPLICATIONS

The applications of the mixed and individual rare earth elements and compounds are many and diverse. A summary of the majority of these applications is presented in Table 6.

Applications, by volume, of rare earths are shifting toward metallurgical uses. This shift is due primarily to expansion and acceptance of rare earth additions in high-strength, low-alloy steels. Table 7 shows an approximate world wide historical distribution, on a volume basis, of rare earths by end use.

The intent of this chapter is to provide a brief description of the major applications of rare earths.

Catalysts

The use of rare-earths in cracking catalysts to increase the yield of gasoline from petroleum feedstocks has historically been the largest consumer of rare earths. However, the market share has been declining and its future share is expected to further decline.

Mixtures of lanthanum, neodymium, and praseodymium chlorides have largely replaced the use of the natural mixed elements in the

Table 6

Rare Earth Applications

	Mixed R.E	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Y
CATALYSTS															
Cracking	X	X	X		X	X		X		X				X	
Inorganic	X	X	X												
Halogenation	X		X			X									
Hydrogenation	X	X	X												
GLASS															
Polishing	X		X												
Coloration			X	X	X										
Filters		X	X	X	X										
Lasers (optical)					X						X	X	X		X
CERAMICS															
Pigments			X	X											X
Opacification	X	X	X												
ELECTRONICS															
Cathodes	X	X	X	X	X			X							X
Garnets		X		X	X	X	X	X	X	X	X	X	X	X	X
Capacitors		X	X		X	X								X	X
Phosphors							X	X							X
NUCLEAR															
Neutron absorption						X	X	X		X					
Structural			X												X
METALLURGICAL															
Low alloy steel	X	X													
Stainless steel	X	X													X
Cast iron	X	X	X												
Magnesium alloys	X	X		X	X										X
Super-alloys	X	X			X										X

Sources: Parker and Baroch, 1971; Moore, 1979; Spedding and Daane, 1961; Industrial Minerals, 1979, No. 138.

Table 7

Historical Market Distributions

(Weight percent on REO basis)

	1975	1976	1977	1978	1979
Metallurgy	45	32	34	32	42
Catalysts/Chemicals	36	38	39	32	26
Glass/Ceramics	17	28	26	35	31
Phosphors/Electronics	2	2	1	1	1

Source: Cannon, 1980, E&MJ, V. 181, No. 3.

production of catalysts for petroleum refining. Rare-earth chlorides also are used as catalysts to recover chlorine from byproduct hydrochloric acid. Rare-earth phosphate, composed of either lanthanum or cerium, is used as a catalyst to produce creosol and xylenol. Cerium is an effective catalyst component in hydrocarbon oxygenation reactions, such as in self-cleaning ovens.

Ceramics/Glass

Cerium and mixed rare-earth oxide powders are used extensively in polishing eyeglasses, camera and instrument lenses, television face plates, mirrors, and plate glass, although its use in polishing plate glass has been reduced by the introduction of the Pilkington float-glass process (Moore, 1979).

The use of certain rare-earth elements as ingredients in the glass is becoming increasingly important in the glass industry. For example, cerium oxide is used as a glass decolorizer; neodymium oxide absorbs ultraviolet light; and cerium oxide in glass inhibits food spoilage in transparent containers.

Cerium oxide prevents discoloration due to radiation in television tube glass and is also used in windows for nuclear reactors. In optical uses, lanthanum oxide increases the refractive index and decreases dispersion (Parker and Baroch, 1971).

A ceramic material containing 90 percent yttrium oxide and 10 percent thorium oxide is used for windows in high-temperature furnaces, microscope lenses for the study of molten materials, and high-intensity incandescent and discharge lamps. Crucibles composed of yttrium oxide are used for vacuum and inert gas melting of reactive metals, such as titanium. Yttrium oxide stabilizes zirconia and forms one of the best high-temperature, high-strength, and thermal-shock-resistant refractory compositions, which is stable under many conditions of oxidation and reduction at elevated temperatures (Poirier and Apgar, 1976).

Electronics/Phosphors

Yttrium-ion garnets (YIG) and gadolinium-ion-garnets (GIG) are widely used as ferrite materials in microwave applications. Lanthanum and neodymium are used individually in capacitors; the oxides of the two elements alter the temperature-compensating, dielectric, and permeability properties of the various barium titanate ceramic compositions for capacitors (Parker and Baroch, 1971).

Yttrium-aluminum-garnets (YAG) are used as simulated diamonds and as host crystals for lasers. Neodymium-doped YAGs produce shortwave length laser beams that are useful in cutting and scribing semiconductors and for drilling and welding. Erbium- and holmium-doped crystal lasers are used in eye operations. Neodymium-doped glasses are also used as lasers; currently they are being evaluated as energy sources in laser-fusion research. Gadolinium-gallium-garnets (GGG) in thin-film, magnetic bubble memory systems are used in communication and computer systems.

Europium oxide in combination with yttrium oxide or yttrium oxysulfide is used in phosphors to provide the red in color television picture tubes. Terbium-activated gadolinium or lanthanum oxysulfide phosphors are used to intensify X-ray images. Phosphor uses, especially for X-ray intensification and in fluorescent lamps, are expected to significantly increase.

Europium and yttrium, as separated and high-purity rare earths, currently account for the greatest dollar volume of business. Molycorp, for instance, bases their operation and economics on europium separation and marketing (Molycorp, personal communication, 1980).

Nuclear

The high neutron-absorption cross section characteristics of several rare-earth elements have led to their use in control rods in commercial nuclear power generators. Of particular interest are the oxides of europium, gadolinium, and samarium. Although more costly, europium is considered the best, because it has a slower burnup than the others due to its greater number of absorbing isotopes (Industrial Minerals, 1979).

Yttrium metal, with its high melting point, low density, and high absorption capacity for hydrogen, is suitable for use as a material in reactor structures. However, in the nuclear field yttrium must compete with cheaper, more commonly used metals, such as zirconium, aluminum, and stainless steel. Nevertheless, the use of rare earth elements in control rods for nuclear power plants is anticipated to increase steadily.

Metallurgical Applications

The largest metallurgical use for mixed rare-earth compounds is in the production of mischmetal. This alloy is used alone or mixed with metals such as aluminum, magnesium, or thorium. Rare earth elements have been tried in many metallic systems, mostly in attempts to reduce brittleness and nitrogen absorption, and to increase ductility and high-temperature corrosion resistance.

The steel industry uses mischmetal as a sulfide inclusion shape control agent to provide cleaner steel. Presently, 80 percent of the rare earths consumed in steelmaking are added to ingot molds, while 20 percent are used in ladle treatment (Luyckx, personal communication, 1980). The most effective ladle treatments use a canister plunging technique. Since rare earths oxidize readily, care must be taken to add them to fully deoxidized steel. Following the addition, care must also be exercised to avoid reoxidation of the melt, as oxygen will attack the rare earths (Luyckx, personal communication, 1980).

Major growth in usage of mischmetal in the steel industry, as an inclusion shape control agent, is expected to increase dramatically. This growth is predicted despite a trend toward usage of 0.75 lbs of mischmetal per ton from the current treatment level of 1.5 lbs/ton. In the very long run, rare earths could be used to reduce Mn requirements in steel should a U.S.S.R. or South African manganese embargo occur (Luyckx, personal communication, 1980).

In ferrous metallurgy, small additions of mischmetal, ferrocerium, or cerium (or cerium oxides and salts) deoxidize and desulfurize low-carbon and low-alloy steels and improve the low-temperature impact properties of low-alloy steels of the nickel-chromium-molybdenum type used in armor plate and gun barrels (Moore, 1979). Rare-earth additions improve the hot workability of certain steels and refine the grain size of high-chromium steels which usually have excessive grain growth at elevated temperatures. Also, the fluidity and ductility of cast steel is improved by the addition of rare earth elements. The use requiring the improvement in physical and rolling properties of the steel was stimulated by the need for large-diameter pipe for the transportation of petroleum products in hostile environments, such as those found in Arctic regions and offshore areas. Rare earths are added to high-strength, low-alloy (HSLA) steels which are being increasingly used in the automobile industry as structural components and in lighter weight sheet applications. Although the metallic or alloy forms are more expensive, they are more satisfactory than compounds because they add little or no oxygen and do not require the addition of a reducing agent (Luyckx, personal communication, 1980).

Rare earths are also used in the production of ductile cast iron. This use is growing due to demand for ductile iron pipe for water transmission systems and for quality castings required by the automotive and farm equipment industries.

Mischmetal is alloyed with iron to impart strength, hardness, and brittleness for producing ferrocerium lighter flints. The addition of neodymium and yttrium hardens magnesium alloys, and the addition of rare earth elements improves magnesium-zinc alloys. Yttrium improves ductility in ordinarily difficult-to-work metals such as vanadium, columbium, tantalum, and molybdenum. Yttrium promotes workability and acts as a grain refiner and improves resistance to oxidation of superalloys at elevated temperatures, such as those found in jet engines.

The use of rare-earth metals including cerium, praseodymium, samarium, and mischmetal in permanent magnets is rapidly expanding because they can be easily fabricated by powder metallurgical methods. These magnets, which are two to three times stronger than other magnets, are used in electric wrist watches, tachometers, traveling wave tubes, line printers, and electric motors and generators. Although samarium is currently in high demand, its use in permanent magnets is expected to decline because samarium is in short supply and expensive. Its use in magnets is gradually being replaced with less expensive mischmetal or rare-earth metals which provide similar alloying qualities.

Other Uses

Applications for high-purity rare earths are steadily increasing. The major fields using high-purity lanthanides include the electronic and metallurgical applications. Electronic applications consist of the addition of high-purity materials in phosphors, permanent magnets, and magnetic-bubble memory systems. Metallurgical uses consist almost exclusively of adding high-purity materials to metals and alloys to improve ductility. Various uses, however, are limited by economic reasons. Nevertheless, an increasingly significant amount of research and development is continually being conducted by industry to increase the potential applications and growth for high-purity lanthanides.

Most of the applications mentioned thus far have been primarily oriented toward the light rare-earths while little has been mentioned about the heavy rare-earths. Although limited information exists in the literature, industrial and government sources indicate that proprietary industrial research, related to increasing the applications of heavy rare-earths, is evolving.

CHAPTER 5

MARKET RELATIONSHIPS

Marketable rare earth products are essentially divided into two groups. The first group ranges from concentrates to intermediate compounds. The second group consists of high-purity compounds and metals.

Marketable products of the first group include bastnaesite concentrates available as unleached (60 percent REO), leached (70 percent REO), and calcined (85 percent REO) bastnaesite. Monazite is available as concentrate containing 55 to 65 percent REO. Xenotime concentrate, a yttrium source, is available as 25 percent Y_2O_3. Uranium-processing residues contain about 25 percent REO and 25 percent Y_2O_3. Intermediate compounds include various separated mixed rare earth hydrates and chlorides, mischmetal, and rare earth silicides. Alloys such as mischmetal and rare earth silicides are marketed in the form of lumps, sponge, and ingots.

High-purity rare earth compounds, metals, and alloys are marketed under a variety of company trade names or sold by purity designations (i.e. 95%-99.999%). High-purity metals are marketed in the form of sponge, ingot, turnings, powder, sheet, foil, rod, and wire.

Supply-Demand

Supply

There has always been a differential demand for the various individual rare earth elements. Consequently, this creates a supply-demand imbalance among the rare earth elements mainly because of the nature of the extraction process. One element cannot be extracted without coproducing other rare earth elements of greater or lesser value. Hence, large surpluses of certain lanthanide elements exist for which there is little or no demand.

Currently, the United States is the world's largest producer of rare earth elements and exports large quantities of rare earth concentrates, compounds, and metals. Monazite from Australia and Malaysia and rare earth chloride from India and Brazil are imported to meet the needs of certain domestic lanthanide processors. High-purity, rare earth metals and compounds are imported from Japan and Western European countries.

The United States, Australia, India, Malaysia, Brazil, and the U.S.S.R. account for more than 95 percent of total world REO production. The United States alone produces about half of the world output. Bastnaesite constitutes more than half of the total world output of rare-earth elements; monazite comprises most of the rest. Prior to 1978, most domestic purified yttrium was extracted from imported yttrium-rich residues that were recovered during the processing of certain Canadian uranium ores. However, in 1978, the Canadian processing facility was closed because of high operating costs. Henceforth, Malaysian xenotime is expected to become the major source of yttrium.

