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An econometric model of the world cobalt industry

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AN ECONOMETRIC MODEL OF THE WORLD
COBALT INDUSTRY

by

Reza Rafati⁺

December 1982

Institut für Weltwirtschaft an der Universität Kiel

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Abstract

One of the main still unresolved issues discussed at the United Nations Conference on the Law of the Sea has been the potential impact of the recovery of cobalt, copper, manganese and nickel from seabed nodules on the markets of those metals. It has been argued that the start of seabed mining could significantly affect both prices and production if a free entry regime prevailed. In order to provide a sound empirical basis for further discussions of this topic the present study aims at quantifying the potential effects of seabed mining on the cobalt market. First, an econometric model of the world cobalt industry is specified and estimated. Next, the model is simulated for different scenarios: no exogenous change, the start of the stockpiling of cobalt by the US government, and the start of seabed mining. The study concludes that the reduction in cobalt prices, as a result of seabed mining, will be drastic, particularly in the free entry case, and that the major revenue loser will be Zaire, the world's largest producer of cobalt.

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I. Introduction

Cobalt (Co) with atomic number 27, is a hard, brittle metal, closely resembling iron and nickel in appearance¹. It has a melting point of 1495° C and a boiling point of 2870° C². Cobalt was first used as a pigment about 2000 B. C., when naturally occurring cobalt compounds were used to color glass³. In 1742 it was isolated as a metal by G. Brant, and in 1780, Bergman established cobalt as an element⁴.

Cobalt has been developed through the centuries from an obscure coloring additive into an essential element in many alloys and chemical compounds. Due to its strength in imparting essential qualities, such as heat resistance, high strength, wear resistance, and superior magnetic qualities, cobalt has become a vital element in the aerospace and electronic products industries. Cobalt is usually mined as a byproduct of nickel or copper mines. Therefore, cobalt supply is not only inelastic with respect to price but its availability also depends on future expansions of nickel and copper operations.

II. A Descriptive Analysis of Supply and Demand for Cobalt

The world cobalt market exhibits a high degree of concentration on the supply side as well as the demand side of the market. On the supply side, about 60 percent of the non-communist world production of cobalt originates from Zaire while, on the demand side, the United States account for about 30 percent of the non-communist nations demand for cobalt. Nevertheless, the cobalt

¹ Metal Statistics (1981), P. 49.

² Ibid.

³ Sibley (1979), P. 2.

⁴ Ibid.

market has been operating in an orderly fashion, the only exception being the late 1970's when a combination of increases in consumption and speculative/precautionary buyings, caused by attacks on the cobalt mines in Zaire, sent cobalt prices skyrocketing and forced rationing in the market. The cobalt prices, almost always set by Zaire, have also been changed infrequently and smoothly, again with the exception of the late 1970's. More will be said about the stability of the cobalt market later on.

1. Historical Production and Future Prospects

Cobalt is mostly obtained as a by-product from nickel, copper, lead, silver, and iron ores¹. There are two known deposits in the world that are valued principally for their cobalt content. One is the nearly exhausted deposit in the Bou-Azzer region of Morocco and the other is the recently discovered deposit in the West Panter Creek area of Idaho in the United States.

a. Major Producers

Zaire has traditionally been the biggest producer of cobalt. In 1979 Zaire contributed 56 % of total metal production². One company, the government owned General des Carrieres et des Mines, mines most of copper and cobalt in Zaire³. It also maintains a technical cooperation agreement with a Belgian Company, Société Général des Minerais (SGM).

¹ Metal Statistics (1981), P. 49.

² Sibley, (1979), P. 2.

³ Ibid.

Société Zairoise de Commercialisation (SOZACOM) is the official marketing agency for Zairian cobalt, but the exclusive rights for the sale of the Zairian and Belgian cobalt in the US is held by an American firm, African Metal Corp. It is anticipated that SOZACOM is intending to take over more of the marketing functions now handled by SGM¹. Almost half of the refined cobalt exported by Zaire is processed in Belgium and then exported to the United States.

The second largest producer of cobalt among the non-communist nations is Zambia. Cobalt in Zambia is produced as a by-product of copper mines which are owned by the two state-owned companies: Nchanga Consolidated Copper Mines, Ltd. (NCCM), and Roan Consolidated Mines, Ltd. (RCM)². Zambia currently accounts for about 12 percent of the Western World's output of cobalt.