Monazite and bastnaesite producers for the most part appear to be content to sell their concentrates to primary-mineral processors. Molycorp is the only producer to diversify into the processing and refining of end products. The other major processors, both domestic and foreign, have depended upon raw material sources purchased from the few primary-mineral producers in the world.

Although it would appear that there should be certain advantages to integration, it is not as prevalent as one would imagine. Molycorp and Rhone-Poulenc are perhaps the most integrated, but neither have achieved full integration. Molycorp does not produce a full range of rare earth products, and Rhone-Poulenc does not have a captive mine source. These two companies are generally regarded as the most important in the Western World rare earth industry and merit some consideration.

Molycorp's principal rare earth asset has to be their bastnaesite deposit at Mountain Pass, California. This property is a low cost, open-pit operation, with a large reserve base; and production reportedly can be expanded without undue effort. On a volume basis, their sales are principally in the area of REO concentrates and combined RE chemicals (Molycorp, Annual Reports, 1972-1976; Union Oil

Company of California, Annual Reports, 1977-1979). Molycorp is the most important supplier of combined RE concentrates and chemicals for further processing by other producers of rare earth products. Molycorp, however, does produce separated rare earth chemicals and emphasizes recovery of europium oxide for the color TV industry. Recent reports indicate that, in the future, some emphasis will shift to samarium recovery (Union Oil Co. of California, News Release, 1980).

Rhone-Poulenc is highly regarded for their rare earth chemical processing capabilities. It has been stated that they are the only company that is capable of disassembling a rare earth concentrate element by element (Rhone-Poulenc, personal communication, 1980). Rhone-Poulenc can process either bastnaesite or monazite but prefers the latter mineral because of its cost advantage. Accordingly, they are capable of dealing with and disposing of the radioactive material that is generally associated with monazite. Furthermore, they have a comparatively large well staffed and equipped laboratory that is involved in both process and application research and development on rare earths.

Because monazite is a byproduct available from a diversity of sources, companies like Rhone-Poulenc can successfully process lanthanides without controlling a mine source. As a large primary producer competing with a diverse number of byproduct producers, Molycorp generally must be considered as a supplier of last resort (Moore, personal communication, 1980). That means monazite will generally clear through the marketplace first; and, whenever demand softens, bastnaesite rather than monazite production cutbacks will prevail. Under normal market conditions, bastnaesite will sell at a premium with respect to monazite. The premium would be established in recognition of the problems and extra costs associated with monazite processing.

The production and capacity of rare earth oxide (REO) is presented in Table 8. As noted from the table, only 60 percent of capacity is being utilized. Demand has been increasing for particular rare earth elements (i.e., samarium and gadolinium). Although capacity utilization is expected to increase, there will still be a substantial underutilization of capacity.

Monazite-xenotime concentrates of domestic and foreign origin are expected to be the principal sources of yttrium and heavy rare earths. However, an adequate domestic supply of both yttrium and the heavy rare earths is possible from the processing of phosphate rock if substantial demand should develop.

World reserves of rare earths are large and expected to be adequate for consumers for several decades at current rates of demand. This situation, of course, could rapidly change depending on research development and advanced industrial technology in developing new uses and markets. Markets need to be expanded to alleviate the excess quantities of rare earths that accumulate, because of the nature of the processing, in which little or no demand exists.

Table 8

World Capacity and Production of Rare Earth Elements - 1979

(Short tons of REO)

	Bastnaesite		Monazite-Xenotime		Other		Total	
	Capacity	Production	Capacity	Production	Capacity	Production	Capacity	Production
North America:								
United States	30,000	18,200	[1]1,500	W	--	--	31,500	18,200
Canada	--	--	--	--	[2]200	--	200	--
South America:								
Brazil	--	--	1,800	1,200	[3]500	--	2,300	1,200
Europe:								
Finland, Norway, Sweden	--	--	--	--	[4]500	--	500	--
Africa:								
Burundi*	500	105	--	--	--	--	500	105
Malagasy Republic	100	--	--	--	--	--	100	--
Other	--	--	1,000	140	--	--	1,000	140
Asia:								
Malaysia	--	--	[5]1,500	1,350	--	--	1,500	1,350
India	--	--	[1]5,000	2,500	--	--	5,000	2,500
Other	--	--	[1]1,000	50	--	--	1,000	50
Oceania:								
Australia	--	--	[1]12,000	10,800	[2]1,000	--	13,000	10,800
U.S.S.R.*	--	--	1,500	1,500	1,500	1,000	3,000	2,500
World Total	30,600	18,305	25,300	17,540	3,700	1,000	59,600	36,845

*Estimated. W - Withheld to avoid disclosing individual company confidential data.

[1]Byproduct of titanium. [2]Byproduct of uranium. [3]Byproduct of columbium. [4]Byproduct of phosphate. [5]Byproduct of tin.

Source: Moore, 1979; U.S. Bureau of Mines, Mineral Commodity Summaries, 1979.

Demand

Although the consumption pattern varies from country to country, most rare earths used by industry are consumed in the form of compounds containing special mixtures of rare-earth elements. More than half of U.S. consumption is in the form of individual or special mixture compounds such as chlorides, hydrates, and oxides. Natural-ratio mixtures of rare-earth elements are mainly consumed in the production of silicide alloys and mischmetal. Consumption of natural-ratio mixtures has increased but, percentagewise, use in this form appears to be decreasing.

As mentioned earlier in this chapter, rare earth marketable products are divided into two groups. The first group, consisting of concentrates and intermediate compounds, provides a base which lends stability to the rare earth market. The second group (made up of high-purity rare earth compounds, metals, and alloys) is less stable. Therefore, it is more difficult to predict future market demand.

The first group accounts for the largest weight percentage of sales, but a relatively small fraction of dollar sales. Consequently, the second group consists of a market characterized by comparatively small annual tonnage sales with higher unit prices which contribute to larger dollar volumes. Table 9 shows the relationship between market distribution and dollar volume during 1979.

Table 9

Market Distribution - Dollar Volume Relationship (1979)

(Percent)

	Market Distribution	Dollar Volume
Metallurgy	42	8
Catalysts/Chemicals	26	38
Glass/Ceramics	31	12
Phosphors/Electronics	1	42
	100	100

Source: Cannon, 1980.

Market demand indicates a continued increase in usage depending primarily on technological advances, minimal substitutions by other materials, and the expansion of markets for those less demanded rare earth elements that accumulate as a result of the extraction process. The anticipated decline in growth for rare earths in the United States in established uses such as petroleum refining is expected to be partially offset by the rapid growth in demand for rare earths in high-strength low-alloy steels, phosphors, and other high-purity uses.

Opportunities for increasing consumption of rare earths in the rest of the world appear to be as good or better than in the United States. In particular, major growth is expected in the iron and steel industries where rare earth treatment in the production of ductile iron and HSLA steels has gained international acceptance (Luyckx, personal communication, 1980). Since several consumer goods contain rare earths in one form or another, consumption of rare earths is expected to increase in this area as foreign populations increase. Although the use of rare earths in foreign petroleum refining is expected to increase, the growth rate will probably be small as petroleum refining will eventually be curtailed by the use of other forms of energy.

Historical world demand figures are not readily available; particularly foreign demand. However, Moore (personal communication, 1980) of the U.S. Bureau of Mines in Washington, D.C., indicated that world demand closely parallels world production. Based on this assumption and the Bureau of Mines historical data, a world demand forecast was made for REO using the Least Squares time series method. The results are illustrated in Table 10. The Bureau of Mines forecast is presented in Table 11 for comparison.

Table 10 requires some explanation. Since the time series analysis is based only on historical data, this author felt that the expected increase in demand by foreign countries was not adequately accounted for in the "Probable" category. Hence, the "Possible" category was developed by the author as an estimated guess to show the increased foreign demand.

Various annual growth rates in Table 10 were derived to illustrate the expected future growth rate. Growth rates from 1979 are shown because 1979 was the last year in which annual data was available. The base year of 1977 was used in order to compare the results to those calculated by the Bureau of Mines.

The Bureau of Mines forecasted growth rate (1977-2000) is 6.1 percent as compared to this author's forecasted growth rate (for the same period) ranging between 3.3 to 3.7 percent. The highest demand forecast in Table 10 (68,000 short tons of REO) corresponds to the low forecast range in Table 11. This seems to be a reasonable REO demand based on current state-of-the-art technology and uses. Historical growth rates have averaged between 2.5-3.0 percent. Hence, it does not seem realistic that the expected use of rare earths in HSLA

Table 10

World Demand Forecasts for REO

(Short tons REO)

	Probable		Possible
	1985	2000	2000
United States	22,700	32,700	32,000
Rest of World	18,500	31,000	36,000
Total World	41,200	63,700	68,000

Probable Average Annual Growth Rate:

1. 1977-2000: 3.3%
2. 1979-1985: 4.6%
3. 1979-2000: 3.1%

Possible Average Annual Growth Rate:

1. 1977-2000: 3.7%
2. 1979-2000: 3.5%

Table 11

U.S. Bureau of Mines - World Demand Forecasts for REO

(Short tons REO)

	Probable		Year 2000 Forecast Range	
	1985	2000	Low	High
United States	30,000	57,000	33,000	72,000
Rest of World	25,000	63,000	35,000	72,000
Total World	55,000	120,000	68,000	144,000

Probable Average Annual Growth Rate:

1. 1977-2000: 6.1%

Source: Moore, 1979, p. 14.

steels, phosphors, and other high purity uses will command an overall average growth rate as forecasted by the Bureau of Mines. Of course, industrial research and development could change the entire demand scenario by creating markets for those rare earths currently in lesser demand or through substitution of rare earths for other elements.

Substitutes

Applications of the rare earth elements have many potential substitutes. However, in most instances, the substitutes are significantly less effective than the rare earth elements (Fallon, personal communication, 1980). In carbon-arc electrodes, iron and calcium fluorides have been used in place of rare earth compounds.

Palladium is a substitute for rare earth elements in catalyzing petroleum-refining processes. Compounds such as calcium phosphate, aluminate, tungstate, or thorium dioxide can be substituted for yttrium as host material in phosphors for color television (Moore, 1979).

On the other hand, steel companies currently using calcium and magnesium for steel desulfurization are also adding mischmetal for inclusion shape control. Apparently, the calcium/magnesium additives are not giving consistent inclusion shape control (Luyckx, personal communication, 1980). Luyckx is also of the opinion that, in the very long term, rare earths could be used as a substitute for manganese in steel. A U.S.S.R./South African manganese embargo could move the Free World in this direction.

Tariffs and Taxes

As of January 1, 1980, new tariff agreements were made between the developed nations of the world. The agreements placed a majority of the nations on a most-favored-nation status. This results in lower rates being phased in over an eight year period beginning January 1, 1980 (Moore, 1980, p. 735). The new tariff schedule is shown in Table 12.

Domestic monazite has a 22 percent depletion allowance; 14 percent on foreign production. All other rare earth minerals, both domestic and foreign, are eligible for a 14 percent depletion allowance.

Prices

As mentioned earlier in this chapter, marketable rare earth products are divided into two groups. Hence, the price structure is also divided into two tiers as illustrated in Table 13.

The price differential between monazite and bastnaesite reflects the fact that monazite is a byproduct. Bastnaesite has tended to replace monazite as the raw material source for the rare earth industry despite the price difference. Bastnaesite commands a higher price

Table 12

U.S. Import Duties

Article	Tariff Classification	Most Favored Nation (MFN) Jan. 1, 1980	Most Favored Nation (MFN) Jan. 1, 1987	Non-MFN Jan. 1, 1980
Ore and concentrate	601.12, 601.45	Free	Free	Free
Cerium chloride, oxide, compounds	418.40, 418.42, 418.44	14% ad valorem	7.2% ad valorem	35% ad valorem
Rare earth oxides except cerium oxide	423.003	4.8% ad valorem	3.7% ad valorem	25% ad valorem
Rare earth metals (including scandium and yttrium)	632.38	4.8% ad valorem	3.7% ad valorem	25% ad valorem
Alloys wholly or almost wholly of rare earth metals (mischmetal)	632.78	47¢/pound	32¢/pound	$2/pound
Other alloys wholly or almost wholly of rare earth metals	632.79	46¢/pound plus 5.6% ad valorem	20¢/pound plus 2.4% ad valorem	$2/pound plus 25% ad valorem
Ferrocerium and other pyrophoric alloys	755.35	46¢/pound plus 5.6% ad valorem	22¢/pound plus 2.6% ad valorem	$2/pound plus 25% ad valorem

Source: Moore, 1980, p. 735.