Cobalt is also produced in Morocco and is sent to France for refining³. Morocco's share has fallen from about 10 % in the 1960's to about 4 % at the present time. Cobalt is also produced in Canada as a by-product of nickel and copper concentrates by the International Nickel Company of Canada, Falconbridge Mines Ltd. and Sherritt Gordon Mines Ltd. Canada's share is about 6 % of the world output. Recent price increases have encouraged the expansion of the production capacities in Canada.

Australia, Finland and Philippines are among other major cobalt producing nations in the world, each one accounting for 6 - 7 percent of the Western World's output of cobalt.

Among the centrally-planned economies, Cuba and the Soviet Union are the major producers of cobalt. Their combined production of cobalt is estimated to be around 8 million pounds per year, each one producing almost half of that amount.

¹ Sibley, (1979), P. 2

² Ibid. P. 3.

³ Ibid.

b. Secondary Sources

The latest data, which are available only for the United States, indicate that the purchased scrap accounts for 6 percent of US demand for cobalt¹. Most cobalt scraps originate from super-alloys but a small quantity of scrap metal is also generated in the production of magnets². Dissipation in the diverse end-uses for cobalt prevents significant recycling. Interests in recovering cobalt from scraps have increased in the past few years in the light of the high cobalt prices. A significant new source of secondary material is spent petroleum catalysts which have been used in desulfurization of crude oil³.

c. Identified Resources

Most of the world's identified resources of cobalt are found in the form of the lateritic nickel ores in tropical regions, such as the Philippines, Indonesia, and New Caledonia. Production from laterites in Australia is also becoming a significant source. The largest identified resource of cobalt is in Cuba, which amounts to about 25 percent of the world's land-based resources of cobalt (see Table (1)). Other major deposits are located in Zaire, which accounts for more than 15 percent of the world's identified resources, in the United States, with a 17 percent share, and in Zambia which accounts for 7 percent of the world's land-based resources of cobalt.

In terms of estimated reserves, Zaire ranks first, followed by New Caledonia, Zambia, the USSR, Cuba and the Philippines. At the current rate of consumption the estimated world reserves of cobalt could last about 60 years.

¹ Sibley (1979), P. 10.

² Hilmy (1975), P. 3.

³ Sibley (1979), P. 11.

The recovery of cobalt from manganese nodules which lie on the ocean floor adds a huge amount of cobalt to the world's resources. The mineral content of these nodules (dry weight) are estimated to be 18 - 24 percent manganese, .75 - 1.25 percent nickel, .5 - 1.1 percent copper and .25 - .35 percent cobalt¹. Further details on the identified reserves and resources of cobalt are given in Table (1).

d. Production Prospects

Future production of cobalt depends on future prices of cobalt and production of nickel and copper ores from which cobalt is produced as a by-product. Cobalt prices went up sharply in 1978 and 1979, giving big incentives to the major producers of cobalt to consider an expansion of the production capacities. In Canada, the International Nickel Company (INCO) announced its plan to double its cobalt output over that of 1977 and Noranda Mines Ltd. started an extensive exploration for cobalt near North Bay, Ontario². Plans were also made to produce 2200 thousand pounds of cobalt in Northern New Caledonia in the early 1980's. In Zaire an expansion plan is underway which is expected to add another 13 million pounds capacity to the present 35 million pounds capacity of Zaire³. Production and capacity expansions were also reported in South Africa and Uganda in 1979. Plans were also being made in the US for the reopening of the Blackbird district cobalt mines in Idaho, with the shipment of ores initially going to an overseas processor⁴. Therefore, the overall supply picture was one of increasing production in the future. However, most of these plans were made in the light of the price of cobalt being at an unusually high level of 25 dollars per pound in 1979. Since then excess supply has

¹ The Future of Nickel (1980), P. 17

² Sibley (1979), PP. 6 - 7.

³ Ibid, P. 8.

⁴ Sibley (1979), P. 8.

Table (1) - Identified World Cobalt Resources in 1979
(Million Pounds)

	Estimated Reserve Base	Other Identified Resources	Total Identified Resources
North America:			
United States	0	1 700	1 700
Canada	66	480	550
Cuba	<u>240</u>	<u>2 100</u>	<u>2 300</u>
Total	300	4 300	4 600
Europe:			
Finland	40	10	50
USSR	<u>460</u>	<u>40</u>	<u>500</u>
Total	500	50	550
Africa:			
Botswana	58	12	70
Morocco	28	2	30
Zaire	1 000	500	1 500
Zambia	<u>250</u>	<u>520</u>	<u>770</u>
Total	1 300	1 000	2 400
Oceania:			
Australia	110	540	650
New Caledonia	600	250	850
Philippines	<u>420</u>	<u>30</u>	<u>450</u>
Total	1 100	820	2 000
World, Land-Based	3 200	6 200	9 600
World, Seabed Nodules	0	500 000	500 000

Source: Sibley (1979), P. 8

appeared in the world cobalt market and in early 1982 prices of cobalt are about 11 - 12 dollars per pound and may go down even further. Current world recession with no hope for a rapid recovery is not helping this situation either. More talks are now being heard about the postponement of the planned capacity expansions. The only positive sign is that the US government is starting to stockpile cobalt again. About 5.2 million pounds of cobalt are scheduled to be bought during 1981 and 1982. The French and the German governments are also planning to build a stockpile of strategic metals, including cobalt¹.

Production of cobalt in countries which produce cobalt as a by-product of other metals is also expected to decline in the short-run. Current world recession is also reducing the demand for nickel and copper. The prices and productions of these metals are falling and they are not expected to recover before 1984. Therefore, it is almost certain that production of cobalt will be falling in the early 1980's.

In the long-run, on the other hand, the recovery of cobalt from seabed nodules is expected to increase the world supply of cobalt. There is no consensus on how much nodules should be extracted each year, but we may assert that the amounts of cobalt recovered are likely to be between 30 to 50 million pounds by the end of the 1980's or by the early 1990's. This amounts to about 50 percent of the world demand for cobalt estimated for the end of the 1980's. Given the inelasticity of the world demand for cobalt, cobalt prices are expected to fall drastically³. Therefore, production of cobalt from current land-based sources is also expected to fall. Even in those countries where cobalt is recovered from nickel and copper ores the

¹ Sibley (1979), P. 7

² The actual production quota is expected to be determined largely by the future growth in the world consumption of nickel. For details on the arguments surrounding the production quotas see Sanders (1980).

³ World demand for cobalt is generally said to have a long-run price elasticity of -.5. For example see Burrows (1971) and Charles River Associates (1976).

output of cobalt is not expected to rise in the long-run because nickel and copper are also recovered from seabed nodules. This means that nickel prices will also have to fall in the future and hence less nickel will be produced from the current land-based sources of nickel¹. Copper prices, on the other hand, are not expected to change significantly since the increase in supply of copper from seabed nodules is very small compared with the estimated future consumption of copper². Therefore, long-run production of cobalt from the land-based sources is likely to fall and could be replaced by the seabed output of cobalt. In the medium-run, given the deteriorating market position of the current land-based producers of cobalt, expansions of land-based cobalt projects are not expected.

2. Historical Consumption and Future Prospects

Except for the United States, no data exist for the consumption of cobalt in the major consuming nations, neither by end-uses nor even as an aggregate. Since only minor amounts of cobalt are traded between the non-communist nations and the centrally-planned economies we may assert that, ignoring changes in stocks, consumption of cobalt in other non-communist nations is roughly equal to the Western World production of cobalt plus the release from the US stock-pile minus US consumption of cobalt. Consumption of cobalt in the communist countries, on the other hand, can be argued to be equal to their production.

¹ See M. R. Rafati (1982) for forecasts of future prices and production of nickel from land-based sources in the event of seabed mining.

² See Sanders (1980), P. 9.

a. Major Consuming Countries

The United States have traditionally been the biggest consumer of cobalt. The share of the US in the Western World consumption of cobalt has declined from more than 66 percent in 1948 to about 30 percent in the late 1970's. This was mainly due to consumption of cobalt in the US expanding less rapidly than in the rest of the Western Nations, especially during the 1950's and 1960's. During prosperous years of the 1950's and 1960's consumption of cobalt in the United States increased by about 4.7 percent and 5 percent, respectively. Consumption of cobalt in the 1970's grew at an annual rate of 1.3 percent. Recessions in the early 1970's and in 1974, and high cobalt prices in the late 1970's are the main causes of decline in the rate of growth in consumption of cobalt in the US.

Consumption of cobalt in the other Western Nations grew at an annual rate of 30 percent from the late 1940's to the late 1950's and at 10 percent from the late 1950's to the late 1960's. During the 1970's consumption of cobalt in these countries also expanded but at a much slower rate, only 1.5 percent. From the estimates of the consumption of cobalt in these countries we can assert that Japan is the biggest consumer among this group. Other major consumers are the Federal Republic of Germany, the United Kingdom, France, Sweden, and Italy. These countries account for about 70 percent of the consumption of cobalt in the non-communist nations¹. The accelerating expansion of the sophisticated Japanese industries and of the European aircraft and electrical industries are the main reasons for the consumption of cobalt in these countries to increase more rapidly than in the United States.