Table 13

Rare Earth Price History

	Base Quantity	Dollars per Pound Contained REO			
		1976	1977	1978	1979
Concentrates and Mixed Compounds					
Bastnaesite (70% REO)	TL/CL[1]	0.55	0.58	0.70	0.76
Monazite (60% REO)	TL/CL	0.18	0.15	0.20	0.25
Cerium (65% CeO_2)	TL/CL	0.90	0.90	1.05	1.25
Lanthanum (75% REO)	TL/CL	0.75	0.75	0.85	0.90
Rare Earth Chlorides[2]	TL/CL	0.50	0.55	0.60	0.75
Mischmetal[3]	2000 lb	3.25	3.50	4.05	4.50
High-Purity Oxides and Metals					
Oxides (99.9% Min.)					
Cerium	200 lb	5.00	5.50	6.75	7.25
Lanthanum	300 lb	5.50	5.50	6.00	6.50
Europium	25 lb	500.00	540.00	650.00	825.00
Samarium	50 lb	30.00	30.00	30.00	30.00
Yttrium	50 lb	33.00	33.00	34.50	38.00
Metals (99.9% Min.)[3]					
Cerium	500 lb	13.50	15.00	17.50	25.50
Lanthanum	1,000 lb	22.50	20.00	21.70	29.50
Samarium	1,000 lb	45.00	45.00	56.80	65.00
Yttrium	500 lb	85.00	105.00	110.00	150.00

[1] Truckload/Carload. [2] Dollars per pound chloride. [3] Dollars per pound metal.

Source: U.S. Bureau of Mines, Mineral Commodity Summaries; Cannon, 1976-1980, E&MJ, Mineral Commodities Annual.

because it has processing advantages, higher rare earth oxide content in the concentrates, and, for several applications, a more useful mix of rare earth elements (Moore, 1979).

The price of the first group of rare earth products, comprised of concentrates and intermediate compounds, has remained fairly steady over the last twenty years providing stability to the market. The overall trend in price for this group has increased at an average annual rate of 3.5 percent from 1954 through 1979 (based on historical figures from the U.S. Bureau of Mines). However, as shown in Table 13, there has been a substantial increase in price reflecting an increase in demand for certain rare earths (i.e. samarium and gadolinium), and operating and energy cost increases.

On the other hand, prices regarding the second group, comprised of high-purity rare earths, have experienced volatile prices as a result of the imbalance in demand for these products.

Market Opportunities

A rare earth industry market diagram is presented in Figure 5. This diagram presents estimates of rare earth production/consumption volumes (as REO equivalent) and estimated revenues at various stages in the industry. Estimated growth rates for principal applications are also provided. It is important to note that these data are based on somewhat imprecise information and should be viewed more in a qualitative than a quantitative sense.

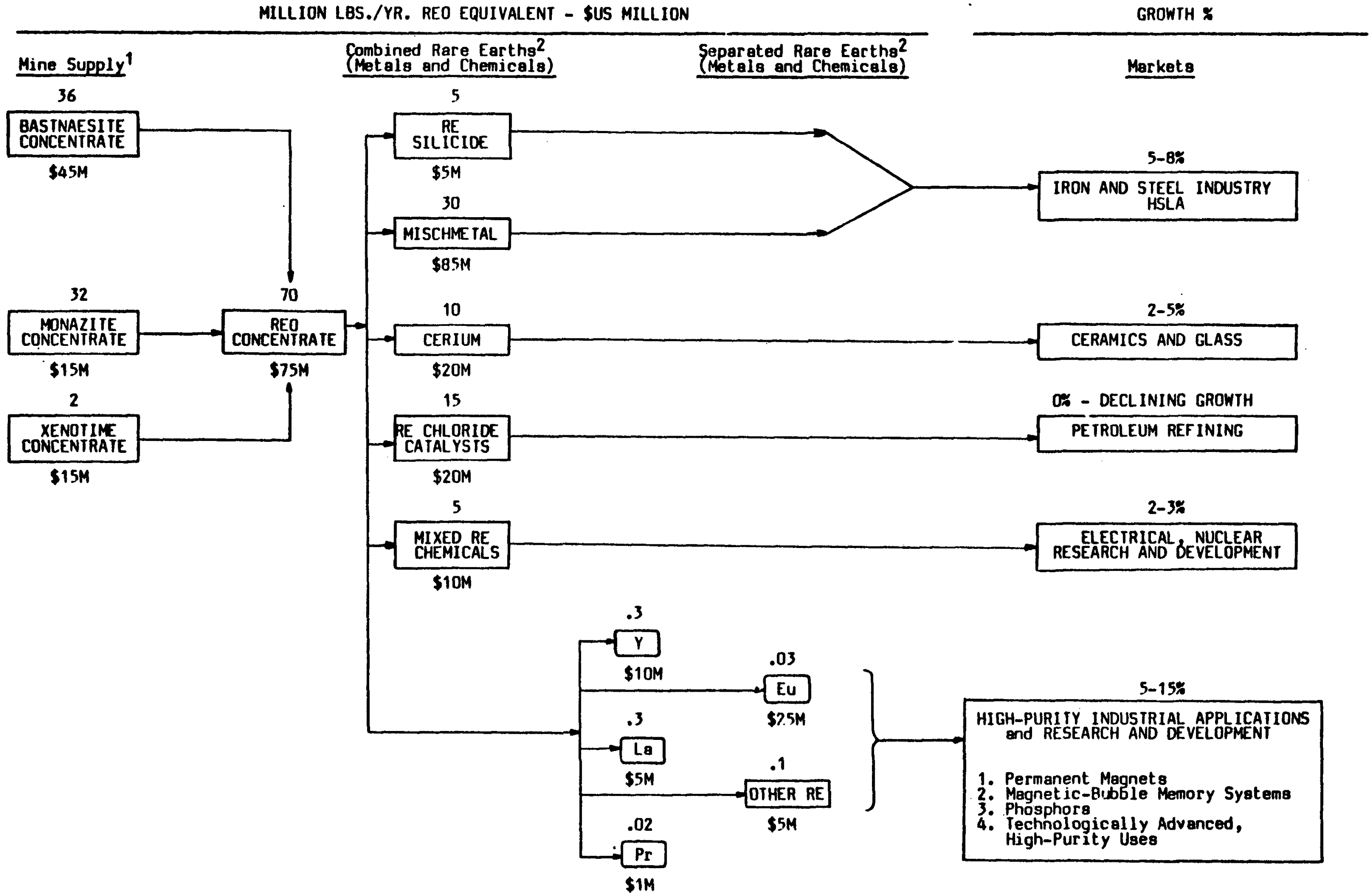


Figure 5. Rare earth industry product-market diagram

[1]Based on 1979 data.

[2]Source: Dunn, Luyckx, and Fallon, personal communication, 1980.

The principal areas of growth for rare earths include the iron and steel industry and the industrial applications of high-purity rare earths. The iron and steel industry's use of rare earths in the production of HSLA steels is becoming increasingly accepted. The major growth is the usage of mischmetal as an inclusion shape control agent.

Probably the most lucrative and potential market for expansion is the industrial application of high-purity rare earth elements. Such technically advanced uses include magnetic-bubble memory systems for use in communication and computer systems, permanent magnets, phosphors, and a host of other high-purity uses in the metallurgical and electronic industries.

The consumption of rare earths in petroleum refining is expected to decline in the industrialized nations because the demand for petroleum is expected to be curtailed by the use of other forms of energy. This is particularly true for the United States, as the United States is the largest single consumer of rare earths for catalytic cracking in petroleum refining.

It is necessary to point out that any rare earth concentate production from new mine sources entering the Western World market would directly compete with Molycorp bastnaesite concentrate. In view of the market structure, it is reasonable to assume that demand for REO concentrate is very inelastic. Hence, the introduction of additional concentrates in Western World markets would tend to destabilize prices.

While the markets for the lower cost mixed rare earth products will continue to expand at a pace dictated by economic conditions, the market for the separated, high-purity rare earth compounds or metals will undoubtedly provide a major portion of the true growth of the rare earth industry. This expected growth in dollar volume of the high-purity products does not particularly favor the development of new mineral deposits but does favor the expansion or acquisition of existing separation installations.

A more rigorous economic analysis will be developed in the following chapters to determine what degree of vertical integration is necessary or required to enter and maintain a profitable position within the rare earth industry.

CHAPTER 6

RARE EARTH INDUSTRY COST MODEL DEVELOPMENT

An analysis of any corporate investment requires three basic steps: information gathering, economic analysis, and an iterative process involving management review. A decision by the executive management must be made regarding what commodity industry would improve the profitability of their company based on assessments of the future supply, demand, price, and market potential for the commodity. Hence, sufficient information must be gathered and properly analyzed such that management can decide:

1) To go with the investment,
2) To reject the investment,
3) To postpone the decision until market conditions become more favorable.

A systematic procedure should then be developed to provide an input-analysis/decision-making sequence to be iterated a number of times based on the economic and strategic objectives of corporate management. The first phase of this iterative process is a market study regarding the history, the current market, and the expected potential of the desired commodity. The second phase of this process is to provide an economic analysis regarding various possible scenarios.

The first part of this thesis provided a market review of the rare earth industry and the future outlook. The remainder of this study will provide the economic analysis regarding different scenarios in the rare earth industry. In order to perform this analysis, a model representing the rare earth industry will be constructed.

Cost Model Parameters

The increasing scale, complexity, and cost of mineral ventures requires an early and continuing assessment of project economics to ensure the effective use of the limited funds available. This assessment process is accomplished by:

- defining and developing the basic model,
- estimating costs and revenues,
- determining the return on investment for the basic model,
- testing the sensitivity of that return to changes in revenues, operating costs, capital requirements, financing arrangements, etc.

This section of the study will entail the construction of a base case model which will represent the entire system (or rare earth industry) from deposit development through marketing the final end product(s). This system will be divided into various units such that mining/milling and chemical processing will be considered separate units. Various unit systems can be devised to allow economic evaluations and sensitivity analyses to be performed in order that a company can determine what degree of vertical integration is necessary or required to enter and maintain a profitable position in the rare earth industry.

The justification of a unit-system model is based on the following:

1) Companies can essentially enter the processing stage of the system (foregoing mining and milling) and proceed through to the marketing stage, provided a raw material source is available,

2) Economic rare earth deposits are limited,

3) The nature of the chemical processing produces multiple end-products, many of which are marketable while others must be stockpiled.

Since the primary objective of this study is to determine what phase is most advantageous and profitable for a company desiring entry into the rare earth industry, three models will be developed to represent the industry. The first model will consist of a mining and milling operation in which rare earth minerals are extracted, beneficiated, and sold as REO concentrate. The second model consists of a chemical plant which buys REO concentrate and, via solvent extraction and refining, produces high-purity rare earth oxides and metals. The third model is a combination of mining, milling, and chemical processing where rare earth minerals are extracted, refined, and sold as a product mix of concentrates, intermediate products (ie, mischmetal), and high-purity oxides and metals. Hence, these models can facilitate decision-making by systematically quantifying the costs and benefits associated with the development of new operations or the expansion of existing operations.

In order to construct these base case models, several project parameters must be quantified regarding geology, mining, metallurgy, marketing, pricing, and financing. The reader should refer to Table 14 for a more comprehensive list of criteria to be considered when constructing mineral venture models.

Mining, Milling, and Chemical Processing Costs

Developing realistic cost and revenue estimates for project modeling is critical in establishing the credibility of the overall modeling process. Although particular costs such as labor, power rates, and transportation vary significantly from mine to mine and country to country, an order-of-magnitude cost estimate will suffice for initial prefeasibility-type economic evaluations such as exemplified by this study. However, in the initial stages of an order-of-

Table 14

Parameters To Be Considered When Developing a Cost Model
for an Economic Analysis

1. Ore reserves - tonnage and grade
2. Pre-production expense (exploration and development)
3. Mining plan
4. Percentage of ore recovered in mining
5. Mining costs
6. Development costs
7. Dilution
8. Rate of production
9. Metallurgical flow sheet
10. Metallurgical percent recoveries
11. Metallurgical material balance
12. Pilot plant tests
13. Labor availability
14. Labor wage rates
15. Labor laws
16. Shift differentials
17. Training programs - costs
18. Water (cost and availability)
19. Power (cost and availability)
20. Heating of buildings
21. Plant site selection
22. Plant site preparation
23. Access roads
24. Transportation of product
25. Housing and townsite
26. Townsite - cost - management - development - design
27. Local taxes
28. Land acquisition cost
29. State or private royalties
30. Local overhead
31. Concentrating or treatment costs
32. Maintenance
33. Depreciation
34. Total operating costs
35. Revenue from sales
36. Operating income
37. Sales cost
38. Research
39. Miscellaneous costs - goodwill - ecology - environmental considerations
40. Insurance
41. Custom duties, sales taxes, property taxes
42. Land rehabilitation
43. Fringe benefits - pensions - hospitalization - termination pay - hiring expense - labor turnover
44. Marketing and competitive position
45. Head office expenses - legal accounting-administration
46. Legal and accounting
47. Working capital
48. Depletion
49. Calculation of net income
50. Calculation of cash flow

magnitude cost estimate, a majority of the specific operating criteria as suggested in Table 14 are unknown. Nonetheless, reasonable estimates can be made based on the experience of the estimator and established operating projects. In this manner, the company will have the opportunity to determine whether or not the proposed commodity will be a profitable venture before investing large sums of capital.

Although exploration plays an important role in every resource company, it will be assumed for this study that all land acquisitions, exploration, and reserve-development drilling necessary to delineate an economic orebody have been completed. Cost estimates for the three models will be based on the data presented in Table 15. These estimates will be based, to the extent possible, on actual rare earth operations. When actual data was not available, reasonable cost estimates were provided, on an order-of-magnitude scale (plus or minus 25 percent), by mining engineers from Climax Molybdenum Company. Costs from the actual operations are proprietary company information and will be incorporated into the cost estimate without documentation. It is assumed that these projects would be developed in the United States.

The capital and operating costs for the mining, milling, and chemical processing of rare earths are presented in Tables 16 through 18. All costs were updated to September 1980 dollars.

No models or cost estimates will be developed for underground mines. There are now no rare earth underground mines in operation,

Table 15

Rare Earth Model Base Data

Mineable Ore Reserves:	3.5 million metric tons
Average Ore Grade:	8.0% REO
Mining Method:	Open Pit
Strip Ratio:	1:1
Mine Production:	500 MTPD ore
Operating Days/Year:	350
Annual Mine Production:	175,000 MTPY
Mine Life:	20 years
Mill Processing:	500 MTPD ore
Overall Mill Recovery:	70%
Annual REO Production:	21.6 million pounds REO
Depletion Allowance:	14%
Financing:	100% Equity
Depreciation:	Sum of Years-Digits
State and Federal Tax Rate:	46%
Chemical Processing:	Acid Leach, Solvent Extraction (For details regarding plant flow, see Chapter 3, Processing Section.)

and in the unlikely event that demand and prices skyrocket for whatever reason, it is doubtful that any new rare earth underground mines will be developed.

The mining, milling, and chemical processing as depicted in Table 15 is a small operation relative to the mining industry in general. However, the model developed for this study would be considered a medium to large facility, compared to other rare earth operations. One could certainly scale-up the existing model, but by doing so, one must bear in mind that the facilities would probably be operating at a rate that is less than economically desirable because the huge amount of additional concentrate that would become available could not be sold without severely depressing the concentrate price. The model size developed in this study is considered a reasonable size such that a company could develop the deposit, produce a saleable quantity of concentrate, and command a reasonable share of the market.

As pointed out earlier in this thesis, there is a differential demand for the various individual rare earth elements. Consequently, this creates a supply-demand imbalance among the rare earth elements mainly because of the nature of the extraction process. One element cannot be extracted without coproducing other rare earth elements of greater or lesser value. Hence, large surpluses of certain lanthanide elements exist for which there is little or no demand. This becomes an important point to consider when trying to decide which one element or group of elements should bear the cost of the project. However, the project's cost distribution is dependent on the marketing strategy of the firm.

Table 16

Rare Earth Mine, Mill, and Chemical Plant Capital Costs

(Costs updated to September 1980 dollars)

MINE/MILL	
Preproduction Development:	$ 1,022,000
Buildings:	1,750,100
Machinery and Equipment:	13,955,700
Replacement Capital (M & E):	3,000,000
	$19,727,800
CHEMICAL PLANT	
Development:	$ 969,900
Buildings:	1,878,800
Machinery and Equipment:	9,151,300
Replacement Capital (M & E):	2,000,000
	$14,000,000
MINE/MILL/CHEMICAL PLANT	
Preproduction Development:	$ 1,460,000
Buildings:	3,314,100
Machinery and Equipment:	20,796,300
Replacement Capital (M & E):	4,500,000
	$30,070,400

Table 17

Rare Earth Mine/Mill and Chemical Plant Operating Costs*

(Costs updated to September 1980 dollars)

MINE/MILL	
100 Employees Required:	
30 salaried, 70 general labor	
Operating Cost/Year:	$ 9,450,000
(Includes labor, supplies, and equipment operation)	
($54.00/MT ore, $0.44/lb. REO)	
CHEMICAL PLANT	
60 Employees Required:	
20 salaried, 40 general labor	
Operating Cost/Year:	$ 8,606,250
(Includes labor, supplies, and equipment operation)	
Concentrate Plant Feed/Year:	$13,500,000
60,000 lbs. REO/Day @ $0.45/lb.	
(Assume concentrate mix of bastnaesite and monazite)	
Total Chemical Plant Operating Costs	$22,106,250

Table 18

Rare Earth Mine/Mill/Chemical Plant Operating Costs*

(Costs updated to September 1980 dollars)

MINE/MILL/CHEMICAL PLANT

140 Employees Required:

40 salaried, 100 general labor

Operating Cost/Year:	$13,162,500

(Includes labor, supplies, and equipment operation)

($75.21/MT ore, $0.61/lb. REO)

*Information regarding operating costs was based on information from Tom Cherrier of the Climax Molybdenum Co. (personal communication, 1980) and actual rare earth mining operations.

CHAPTER 7

A DISCOUNTED CASH FLOW RATE OF RETURN ANALYSIS FOR THE THREE RARE EARTH MODELS

Economic Evaluation

An economic analysis was performed on the three base case models using the discounted cash flow rate of return (DCFROR) and net present value (NPV) methods. Both of these methods take into account the time value of money in order to provide a valid measure of project profitability.

Cash flow schedules were prepared covering the models' entire period including preproduction through to the last year of production. The cash flow schedule is intended to show, on an annual and cumulative basis, the net flow of cash from the project's operations. The procedure for calculating annual cash flows is presented in Table 19.

A project's NPV, when discounted using the firm's weighted average cost of capital, represents the amount by which the value of the firm should increase if the investment is made. Thus, if the NPV is positive, the firm's value will increase and the project should be undertaken. If, on the other hand, the NPV is negative, the firm's total value will decrease, and the project should be rejected.

Table 19

Procedure for Calculating Annual Project Cash Flow

	Sales Revenue
-	Operating Costs
	Gross Profit
-	Depreciation
-	Depletion
	Taxable Income
-	Taxes
+	Tax Credits
	Net Profit
+	Depreciation
+	Depletion
	Cash Flow
-	Capital Costs
	Net Cash Flow

In a like manner, the project's DCFROR should be compared to the firm's weighted average cost of capital. (The weighted average cost of capital is the sum of the weighted percentage of the firm's cost of equity and cost of debt.) If the DCFROR is greater than the firm's cost of capital, then the project is profitable and should be undertaken. If, on the other hand, the DCFROR is below the cost of capital, the project should not be considered with respect to the current situation.

The relationship between DCFROR and NPV for a particular project is that the DCFROR is the discount rate at which the NPV of a series of cash flows equals zero. Generally, companies like to see the results of several evaluation methods in addition to the DCFROR and NPV. However, DCFROR and NPV are regarded as the more valid measures of a project's profitability. Hence, DCFROR and NPV will be presented for the three rare earth industry models.

As with most evaluations, certain assumptions are a necessary requirement. It will be assumed that a large company is evaluating the rare earth industry's investment potential. The firm's average cost of capital is 12 percent.

Assume that the company has other taxable income against which to use project tax deductions and tax credits in the year incurred. This will enhance the project's economics somewhat since the tax benefits will be used early in the project's life. Although this approach is not completely conservative, it is a commonly used industry practice. The alternative approach would be to assume no other taxable income exists. Hence, the negative taxable income and tax credits would be carried forward to use against the project's future income. This is the more conservative approach which would tend to decrease the overall economics of the project mainly because the tax benefits could not be taken early in the project's life.

It will be assumed that any escalation of capital and operating costs over the project's life will be offset by escalation of revenues. Assume that all appropriate assets will qualify for the investment tax credit.

For all three rare earth industry models, assume two years for preproduction development and 20-year project life with production beginning in the third year. Working capital for the mine/mill and mine/mill/chemical plant models will be equivalent to three months of operating costs. Working capital for the chemical plant model will be equivalent to four months of operating costs because of plant feed (concentrate) purchases and large supplies in inventory.

Revenue for the mine/mill model is based on \$0.70/lb. sale of concentrate containing 70 percent REO. Revenue for the chemical plant model is based on the sale of a combination of high-purity oxides and metals including lanthanum, cerium, samarium, gadolinium, yttrium, europium, and a variety of the heavy rare earths. Hence, the combined sales equate to approximately \$35 million per year. Revenue for the mine/mill/chemical plant model is based on a product mix of one-third of the concentrate being sold to other chemical processors, while the remaining two-thirds is processed to intermediate and higher purity products in the company's own chemical plant. Hence, the combined sales equate to approximately $27 million per year. The reasons for variations in the product-mix sales will be explained in a later chapter on market strategy.

The depletion allowance will be used in the mine/mill and mine/mill/chemical plant models, but not in the chemical plant model. The chemical plant is not eligible for the depletion allowance because the plant does not own an economic interest in a rare earth mineral deposit.

Based on the data presented in Tables 15, 16, 17, 18, and the aforementioned assumptions, the following results were obtained for the DCFROR, NPV, and payback period:

	Mine/Mill	Chem/Plant	Mine/Mill/Chem Plant
DCFROR	39.12	33.99	32.10
NPV @ 12% ($ million)	36.43	29.56	37.72
PAYBACK (Years)	1.80	2.24	2.29

The three base case models' annual cash flow calculations with resulting NPV (@ 12%) and DCFROR are illustrated in Appendix C. The three rare earth models presented in this study are all economically feasible. All three projects exceed the company's minimum rate of return. The payback period is presented as a financial tool rather than an economic evaluation tool. The payback results indicate that the company would receive their money back on the projects in a relatively short time. The payback period is an adequate financial tool to determine whether or not the company will go broke before the project commences. However, payback should not be used as an economic evaluation tool because it neglects the time value of money and the remaining cash flows in the project's life beyond the payback period.

Although the results of the three base case models indicate that the base case projects were economically feasible, there are many uncertainties that must be addressed in project analyses. The project's vulnerability to the impact of contingencies that could occur before or after the start of operations should be investigated. A sensitivity analysis is recommended for this purpose and will be conducted in the following section.

Sensitivity Analysis

Mineral projects are particularly vulnerable to changing conditions by virtue of the scale of investment and the time lag between expenditure and recovery. Sensitivity analysis allows one to determine how an investment's profitability is affected by a variation in the base case parameters. This approach provides the company with another useful evaluation tool to analyze their investments. When a project's economic results meet the company's minimum economic standards for the most pessimistic case, then obviously the project would be a good investment. On the other hand, when the most optimistic case falls below the company's minimum economic standards, project investment should be delayed until the necessary conditions improve.