¹ All the figures are calculated from estimates of 1976 consumption data reported in Investigations into Supply and Demand of Mineral Raw Materials (1976).

Among the centrally-planned economies the Soviet Union is estimated to consume about 65 percent of the total production of cobalt in those countries. The next major consumer is the People's Republic of China, which is estimated to consume about 14 percent of the total consumption of cobalt in the communist countries¹. The average rate of growth of consumption of cobalt in the centrally-planned countries is about 6 percent. For comparison of historical growth rates for different end-uses and regions see Table (2).

b. Major End-Uses

The main uses of cobalt are in the production of superalloys, magnetic alloys, cutting and wear resistant materials, welding materials, and salt and driers. Unfortunately, data for consumption of cobalt by end-use categories are only available for the United States.

(i) Consumption of Cobalt in Superalloys

Superalloys, also called high-temperature alloys, have been the most important end-use of cobalt in the postwar period, accounting for about 30 percent of total consumption of cobalt². Superalloys are alloys of nickel and cobalt with high strength and corrosion resistance at high temperatures³. Superalloys are mainly used in gas turbines which are largely needed for the production of aircraft engines. Cobalt based superalloys were not widely used until World War II, when a number of new alloys were developed⁴.

¹ Investigations into Supply and Demand of Mineral Raw Materials (1976).

² Burrows (1971), P. 53.

³ Charles River Associates (1976), P. 11.

⁴ Burrows (1971), P. 53.

Table (2) - Comparative Growth Rates of the Consumption of Cobalt

	1948 to 1958	1959 to 1969	1970 to 1980
	Annual Average Rate of Growth		
United States:	4.7 %	5 %	1.3 %
Superalloys	11 %	4.6 %	15 %
Magnetic Alloys	7 %	-1 %	-.4 %
Cutting and Wear Resistant	-3 %	20 %	-3 %
Hardfacing and Rods	20 %	-2 %	22 %
Salts and Driers	2 %	11 %	-4 %
Other Uses	1 %	9 %	-1 %
Other Western Nations	30 %	10 %	1.5 %
Centrally Planned Economies	-	-	6 % ⁺

Source: US growth rates were calculated from Bureau of Mines figures. Data for other Western Nations were taken from Charles River Associates (1976). The average growth rate of the consumption of cobalt in the centrally planned economies were computed from Investigations into Supply and Demand of Mineral Raw Materials (1976).

+ The average growth rate is based on 1966 to 1976 data.

Other uses of turbines are for generating electricity, pumping natural gas, and propelling marine craft. The use of gas turbines in generating electric power has grown rapidly since the technology was introduced in 1965¹.

There are four types of superalloys which are currently in use: iron-base alloys with chromium and nickel, complex chromium-nickel-cobalt-iron alloys, nickel-base alloys, and cobalt-base alloys. The composition of individual alloys within each category varies considerably. The nickel-base superalloys contain from 45 to 72 percent nickel, while the cobalt content varies from 0 to 22 percent². The cobalt-base alloys contain from 1 to 20 percent nickel, up to 6 percent molybdenum, and from 0 to 4 percent columbium³. Nickel might be used to some extent as a substitute for cobalt in these alloys.

There is no apparent trend in consumption of cobalt in superalloys. Consumption has generally been high during the Korean War and the Vietnam War mainly due to the increase in the production of aircrafts. Consumption of cobalt in superalloys, for instance, was higher in 1952 than in all other years from 1950 to 1980. Future consumption of cobalt in this category is expected to increase, as aging commercial airline fleets are replaced and new military aircrafts are built. Fuel economy and the anti-noise regulations, which must be met by 1985, have provided incentives to build new aircrafts and engines⁴. At the same time demand for turbines for power plants and natural gas pipelines are expected to be strong in the 1980's.

¹ Charles River Associates (1976), P. 13.

² Burrows (1971), P. 54.

³ Ibid.

⁴ Sibley (1979), P. 3.

(ii) Consumption of Cobalt in Magnetic Alloys

About 20 percent of the consumption of cobalt in the US is in production of permanent magnets. These magnets are mostly used in loudspeakers. Other uses of magnetic alloys include radar systems, separator magnets, motors and generators, and precision instruments for measurement¹. The principal consumption of cobalt in magnets is in the production of Alnico (aluminium-nickel-cobalt) magnets. Ceramic magnets, made from barium or strontium ferrite, were introduced in 1957 and compete strongly with Alnico magnets².

An approximate breakdown in the use of cobalt magnets is 25 percent in loudspeakers, 25 percent in rotating electric machines, 25 percent in measuring instruments, 20 percent in telecommunications, and 5 percent in all other uses³. As a result of the drive toward lighter vehicles, the auto industry is considering the replacement of ferrite magnets by the more powerful, but more expensive, cobalt rare earth magnets⁴.