For the three models presented in this study, one parameter was varied within a specified range while all other factors were held constant. The parameters which were varied include revenue, operating costs, and capital costs. The parameters were increased and decreased in a 50 percent range. The results of these analyses are presented in Table 20 and Figures 6 through 8.

The results indicate that in all three cases, the models' revenues have the most significant impact on the returns available to the company. The return, on the other hand, is not as sensitive to changes in capital and operating costs except in the chemical plant model. The chemical plant model's return is highly sensitive to the change in operating costs. Hence, more time should be spent determining project revenue estimates and operating costs associated with the chemical plant model if the firm considers these parameters significant in the overall evaluation. Obviously, one would consider revenues reasonably significant.

Before making a conclusion that the three rare earth models presented would be a profitable investment, it would behoove the company to conduct a market strategy analysis. This analysis is provided in the following chapter.

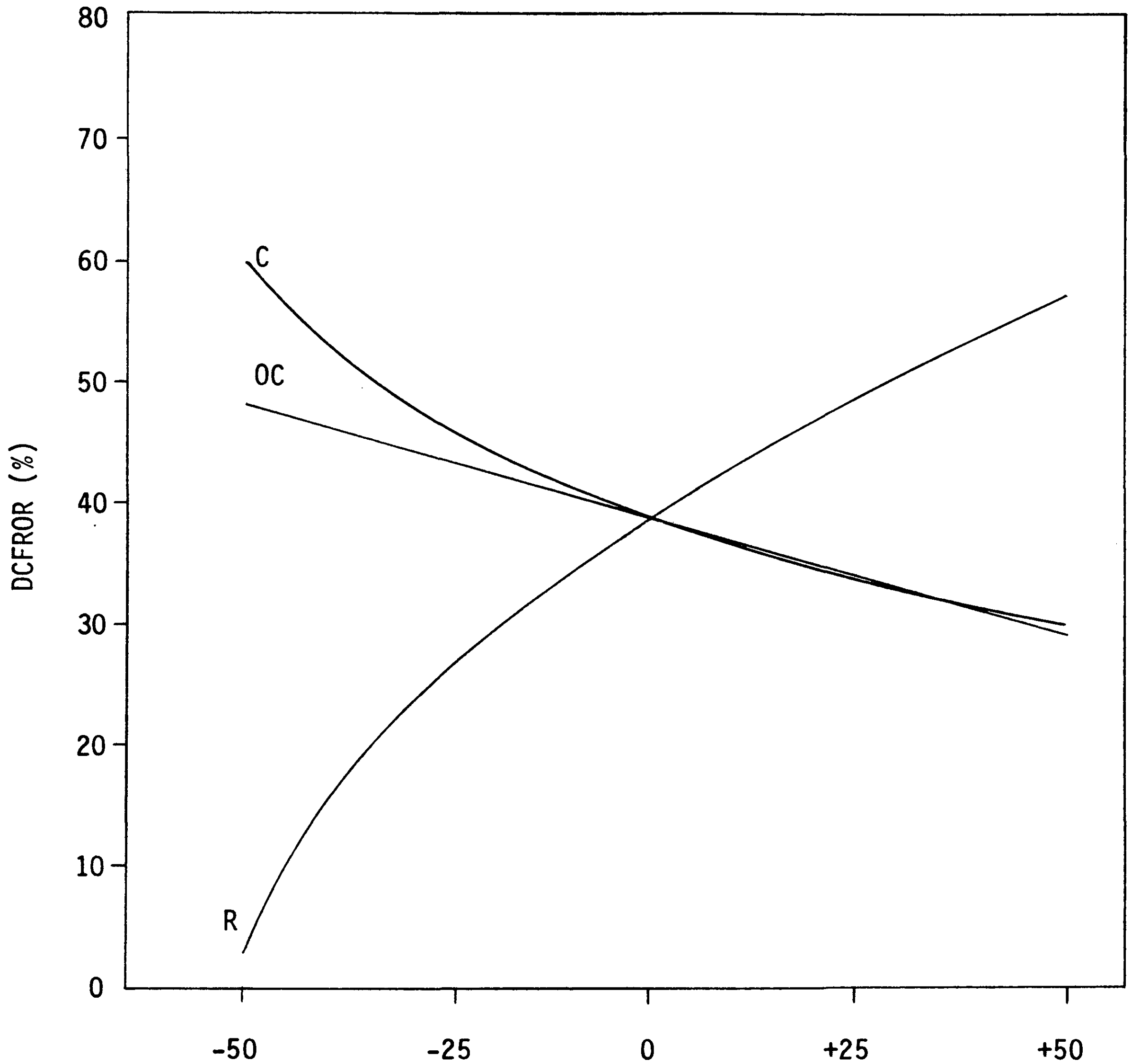
Table 20

DCFROR Sensitivity Results for the Base Case Models

(Percent)

		Mine/Mill	Chemical Plant	Mine/Mill/Chem Plant
	+50	57.65	61.42	49.47
	+25	49.14	49.18	41.48
Revenue	0	39.12	33.99	32.10
	-25	26.68	13.23	19.58
	-50	4.40	0	0
	+50	28.75	5.50	19.70
	+25	34.38	21.79	26.98
Operating	0	39.12	33.99	32.10
Cost	-25	43.56	44.27	36.67
	-50	47.77	53.29	40.96
	+50	29.63	25.03	23.95
	+25	33.67	28.81	27.41
Capital	0	39.12	33.99	32.10
	-25	46.96	41.58	38.93
	-50	59.46	53.97	50.01

Note: "0" indicates the base case model.



Percent change from the base case for
revenue (R), operating costs (OC), and capital (C).

Figure 6. DCFROR Sensitivity Analysis for the Mine/Mill Model

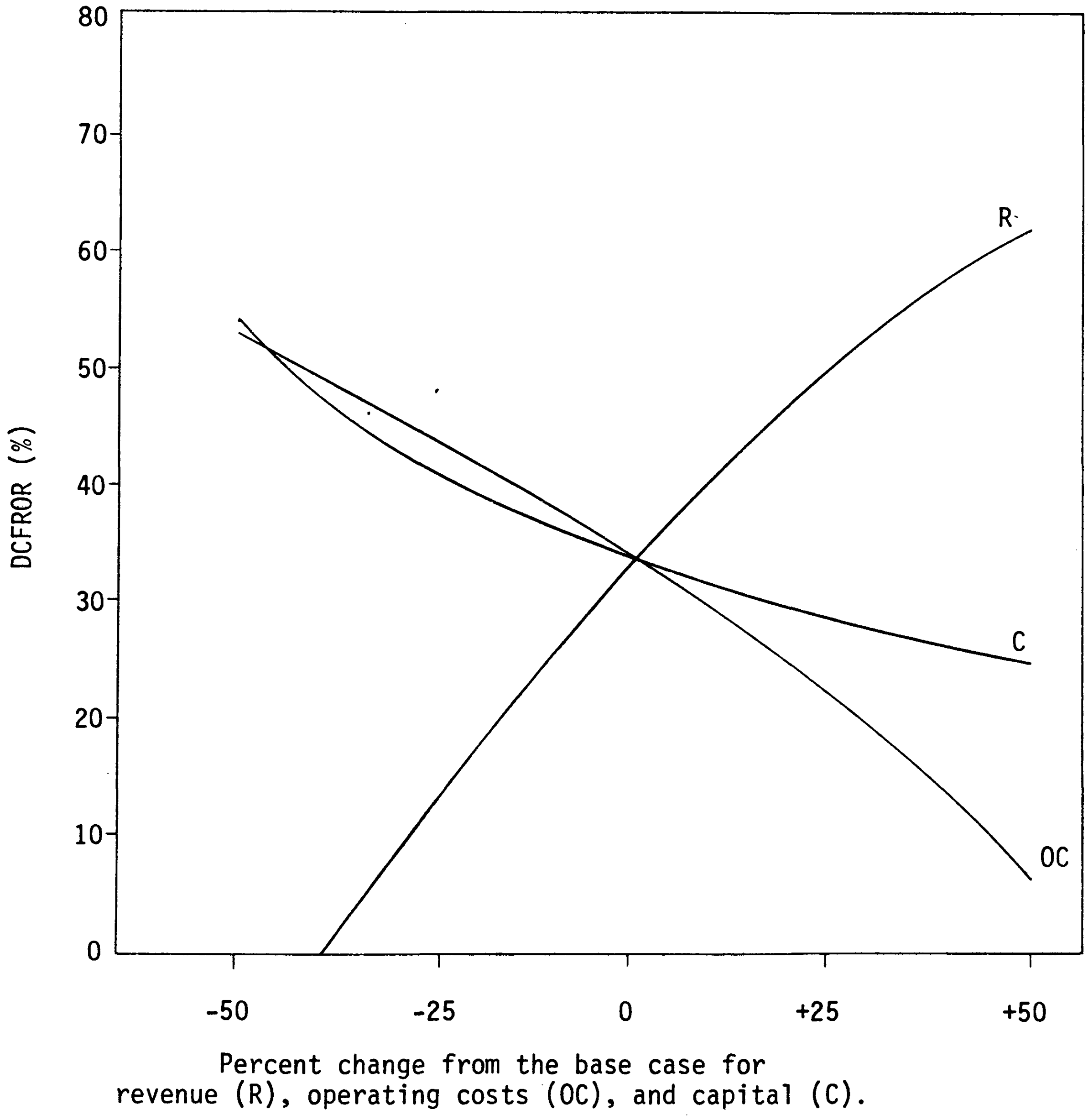


Figure 7. DCFROR Sensitivity Analysis for the Chemical Plant Model

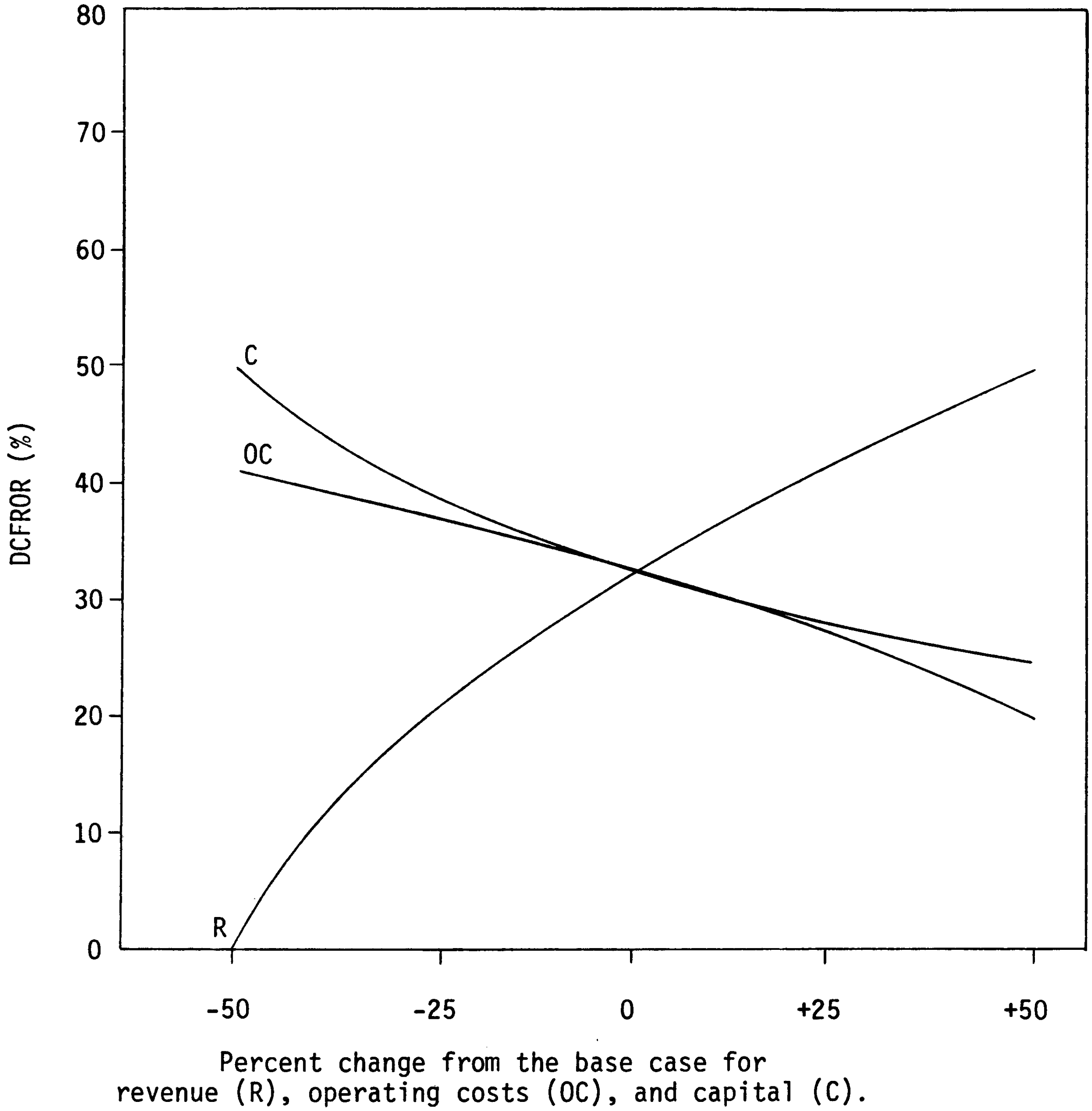


Figure 8. DCFROR Sensitivity Analysis for the Mine/Mill/Chemical Plant Model

CHAPTER 8

MARKET STRATEGY

The economic evaluation presented in the previous chapter has an underlying assumption that 100 percent of the product produced will be sold. In essence, the sensitivity analysis allows for some deviation from this basic assumption by varying the revenue. However, the sensitivity analysis indicated that the project's rate of return was significantly sensitive to changes in revenue. Hence, an analysis of the rare earth market in conjunction with the economic evaluation and sensitivity analysis would provide the company with a market strategy in which profitability could be maximized per investment dollar.

As pointed out earlier in the rare earth supply/demand scenario, there exists a substantial underutilization of mine capacity. If demand increases faster than predicted, it would seem reasonable to assume that existing mine operations could supply this incremental amount of concentrate supply much more readily and with less capital investment than a new producer. As shown in the sensitivity analysis, if mine/mill revenues decreased 50 percent (or only half of the total production is sold, which is a very realistic case in the rare earth industry), the mine/mill model is no longer economic.

The high-purity rare earths produced by the chemical plant, on the other hand, have the highest growth potential. Although the chemical plant model resulted in a lower NPV (@ 12%) and DCFROR than the mine/mill model, there appears to be less risk associated with declining revenues in the chemical plant model than the mine/mill model. Based on the market outlook presented earlier in this study regarding high-purity rare earths, and the fact that the product mix of the chemical plant could expand to include more rare earth products, lends positive indications that the chemical plant revenues would tend to increase rather than decrease, thus enhancing the economic results. However, it should be pointed out that the rate of return for the chemical plant model was sensitive to large variations in the operating costs. In view of the foregoing discussion, it would seem that the potential increase in revenues in the chemical plant model would offset any expected increase in operating costs. In order to test this assumption, additional sensitivity analyses would be required.

The mine/mill/chemical plant model was basically presented to show the results of a vertically integrated operation. The economic results indicated that the model was an economically feasible venture which was the least sensitive to changes in revenue, operating and capital costs when compared to the other two models. The main point a company must consider is whether or not a captive mine source is desired. Also the company should investigate if the additional investment for the mine/mill/chemical plant over the other two models is economically justifiable.

CHAPTER 9

CONCLUSION

An analysis of the rare earth industry was conducted to determine if a company could enter and maintain a profitable position within the rare earth industry. This analysis was accomplished by 1) evaluating the historical and current rare earth industry and forecasting the future supply/demand and market potential of rare earths, and 2) by developing a base case model in which economic evaluations and sensitivity analyses were performed using the discounted cash flow rate of return (DCFROR) and net present value (NPV) methods.

In regard to the market analysis, the following conclusions were made:

1. Reserve and production capabilities are such that Western World supplies could satisfy market requirements for the foreseeable future.

2. Current rare earth concentrate production from the two principal minerals, bastnaesite and monazite, is significantly below existing capacity.

3. The high-purity, separated rare earths and metallurgical additives have a higher growth potential than the growth potential of concentrates and intermediate compounds.

Three rare earth models were developed which included a mine/mill model, a chemical plant model, and a mine/mill/chemical plant model. Capital and operating cost estimates were included with each model in order that economic and sensitivity analyses could be conducted. The results of the economic analysis indicated that, based on a minimum rate of return of 12 percent, all three models were economically feasible. However, the sensitivity analysis showed that all three models' rate of return was significantly sensitive to changes in revenue. Changes in capital and operating costs had less of an impact on the rate of return except in the chemical plant model. Changes in the operating costs in the chemical plant model significantly influenced the rate of return.

In view of the impact revenue changes had on the models' rate of return, a market strategy analysis was conducted. In regard to this analysis, the following conclusions were made:

1. The mine/mill operation would probably have to operate at an economically undesirable rate below capacity because of the downward pressure on prices from excess concentrates on the market.
2. The chemical plant operation has the best potential in maintaining or increasing profits with the least amount of risk involved.

3. The mine/mill/chemical plant option is valid only if a company requires a captive mine source.

In reviewing the foregoing discussion, it can be concluded that a low operating cost primary rare earth mine with a substantial reserve base is not necessarily advantageous for a successful entry into the rare earth industry. Conversely, a rare earth chemical processing plant would be an essential element for entering and maintaining a profitable position within the rare earth industry.

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APPENDIX A. PHYSICO-CHEMICAL PROPERTIES OF RARE EARTH ELEMENTS

Atomic number	Symbol	ELEMENT	Atomic weight O = 16.00	Melting point of the metal ± 5° C	Specific gravity	Crystalline form	Approximative temperature at which the metal has a vapour pressure of 1-2 mm Hg	Boiling point °K 760 mm Hg	Formula of the oxide	Molecular weight of the oxide	Specific gravity of the oxide	Crystalline form of the oxide	Melting point of the oxide °C
							°C	°K					°C
39	Y	YTTRIUM	88.92	1.539	4.47	hexagonal	1.750	3.200	Y_2O_3	225.8	4.8-5.0	cubic	2.415
57	La	LANTHANUM	138.92	920	6.17	hexagonal	2.600	3.772	La_2O_3	325.8	6.51	hexagonal	2.250
58	Ce	CERIUM	140.13	795	6.77	cubic	2.500	3.741	CeO_2	172.1	7.3	cubic	1.950
					6.67	hexagonal							
59	Pr	PRASEODYMIUM	140.92	935	6.78	hexagonal	2.230	3.400	Pr_6O_{11}	1021.5		cubic	2.200
					6.64	cubic							
60	Nd	NEODYMIUM	144.27	1.024	7.00	hexagonal	2.200	3.300	Nd_2O_3	336.5	7.24	hexagonal	2.272
					6.80	cubic							
62	Sm	SAMARIUM	150.35	1.072	7.53	rhomb.		2.173	Sm_2O_3	348.7	7.43	cubic	2.325
63	Eu	EUROPIUM	152.00	826	5.25	cubic	1.140	1.712	Eu_2O_3	352.0	7.42	cubic	2.050
64	Gd	GADOLINIUM	156.90	1.312	7.89	hexagonal		3.273	Gd_2O_3	362.5	7.4	cubic	2.340
					7.80	cubic							
65	Tb	TERBIUM	158.93	1.356	8.27	hexagonal	1.670	3.073	Tb_4O_7	747.7		cubic	2.200
66	Dy	DYSPROSIUM	162.51	1.407	8.53	hexagonal	1.500	2.873	Dy_2O_3	373.0	7.8	cubic	2.340
67	Ho	HOLMIUM	164.94	1.461	8.80	hexagonal	1.600	2.873	Ho_2O_3	377.9		cubic	2.360
68	Er	ERBIUM	167.27	1.497	9.05	hexagonal	1.500	3.173	Er_2O_3	382.5	8.6	cubic	2.355
69	Tm	THULIUM	168.94	1.545	9.33	hexagonal	1.225	2.000	Tm_2O_3	385.9	8.6	cubic	2.400
70	Yb	YTTERBIUM	173.04	824	6.97	cubic		1.700	Yb_2O_3	394.1	9.2	cubic	2.346
					6.54	cubic							
71	Lu	LUTECIUM	174.99	1.652	9.84	hexagonal	1.800	3.600	Lu_2O_3	398.0		cubic	2.490
90	Th	THORIUM	232.04	1.700	11.7	cubic	-	4.000	ThO_2	264.04	9.86	cubic	3.050

Electronic Structure of Rare Earth Elements, Y, and Th.

		K	L		M			N				O				P			Q
		1s	2s	2p	3s	3p	3d	4s	4p	4d	4f	5s	5p	5d	5f	6s	6p	6d	7s
Y	39	2	2	6	2	6	10	2	6	1		2							
La	57	2	2	6	2	6	10	2	6	10		2	6	1		2			
Ce	58	2	2	6	2	6	10	2	6	10	1	2	6	1		2			
Pr	59	2	2	6	2	6	10	2	6	10	2	2	6	1		2			
Nd	60	2	2	6	2	6	10	2	6	10	3	2	6	1		2			
Sm	62	2	2	6	2	6	10	2	6	10	5	2	6	1		2			
Eu	63	2	2	6	2	6	10	2	6	10	6	2	6	1		2			
Gd	64	2	2	6	2	6	10	2	6	10	7	2	6	1		2			
Tb	65	2	2	6	2	6	10	2	6	10	8	2	6	1		2			
Dy	66	2	2	6	2	6	10	2	6	10	9	2	6	1		2			
Ho	67	2	2	6	2	6	10	2	6	10	10	2	6	1		2			
Er	68	2	2	6	2	6	10	2	6	10	11	2	6	1		2			
Tm	69	2	2	6	2	6	10	2	6	10	12	2	6	1		2			
Yb	70	2	2	6	2	6	10	2	6	10	13	2	6	1		2			
Lu	71	2	2	6	2	6	10	2	6	10	14	2	6	1		2			
Th	90	2	2	6	2	6	10	2	6	10	14	2	6	10		2	6	2	2

APPENDIX B. MAJOR PROCESSORS OF RARE EARTHS

Major Processors of Rare Earths

Company	Ownership	Plant/Raw Materials	Products/Capacity	Remarks
AUSTRIA				
Treibacher Chemische Werke AG	--	Treibach, Austria Crude rare earth chloride and bastnaesite concentrates.	Mischmetal 800-1,000 tpa, flints, pure rare earth compounds, metals and samarium concentrates, polishing compounds marketed under the brand name "Tecepol"	Founded in 1898. Separation of individual rare earths by liquid-liquid extraction.
BRAZIL				
Empresas Nucleares Brasileires SA (Nuclebras) da Monazita e Associados Ltda.	Government with some private participation	Santo Amora, Sao Paulo, Monazite	Rare earth chloride, carbonate, oxide	Processing plant built in 1948. Plans for new plant awaiting approval.
Companhia Industrial Fluminense	--	Sao Joaodel Rei, Minas Gerais, Brazil Crude rare earth chloride	Mischmetal (50-55% Ce) in ingots, capacity approximately 108 tpa	Combined total Brazilian mischmetal capacity 1,000 tpa
Metalurgica "Colibri" Ltda.	--	Sao Paulo, Brazil Crude rare earth chloride	Mischmetal	--
Metalurgica Corona Ltda.	--	Embu-Guacu, Sao Paulo Crude rare earth chloride	Mischmetal (57.7% Ce) in rods, waffles, dough-nuts, balls, nuggets, etc.	Brazil's largest mischmetal producer accounting for approximately 60% total Brazilian production.
FRANCE				
Etablissements Tricot	--	Parny-sur-Saulx Monazite	Mischmetal	--
Rhone-Poulenc Industries, Fine Chemicals Division	-- --	La Rochelle, Charente Maritime, Monazite	Mischmetal approximately 250 tpa. Polishing com-pounds. High purity rare earth metals and chemi-cals - see text for capacities. 5,000 tpa ore reduction capacity.	Plans for expansion in the USA. Recently formed joint company with French Com-missariat a l'Energie Atomique -Crismatec SA for production of GGG & other electronic devices.
INDIA				
Indian Rare Earths Ltd.	Government-controlled	Udyogamandal, Kerala Monazite	Rare earth chloride - 4,600 tpa, fluoride - 180 tpa, oxide - 60 tpa, small scale yttrium, samarium, and gadolinium	IRE currently setting up mineral sands complex and processing plant in the State of Orissa with com-pletion around mid-1981, estimated to produce 4,000 tpa of monazite

Source: Industrial Minerals, no. 138, 1979.