(iii) Consumption of Cobalt in Cutting Tool Steels and Wear Resistant Materials

About 14 percent of the US consumption of cobalt in 1979 was in production of cutting tool steels and wear resistant materials. Tool steels and cemented or sintered carbides are the major components of this end-use⁵. The cobalt content of the cemented carbides varies from 3 to 25 percent, with the cobalt content determining the principal properties⁶. As the cobalt content increases, hardness, compressive strength, thermal conductivity, and corrosion resistance decrease and transverse rupture, impact strength, and endurance limit increase⁷.

¹ Charles River Associates (1976), P. 13.

² Ibid.

³ Sibley (1979), P. 6.

⁴ Sibley (1979), P. 14.

⁵ Charles River Associates (1976), P. 13.

⁶ Burrows, P. 87.

⁷ Ibid.

Cemented carbides are used in mining and drilling operations. Alloys containing 35.3 percent cobalt have found limited use for parts such as logging tools and valve systems. Tool steels are used in dies and punches because of their high resistance to wear and abrasion. Consumption of cobalt in this end-use, like other end-uses, is not price elastic mainly for two reasons. First, there are no close substitutes for cobalt, and second because cobalt represents a small percentage of the value of the final product.

(iv) Consumption of Cobalt in Hardfacing and Welding Materials

A large number of wear resistant alloys are suitable for hardfacing. Among these the cobalt-base alloys lie somewhere in the middle of the toughness-hardness range covered by the current types of the wear resistant materials¹. Cobalt-base alloys contain about 60 percent cobalt, with 26 to 30 percent chromium, 3 percent iron, 3 percent nickel, 3 to 14 percent tungsten, and small amounts of carbon and manganese and silicon². These alloys are the most effective hardfacing alloys at temperatures above 1200° F. They are commonly used to hardface such parts as valves and valve seats, bearings, brushings, and sleeves for shafting. They have also found applications in nonelectrical machinery and in welding jet engine components made of cobalt-base alloys³. Recent metallurgical progress has allowed substitution of less expensive metals for cobalt in welding rods, beginning around 1968⁴.

¹ For a list of these alloys see Burrows, P. 89.

² Ibid.

³ Charles River Associates, P. 14.

⁴ Ibid.

(v) Consumption of Cobalt in Salts and Driers

In 1978 about 25 percent of the US consumption of cobalt was in manufacturing cobalt salts and driers. No disaggregated data are available on consumption of cobalt in salt and driers but it is known that the most important end-uses are in drying of paints and varnishes, and desulfurization of petroleum fractions¹.

Cobalt is the most powerful drier known and acts much faster than lead and manganese, its principal substitutes in this use. Consumption of cobalt in paints might have been adversely affected by the use of the synthetic latex-base paints for houses in the 1950's. This was perhaps offset by the development of a new cobalt-manganese-lead drier which was developed in 1960. Government regulation of the lead content of paint seems to have increased cobalt consumption in this end-use². Consumption of cobalt in this category is expected to have a low price elasticity because cobalt represents a very small percentage of the total cost of the product. For example, a number of cobalt compounds used as driers of paints, varnishes, printing inks and other materials contain about .05 percent cobalt³.

(vi) Consumption of Cobalt in all Other Uses

About 15 percent of the consumption of cobalt is in this category which includes cobalt consumption in catalysts, ceramics, pigments, stainless steels, nonferrous alloys, other alloys, glass decorizer, ground coat frit and other nonmetallic uses. Other nonmetallic uses of cobalt include applications in pharmacology and as a supplement to the diet

¹ Burrows, P. 92.

² Charles River Associates, P. 14.

³ Burrows, P. 92.

of animals. Since a certain amount of cobalt is absolutely necessary in the diet of animals, the demand for cobalt in other nonmetallic uses can be completely inelastic¹. Catalysts and pigments are the major components of this end-use category. Cobalt is also used in corrosion-resistant prosthetic devices such as hip and arm joints, and in alloys used in the dental field².

c. Consumption Prospects

The average rate of growth in consumption of cobalt in the 1980's is likely to be between 2 to 3 percent, with most of the increase in demand for cobalt appearing in the second half of the 1980's. This is mainly because of two reasons. First, the 1978 - 1980 prices of cobalt were too high and the consumers of cobalt are beginning to respond to those high prices now. Second, and more importantly, the average rate of growth in the industrial production of the major consuming nations of cobalt in the 1980's is expected to be well below those of the 1950's and 1960's. Demand for cobalt and other metals in general should therefore increase less rapidly than in the past few decades.