Major Processors of Rare Earths (Continued)

Company	Ownership	Plant/Raw Materials	Products/Capacity	Remarks
JAPAN				
Nippon Yttrium Co. Ltd.	Mitsui Mining and Smelting Co., and Tohoku Metal Industries Ltd., etc.	Mitaka, Tokyo Monazite	Rare earth oxides, etc. especially yttrium, samarium and gadolinium oxides	A large number of companies process rare earths in Japan using ore minerals or crude rare earth chemicals.
Shin-Etsu Chemicals	--	--	Separated high purity oxides	--
Sankin Rare Earths	--	--	Lanthanum oxide and cerium oxide	--
Tohoku Kinzoku Kagaku	--	--	Lanthanum oxide and cerium oxide	--
Shin Nippon Kinzoku Kagaku	--	--	Mischmetal, cerium oxide	--
Nissan Kigenso Kagaku	--	--	Cerium compounds	--
Seimi Chemicals	--	--	Cerium oxide	--
Ogino Kagaku Kenkyushu	--	Hikami, Hyogo Pref. Monazite	Produces mischmetal, flints, cerium oxide	--
Santoku Kinzoku Kogyo K.K.	--	Kobe Monazite, crude rare earth chloride, and bastnaesite	Mischmetal, flints, yttrium and europium oxide, cerium chloride, light rare earth oxides, etc.	--
MALAYSIA				
Malaysian Rare Earth Corporation Sdn. Bhd.	Misubishi Chemical Industries Ltd. and Beh Minerals Sdn. Bhd.	Lahat Xenotime	Produces yttrium oxide concentrate (Y_2O_3, 60%+) 135 tpa capacity	Established 1973. Plans to produce crude rare earth chloride from monazite
NORWAY				
A/S Metal Extractor Group of Norway (Megon)	Elkem-Spigerverket, Dyno Industries, Ardall og Sunndall Verke, Norzink, Sulitjelma Gruber, H. Bjorum, S. D. Cappelen, Norwegian Talc, Sydvaranger	Kjeller, near Oslo Xenotime	High purity yttrium oxide (99.999%) 30-50 tpa	Participating with the Malaysians to operate a concentrator near Kuala Lumpur designed to produce 27 tpa 60% YO_{23}

Major Processors of Rare Earths (Continued)

Company	Ownership	Plant/Raw Materials	Products/Capacity	Remarks
UNITED KINGDOM				
British Flint & Cerium Manufacturers Ltd.	Ronson Metals Corporation, USA	Tonbridge, Kent Rare earth chloride	Mischmetal, flints, etc.	Ronson took over from Spark Holding Ltd. in 1969
London & Scandinavian Metallurgical Company Ltd.	Metallurg Inc., USA	Rotherham, Yorkshire Rare earth concentrates	Mischmetal under the trade name "Raremet", rare earth silicide, polishing compounds under the trade name "Regipol"	--
Rare Earth Products Ltd.	Johnson Matthey Chemicals Ltd.	Widnes Rare earth oxide	High purity rare earth chemicals, metals, alloys.	Johnson Matthey took full control in 1976 when RTZ pulled out.
Steetley Chemicals Ltd.	The Steetley Company Ltd.	Widnes Monazite	Rare earth chloride, hydrates, oxides, salts, polishing compounds under the trade name "Optipol"	Steetley are scheduled to begin production in mid-1979, capacity and capital outlay will be published in the near future.
USA				
Atomergic Chemetals Corporation	--	--	High purity rare earth chemicals	--
Electralloy Corp.	--	175 Main Street, Oil City, Pa. 16301	Mischmetal	--
Foote Mineral Company	--	--	Rare earth ferrosilicon alloys	--
Rare Earth Metals Company of America (Remcoa)	Aluminium Company of America (Alcoa) and Molycorp Inc.	Pittsburgh, Pennsylvania Pilot plant Rare earth oxide	Mischmetal 125 tpa	No mischmetal produced during 1977 although work continued on a pilot-scale programme
Ronson Metals Corporation	Ronson Corporation	Newark, New Jersey	Mischmetal under the trade name "Ceralloy" Pure rare earth metals cerium, lanthanum, didymium (Nd + Pr), cerium-free mischmetal, samarium, various electronic products	Newark plant commissioned in 1974, underwent 100% expansion 1977. 1977 mischmetal sales increased 100% over 1976.

Major Processors of Rare Earths (Continued)

Company	Ownership	Plant/Raw Materials	Products/Capacity	Remarks
The Pesses Company	--	Pulaski, Pennsylvania	Mischmetal and mischmetal silicide	--
Transelco Inc.	Ferro Corporation	Dresden, New York Crude rare earth oxides, etc.	Optical polishing compounds under the trade names "Zox-Ce", "Ce-rite", "Miramex-B", and "Oxyrit"	--
W. R. Grace & Co. Davison Chemical Division	--	Chattanooga, Tennessee Pompton Plains, New Jersey Monazite, bastnaesite, etc.	High purity rare earth oxides, compounds and polishing compounds	Monazite processing capacity increased in 1977 at the Chattanooga plant
Molycorp Inc.	Union Oil Company of California	Mountain Pass, California; Louviers, Colorado; and York and Washington, Pennsylvania Bastnaesite	High purity rare earth chemicals, oxides, etc. Mischmetal capacity is approximately 45 tpa marketed in ingots	50% expansion in 1975 at Mountain Pass to 15,000 stpa and in 1978 construction of six new solvent extraction circuits for cerium, lanthanum, samarium, gadolinium, needymium, praseodymium
Nucor Corporation, Research Chemicals Division	--	--	High purity rare earth oxides and compounds	--
Ohio Ferro-Alloys Corporation	--	--	Rare earth ferrosilicon alloys	--
Reactive Metals & Alloys Corporation (Remacor)	--	West Pittsburgh, Pennsylvania (near New Castle)	Mischmetal, 1,800 tpa, under the trade name "Mischaloy" in bails, doughnuts, and canisters. Rare earth silicide under the trade name "Resaloy"	One of the largest producers of mischmetal in the USA. Announced expansion programme in November 1977 to double production capacity, which presently is over 1,800 tonnes per year.

Major Processors of Rare Earths (Continued)

Company	Ownership	Plant/Raw Materials	Products/Capacity	Remarks
USSR				
Techsnabexport Smolenskaya	Government-owned	Unknown	Rare earth metals and alloys. Polishing compounds under the trade name "Polirit"	--
WEST GERMANY				
Th. Goldschmidt AG	--	Essen, Ruhr Bastnaesite, etc.	Rare earth metals, RECo alloys capacity is 200 tpa, mischmetal capacity around 800-1,000 tpa	--

APPENDIX C. CASH FLOW DIAGRAMS FOR THE THREE BASE CASE RARE EARTH MODELS

RE MINE/MILL BASE CASE

YEAR	GRADE	TONS/YR	RECOVERY FACTOR	LBS/YR	SALES PRICE	SALES	LESS OPERATING COSTS	LESS PREPROD. COSTS	GROSS MARGIN	YEAR
1	0.000	0.	0.00000	0.	0.000	0.	0.	613.	-613.	1
2	0.000	0.	0.00000	0.	0.000	0.	0.	409.	-409.	2
3	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	3
4	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	4
5	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	5
6	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	6
7	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	7
8	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	8
9	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	9
10	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	10
11	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	11
12	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	12
13	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	13
14	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	14
15	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	15
16	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	16
17	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	17
18	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	18
19	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	19
20	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	20
21	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	21
22	8.000	193.	0.70000	21609.	1.000	21609.	9450.	0.	12159.	22
	0.12000	36431.								
	0.21236	13554.								
	0.30347	4295.								
	0.33234	2555.								
	0.34952	1690.								
	0.36087	1176.								
	0.36878	844.								
	0.37445	617.								
	0.37860	457.								
	0.38167	341.								
	0.38396	257.								
	0.38569	194.								
	0.38699	147.								
	0.39111	2.								
TOTALS		3860		432180		432130	189000	1022	242158	

EXPECTED RATE OF RETURN IS 39.12 PERCENT

RE MINE/MILL BASE CASE

* * * * * * * * * * * * * * * CAPITAL * * * * * * ** * * * * * * * *

	WORKING CAPITAL				* * * MACHINERY & EQUIPMENT * * *								
YEAR	INVENT.	RECEIV.	LAND	WATER	TYPE 1 M & E	TYPE 2 M & E	TYPE 3 M & E	TOTAL M & E	BLDGS	TOTAL CAPITAL	LESS DEPRE-CIATION	PROFIT BEFORE TAXES	YEAR
1	0.	0.	0.	0.	4187.	0.	0.	4187.	700.	4887.	411.	-1024.	1
2	2363.	0.	0.	0.	9769.	0.	0.	9769.	1050.	10819.	1718.	-2127.	2
3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2484.	9675.	3
4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2223.	9936.	4
5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1962.	10197.	5
6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1701.	10458.	6
7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1440.	10719.	7
8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1179.	10980.	8
9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	918.	11241.	9
10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	695.	11464.	10
11	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	447.	11713.	11
12	0.	0.	0.	0.	3000.	0.	0.	3000.	0.	3000.	357.	11802.	12
13	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	595.	11564.	13
14	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	533.	11626.	14
15	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	471.	11688.	15
16	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	409.	11750.	16
17	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	348.	11812.	17
18	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	286.	11874.	18
19	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	224.	11935.	19
20	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	162.	11997.	20
21	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	127.	12032.	21
22	-2363.	0.	0.	0.	0.	0.	0.	0.	0.	0.	15.	12145.	22
	0	0	0	0	16956	0	0	16956	1750	18706	18705	223457	

RE MINE/MILL BASE CASE

YEAR	DEPLE- TION	TAXABLE INCOME	LESS F.I.T.	INVEST. TAX CRED.	PROFIT AFTER TAXES	PLUS DEPRE- CIATION	OPERAT. CASH FLOW	LESS WORKING CAPITAL	LESS CAPITAL EXPEND.	NET CASH FLOW	CUMULA- TIVE NET CASH FLOW	YEAR
1	0.	-1024.	-471.	419.	-134.	411.	277.	0.	4887.	-4610.	-4610.	1
2	0.	-2127.	-979.	977.	-172.	1718.	1547.	2363.	10819.	-11635.	-16245.	2
3	3025.	6650.	3059.	0.	6616.	2484.	9100.	0.	0.	9100.	-7145.	3
4	3025.	6911.	3179.	0.	6757.	2223.	8980.	0.	0.	8980.	1836.	4
5	3025.	7172.	3299.	0.	6898.	1962.	8860.	0.	0.	8860.	10696.	5
6	3025.	7433.	3419.	0.	7039.	1701.	8740.	0.	0.	8740.	19436.	6
7	3025.	7694.	3539.	0.	7180.	1440.	8620.	0.	0.	8620.	28056.	7
8	3025.	7955.	3659.	0.	7321.	1179.	8500.	0.	0.	8500.	36556.	8
9	3025.	8216.	3779.	0.	7462.	918.	8380.	0.	0.	8380.	44936.	9
10	3025.	8439.	3882.	0.	7582.	695.	8277.	0.	0.	8277.	53214.	10
11	3025.	8687.	3996.	0.	7716.	447.	8163.	0.	0.	8163.	61377.	11
12	3025.	8777.	4037.	300.	8065.	357.	8422.	0.	3000.	5422.	66798.	12
13	3025.	8539.	3928.	0.	7636.	595.	8231.	0.	0.	8231.	75030.	13
14	3025.	8601.	3956.	0.	7670.	533.	8203.	0.	0.	8203.	83233.	14
15	3025.	8663.	3985.	0.	7703.	471.	8174.	0.	0.	8174.	91407.	15
16	3025.	8725.	4013.	0.	7737.	409.	8146.	0.	0.	8146.	99553.	16
17	3025.	8786.	4042.	0.	7770.	348.	8118.	0.	0.	8118.	107671.	17
18	3025.	8848.	4070.	0.	7803.	286.	8089.	0.	0.	8089.	115760.	18
19	3025.	8910.	4099.	0.	7837.	224.	8061.	0.	0.	8061.	123820.	19
20	3025.	8972.	4127.	0.	7870.	162.	8032.	0.	0.	8032.	131852.	20
21	3025.	9007.	4143.	0.	7889.	127.	8016.	0.	0.	8016.	139869.	21
22	3025.	9119.	4195.	0.	7950.	15.	7964.	-2363.	0.	10327.	150196.	22
	60500	162953	74956	1696	150195	18705	168900	0	18706			