Among the end-uses of cobalt superalloys seem to have a good chance to grow faster than other end-use categories. This is mainly due to an increase in demand for new aircrafts with less noise and higher fuel efficiency. Production of military aircrafts is also expected to be higher in the 1980's. The markets for power plant turbines and natural gas pipelines are also expected to be strong in the 1980's.

¹ Burrows, P. 95.

² Sibley (1979), P. 7

The use of gas turbines in cars and trucks is also being investigated at the present time. The main deficiency of gas turbines is their high fuel consumption. Therefore, gas turbines are not expected to be widely used at the present rate of fuel consumption. But even if 20 percent of the new autos use gas turbines the impact will be to increase the US consumption of cobalt by about 15 to 20 percent¹.

Consumption of cobalt in magnetic alloys and catalysts is also expected to grow at modest rates. The rare earth magnets, containing about 65 percent cobalt, are beginning to penetrate the market. These magnets are competitive with Alnico magnets but have up to four times the strength². However, due to the substantial efforts needed in employing rare earth magnets as a substitute for the ones currently used, they have not penetrated the loudspeaker market. Other uses for the new strong magnets will be in rapid transit propulsion systems, which are expected to cause a big increase in demand for cobalt. Consumption of cobalt in catalysts is also expected to increase. Current efforts in the US to become self sufficient in energy via coal liquefaction and gasification are increasing the demand for cobalt which is needed to purge coal of sulfur impurities³.

3. Complements and Substitutes

Nickel and cobalt can substitute each other. For example, in 1969, during the nickel mining strike in Canada, cobalt was used in electroplating. Although nickel has traditionally been cheaper than cobalt it has not been generally used as a substitute for cobalt because such a substitution would result in

¹ Charles River Associates, P. 15

² Ibid, P. 16.

³ Ibid, P. 17.

a sacrifice of important properties possessed by the end product made with cobalt. Nickel and cobalt are complements in superalloys, although some substitution is technically possible. The current trend is toward greater use of alloys with less cobalt content, especially in superalloys and hardfacing and wear resistant materials. For example, nickel-based Inconel 718 is replacing the L 605 cobalt-based alloy in the rocket propulsion system application¹.

Substitution for cobalt as a catalyst or as a drier in paints is usually not effective. In drier applications manganese and lead each can act as a complement or as a substitute². In catalytic applications, molybdenum and aluminum are complements, and nickel and tungsten together are substitutes for cobalt³.

Any substitution for cobalt in magnetic alloys results in a loss of weight advantage or other physical properties. Nevertheless, ceramic magnets, which are made of barium and strontium ferrite, are potentially strong competitors⁴. No satisfactory substitutes have been developed for use of cobalt as a binder for carbides. But, molybdenum-based tool steels, which can contain up to 12 percent cobalt, may achieve the performance characteristics of cemented carbides⁵.

The major problems in substituting other metals for cobalt are that this either results in a sacrifice of the main characteristics of the end product, or cobalt is replaced by other metals which are likely to become equally or more scarce and expensive. Replacement of the cobalt-base alloys with alloys relatively high in columbium and tantalum is a good example of the latter case⁶.

¹ Sibley (1979), P. 14.

² Ibid.

³ Ibid.

⁴ Ibid.

⁵ Ibid.

⁶ Ibid.

4. Trade and Trade Barriers

Transportation costs do not seem to be of any significance in the cobalt market. There are no specific data for transport costs of cobalt, but the transport costs for a comparable metal carried over similar distances were about 1.4 to 3 percent of the value of the metal in question¹. The above-mentioned study was carried out in the late 1960's. Since then, with the rapidly rising costs of energy the magnitude of the transportation costs must have gone up by a few hundred percent. Given that the price of cobalt has also increased by about 400 percent. It is not unrealistic to assume that transportation costs are still small compared with the market value of cobalt².

With the exception of war years, tariffs and other government regulations have not been an important factor in the cobalt market. Most countries do not impose any tariffs or other restraints on imports or exports of cobalt ore and metal³. Other more processed forms of cobalt, such as cobalt alloys and chemical compounds, are often subject to tariffs. In the US these tariffs vary from the high rate of 9 percent for the imports of alloys to 20 cents per pound for the imports of cobalt oxides⁴. But the categories which are subject to tariffs account for less than 5 percent of the US imports of cobalt and hence the impact of these tariffs is negligible. Besides, lower tariffs are used when the imports originate from a "favoured nation"⁵. An export-reporting system, effective January 1979, requires that exporters send to the Department of Commerce a

¹ Burrows, P. 5.