RE CHEMICAL PLANT BASE CASE

YEAR	GRADE	TONS/YR	RECOVERY FACTOR	LBS/YR	SALES PRICE	SALES	LESS OPERATING COSTS	LESS PREPROD. COSTS	GROSS MARGIN	YEAR
1	0.000	0.	0.00000	0.	0.000	0.	0.	582.	-582.	1
2	0.000	0.	0.00000	0.	0.000	0.	0.	388.	-388.	2
3	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	3
4	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	4
5	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	5
6	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	6
7	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	7
8	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	8
9	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	9
10	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	10
11	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	11
12	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	12
13	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	13
14	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	14
15	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	15
16	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	16
17	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	17
18	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	18
19	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	19
20	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	20
21	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	21
22	0.100	193.	0.91000	351.	100.000	35115.	22106.	0.	13009.	22
0.12000		29563.								
0.20430		10609.								
0.28113		3107.								
0.30363		1732.								
0.31617		1073.								
0.32394		698.								
0.32899		467.								
0.33237		317.								
0.33467		218.								
0.33625		151.								
0.33734		105.								
0.33810		73.								
0.33863		51.								
TOTALS		3860		7020		702300	442120	970	259210	

EXPECTED RATE OF RETURN IS 33.99 PERCENT

RE CHEMICAL PLANT BASE CASE

* * * * * * * * * * * * * * * CAPITAL * * * * * * ** * * * * * * *

YEAR	*WORKING CAPITAL* INVENT.	RECEIV.	LAND	WATER	* * * MACHINERY & EQUIPMENT * * * TYPE 1 M & E	TYPE 2 M & E	TYPE 3 M & E	TOTAL M & E	BLDGS	TOTAL CAPITAL	LESS DEPRE- CIATION	PROFIT BEFORE TAXES	YEAR
1	0.	0.	0.	0.	2745.	0.	0.	2745.	752.	3497.	282.	-864.	1
2	7402.	0.	0.	0.	6406.	0.	0.	6406.	1127.	7533.	1172.	-1560.	2
3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1692.	11317.	3
4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1517.	11491.	4
5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1343.	11666.	5
6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1169.	11840.	6
7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	995.	12014.	7
8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	821.	12188.	8
9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	646.	12363.	9
10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	497.	12512.	10
11	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	331.	12678.	11
12	0.	0.	0.	0.	2000.	0.	0.	2000.	0.	2000.	272.	12737.	12
13	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	428.	12581.	13
14	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	384.	12625.	14
15	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	339.	12669.	15
16	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	295.	12714.	16
17	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	251.	12758.	17
18	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	207.	12802.	18
19	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	163.	12846.	19
20	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	118.	12890.	20
21	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	92.	12916.	21
22	-7402.	0.	0.	0.	0.	0.	0.	0.	0.	0.	16.	12993.	22
	0	0	0	0	11151	0	0	11151	1879	13030	13030	246176	

RE CHEMICAL PLANT BASE CASE

YEAR	DEPLE- TION	TAXABLE INCOME	LESS F.I.T.	INVEST. TAX CRED.	PROFIT AFTER TAXES	PLUS DEPRE- CIATION	OPERAT. CASH FLOW	LESS WORKING CAPITAL	LESS CAPITAL EXPEND.	NET CASH FLOW	CUMULA- TIVE NET CASH FLOW	YEAR
1	0.	-864.	-398.	275.	-192.	282.	90.	0.	3497.	-3407.	-3407.	1
2	0.	-1560.	-717.	641.	-202.	1172.	970.	7402.	7533.	-13965.	-17372.	2
3	0.	11317.	5206.	0.	6111.	1692.	7803.	0.	0.	7803.	-9569.	3
4	0.	11491.	5286.	0.	6205.	1517.	7723.	0.	0.	7723.	-1846.	4
5	0.	11666.	5366.	0.	6299.	1343.	7643.	0.	0.	7643.	5796.	5
6	0.	11840.	5446.	0.	6394.	1169.	7563.	0.	0.	7563.	13359.	6
7	0.	12014.	5526.	0.	6488.	995.	7482.	0.	0.	7482.	20841.	7
8	0.	12188.	5607.	0.	6582.	821.	7402.	0.	0.	7402.	28244.	8
9	0.	12363.	5687.	0.	6676.	646.	7322.	0.	0.	7322.	35566.	9
10	0.	12512.	5755.	0.	6756.	497.	7253.	0.	0.	7253.	42819.	10
11	0.	12678.	5832.	0.	6846.	331.	7177.	0.	0.	7177.	49996.	11
12	0.	12737.	5859.	200.	7078.	272.	7350.	0.	2000.	5350.	55346.	12
13	0.	12581.	5787.	0.	6794.	428.	7222.	0.	0.	7222.	62568.	13
14	0.	12625.	5808.	0.	6818.	384.	7201.	0.	0.	7201.	69769.	14
15	0.	12669.	5828.	0.	6841.	339.	7181.	0.	0.	7181.	76950.	15
16	0.	12714.	5848.	0.	6865.	295.	7161.	0.	0.	7161.	84110.	16
17	0.	12758.	5869.	0.	6889.	251.	7140.	0.	0.	7140.	91251.	17
18	0.	12802.	5889.	0.	6913.	207.	7120.	0.	0.	7120.	98370.	18
19	0.	12846.	5909.	0.	6937.	163.	7100.	0.	0.	7100.	105470.	19
20	0.	12890.	5930.	0.	6961.	118.	7079.	0.	0.	7079.	112549.	20
21	0.	12916.	5942.	0.	6975.	92.	7067.	0.	0.	7067.	119617.	21
22	0.	12993.	5977.	0.	7016.	16.	7032.	-7402.	0.	14434.	134050.	22
	0	246176	113242	1116	134050	13030	147081	0	13030			

RE MINE/MILL/CHEM PLANT BASE CASE

YEAR	GRADE	TONS/YR	RECOVERY FACTOR	LBS/YR	SALES PRICE	SALES	LESS OPERATING COSTS	LESS PREPROD. COSTS	GROSS MARGIN	YEAR
1	0.000	0.	0.00000	0.	0.000	0.	0.	876.	-876.	1
2	0.000	0.	0.00000	0.	0.000	0.	0.	584.	-584.	2
3	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	3
4	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	4
5	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	5
6	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	6
7	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	7
8	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	8
9	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	9
10	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	10
11	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	11
12	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	12
13	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	13
14	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	14
15	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	15
16	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	16
17	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	17
18	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	18
19	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	19
20	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	20
21	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	21
22	0.008	193.	0.87000	27.	1000.000	26857.	13163.	0.	13695.	22
	0.12000	37717.								
	0.20344	13186.								
	0.27521	3604.								
	0.29482	1891.								
	0.30511	1099.								
	0.31109	669.								
	0.31474	418.								
	0.31701	265.								
	0.31845	169.								
	0.31937	109.								
	0.31996	70.								
	0.32034	45.								
	0.32059	29.								
TOTALS		3860		540		537140	263260	1460	272440	

EXPECTED RATE OF RETURN IS 32.10 PERCENT

RE MINE/MILL/CHEM PLANT BASE CASE

	WORKING CAPITAL		* * * * * * * * * * * * * * * * CAPITAL * * * * * * ** * * * * * * * *		* * * MACHINERY & EQUIPMENT * * *								
YEAR	INVENT.	RECEIV.	LAND	WATER	TYPE 1 M & E	TYPE 2 M & E	TYPE 3 M & E	TOTAL M & E	BLDGS	TOTAL CAPITAL	LESS DEPRE-CIATION	PROFIT BEFORE TAXES	YEAR
1	0.	0.	0.	0.	6239.	0.	0.	6239.	1326.	7564.	625.	-1501.	1
2	3291.	0.	0.	0.	14557.	0.	0.	14557.	1988.	16546.	2604.	-3188.	2
3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3763.	9932.	3
4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3371.	10324.	4
5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2979.	10716.	5
6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2587.	11108.	6
7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2195.	11500.	7
8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1803.	11892.	8
9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1411.	12284.	9
10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1076.	12619.	10
11	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	702.	12992.	11
12	0.	0.	0.	0.	4500.	0.	0.	4500.	0.	4500.	568.	13126.	12
13	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	923.	12772.	13
14	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	827.	12868.	14
15	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	731.	12963.	15
16	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	636.	13059.	16
17	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	540.	13155.	17
18	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	444.	13250.	18
19	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	349.	13346.	19
20	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	253.	13442.	20
21	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	198.	13496.	21
22	-3291.	0.	0.	0.	0.	0.	0.	0.	0.	0.	28.	13667.	22
	0	0	0	0	25296	0	0	25296	3314	28610	28613	243822	

RE MINE/MILL/CHEM PLANT BASE CASE

YEAR	DEPLE-TION	TAXABLE INCOME	LESS F.I.T.	INVEST. TAX CRED.	PROFIT AFTER TAXES	PLUS DEPRE-CIATION	OPERAT. CASH FLOW	LESS WORKING CAPITAL	LESS CAPITAL EXPEND.	NET CASH FLOW	CUMULA-TIVE NET CASH FLOW	YEAR
1	0.	-1501.	-690.	624.	-187.	625.	438.	0.	7564.	-7126.	-7126.	1
2	0.	-3188.	-1467.	1456.	-266.	2604.	2338.	3291.	16546.	-17499.	-24625.	2
3	3760.	6172.	2839.	0.	7093.	3763.	10856.	0.	0.	10856.	-13769.	3
4	3760.	6564.	3020.	0.	7305.	3371.	10675.	0.	0.	10675.	-3094.	4
5	3760.	6956.	3200.	0.	7516.	2979.	10495.	0.	0.	10495.	7401.	5
6	3760.	7348.	3380.	0.	7728.	2587.	10315.	0.	0.	10315.	17716.	6
7	3760.	7740.	3560.	0.	7940.	2195.	10134.	0.	0.	10134.	27850.	7
8	3760.	8132.	3741.	0.	8151.	1803.	9954.	0.	0.	9954.	37804.	8
9	3760.	8524.	3921.	0.	8363.	1411.	9774.	0.	0.	9774.	47578.	9
10	3760.	8859.	4075.	0.	8544.	1076.	9620.	0.	0.	9620.	57197.	10
11	3760.	9232.	4247.	0.	8745.	702.	9448.	0.	0.	9448.	66645.	11
12	3760.	9366.	4309.	450.	9268.	568.	9836.	0.	4500.	5336.	71981.	12
13	3760.	9012.	4146.	0.	8627.	923.	9549.	0.	0.	9549.	81530.	13
14	3760.	9108.	4190.	0.	8678.	827.	9505.	0.	0.	9505.	91036.	14
15	3760.	9203.	4234.	0.	8730.	731.	9461.	0.	0.	9461.	100497.	15
16	3760.	9299.	4278.	0.	8782.	636.	9417.	0.	0.	9417.	109914.	16
17	3760.	9395.	4322.	0.	8833.	540.	9373.	0.	0.	9373.	119287.	17
18	3760.	9490.	4366.	0.	8885.	444.	9329.	0.	0.	9329.	128616.	18
19	3760.	9586.	4410.	0.	8936.	349.	9285.	0.	0.	9285.	137901.	19
20	3760.	9682.	4454.	0.	8988.	253.	9241.	0.	0.	9241.	147143.	20
21	3760.	9736.	4479.	0.	9018.	198.	9216.	0.	0.	9216.	156359.	21
22	3760.	9907.	4557.	0.	9110.	28.	9138.	-3291.	0.	12429.	168787.	22
	75200	168622	77571	2530	168787	28613	197397	0	28610			