² In 1975 when Zaire's main trade route was closed, due to the closure of Benguela railway to Lobito, there were some airborne shipments of cobalt.

³ Burrows, P. 5.

⁴ Sibley (1979), P. 6.

⁵ Ibid, P. 6.

copy of the export declaration covering a list of specified materials containing 10 percent or more cobalt¹. The purpose of the system is to determine whether exports of cobalt bearing materials are having an adverse effect on supplies or prices of cobalt in the United States. But this measure was taken during the temporary shortage of cobalt in the late 1970's, given the present excess supply situation no further action is expected to restrict cobalt exports.

5. Historical Price Changes

The dominant position of Zaire in the cobalt market has enabled it to act as a price setter, though the hypothesis that Zaire, or its marketing agency, cooperates with other producers has also been put forward². In any case, world demand for cobalt, US government purchases (sales), supply of other producers, and the costs of production in Zaire have been the main factors in determining cobalt prices.

From the late 1940's to mid 1950's cobalt prices increased steadily in response to the increase in the consumption of cobalt in the US during the Korean War and the large stockpile purchases by the US government. Then they began to decline from 1955 to 1965 as the US consumption of cobalt and stockpile purchases started to decline. From 1965 till the end of the 1970's cobalt prices rose exponentially in the face of the increase in the world demand for cobalt. In addition to this, political events in Zaire and the fear of future supply disruptions were responsible for the extremely high cobalt prices of 1978 - 1980. Nevertheless, cobalt prices have traditionally been stable. Price adjustments have often been infrequent, changed once a year, except during the exceptional periods of the late 1970's.

¹ Sibley (1979), p. 12.

² See Burrows (1971) and Gupta (1981).

In the short-run cobalt prices are expected to be lower than the early 1982 price of 12.5 dollars per pound. This is mainly due to the current world recession and the huge stocks of cobalt. In the medium-run the cobalt price should rise as the world economy begins to recover and because of the rising costs of production in Zaire¹. Much also depends on whether the US-government purchases of 1981 and early 1982 will continue or not.

By the late 1980's the recovery of cobalt from seabed nodules is expected to reduce cobalt prices drastically. The extent of which, of course, depends on the amounts of cobalt which will be extracted. It is quite possible that with unrestricted entry cobalt prices may approach the price of nickel. Forecasts of the future prices of cobalt under alternative scenarios are given in section IV.

6. Producer and Consumer Stocks

Like other metals, a certain percentage of consumption and production of cobalt are normally held by consumers and producers of cobalt for smooth operation. With the exception of the United States no data could be found for the magnitudes of cobalt stocks held by individual countries. In the US, on average, 20 percent of the annual consumption of cobalt has been held in consumers' stocks. The industry stocks of cobalt are about 40 percent of the annual consumption of cobalt in the US².

Like consumption of cobalt, the stocks of cobalt held by consumers and producers of cobalt have been generally increasing. Sharp increases in industry stocks are usually observed during recessions, when the industrial activity starts to decline. The industry stocks in the United States doubled from 4534 thousand pounds at the end of 1973 to 9184 thousand pounds at the end of 1974³. Expectations about the future price of cobalt, and/or the

¹ The rates of inflation in Zaire in the past 6 years have been above 50 percent.

² Sibley (1979), p. 13.

³ Ibid.

possibility of supply disruptions also encourage stockpiling of cobalt. Such expectations concerning future prices are often self fulfilling. If everyone tries to build a big stockpile of cobalt, this is bound to increase the demand for cobalt and result in higher prices. A good example of such a situation is the cobalt market in 1978 - 1979. The guerrilla attacks on the cobalt mines in Zaire caused a brief disruption of the supply of cobalt. This caused a wave of precautionary buying in the cobalt market which was also reinforced by expectations of the future higher prices of cobalt¹. The producer price of cobalt surged from 5.59 dollars per pound in 1977 to 25 dollars per pound in 1979. The dealer price of cobalt passed the 55 dollars per pound mark.

Consumption of cobalt in the United States in 1978 was about 20 percent higher than the 1977 figure. But even if we assume that such an increase in consumption of cobalt was widespread, there is still very little reason for the price of cobalt to increase by about 400 percent. World production of cobalt increased by 20 percent during the same period. Even in Zaire production of cobalt in 1978 was about 30 percent above its 1977 level. The precautionary and speculative purchases of cobalt created a shortage which should not have been there, at least not to such extents. Major producers and marketing agencies of cobalt started to accept metal orders on an allocation basis in 1978. The allocation, which lasted through 1979, was based on the average purchase during the calendar year 1977.

It seems that both the rationing and the rise in the price of cobalt went on too long and too far. Had it not been for the speculative and precautionary purchases of cobalt, the market would have been able to accomodate the increase in consumption

¹ Even the Soviet Union was reported to be making big purchases. See The Economist, (November 11, 1978).

of cobalt in 1978. The consumers' and dealers' stocks of cobalt, reported to be around 17 million pounds in 1977, should have been able to absorb the increase in demand¹. By mid-1979 this became obvious. The dealer price reportedly fell below the producer price². By 1980 the stocks of cobalt were increasing, the rationing scheme was felt to be unnecessary and removed. High cobalt prices coupled with the 1980 - 1981 recession made the situation even worse. By December 1981 the cobalt prices were 30 percent below the 1980 level of 25 dollars per pound. Yet, the stocks were increasing. Zaire's stocks of cobalt were reported to be around 14 thousand tons³. Such huge stocks of cobalt are bound to depress the cobalt prices even further because by now everyone has noticed the state of the market. Expectations of lower prices in the near future will encourage a reduction in stocks and delays in purchases for current consumption, especially when high interest rates make the opportunity costs of holding stocks so high.

7. Government Stocks

Cobalt is considered to be a strategic and critical material because it is a vital component of jet engines and of armor-piercing shells. The problem facing the United States and some other Western countries is their excessive dependence on foreign sources of supply⁴. The worries of these governments are compounded by the fact that most of the high grade deposits are concentrated in a few areas which are not known for their political stability. Therefore, the risks of the disruption of supplies are always present. This has led some of these nations into stockpiling of cobalt as a safeguard against temporary supply disruptions.

¹ See The Financial Times (May 13, 1977).

² See The South African Financial Mail (26 October, 1979).

³ See The Economist (15 April, 1981).

⁴ The Soviet Union is much more secure because its production coupled with that of Cuba seems to have been enough to cover their needs.

Except for the United States, no data could be found for the amounts of cobalt held by these governments. The inspection of the US stockpile data reveals two important points. First, cobalt has been stockpiled during the periods of major wars and international tensions. During the 1950's and the early 1960's the United States bought about 85 million pounds of cobalt for stockpile purposes, about 65 million pounds of which were disposed of during the late 1960's and 1970's. Second, these stockpile changes which, due to their magnitudes, have played an important role in affecting supply and demand for cobalt, have been carried out in such a manner as to stabilize the market. For example, no purchases were made during the 1978 - 1979 period, when excess demand for cobalt was present, but the purchase started in 1981 when the commercial stocks were at a record level. This policy tends to reduce wide fluctuations in cobalt prices and hence helps to avoid drastic changes in production¹.

The US administration was aware that the 1981 price of cobalt was too high; to keep the production running and avert production cut-backs, as well as for security reasons, it is starting to approach the 85.4 million pounds target for the national stockpile of cobalt. The start of seabed mining is expected to reduce the dependency of the US on foreign sources of cobalt drastically, if not totally, rendering it unnecessary to hold such big stocks. Nevertheless, security reasons are the overriding factor at the present time and cobalt purchases are expected to continue in the near future², considering that the beginning of seabed mining on a commercial scale is highly uncertain as long as the property rights issue remains unsettled.

¹ For more details of the costs and benefits of price stabilization in the raw material markets see Miskel (1979), pp.189-207.

² More than 39 million pounds of cobalt are still needed to reach the stockpile objective from the current level of 46 million pounds.

III. An Econometric Model of the World Cobalt Industry

1. Price Setting by Zaire

It is assumed that Zaire sets the price to maximize its own profit given the world demand for cobalt, the supply of the other small producers of cobalt, and the stockpile changes by the US government. World demand for cobalt was postulated to be of the form¹

$$D = a_0 + a_1 \cdot Y_{t-1} - a_2 \cdot \frac{P}{P_M} \quad (1)$$

where Y is the OECD index of industrial production, P is the producer price of cobalt in US-dollars and P_M is the US producer price index for metals and metal products.

The net demand for Zaire is obtained by subtracting the supply of cobalt from non-Zairean sources from the world demand for cobalt. That is

$$ED = a_0 + a_1 \cdot Y_{t-1} - a_2 \cdot \frac{P}{P_M} - Z - QRW \quad (2)$$

where Z is the US government release of cobalt from its strategic stockpile and QRW is the production of cobalt from other sources².

Therefore, Zaire's profit in domestic currency units can be written as

$$\pi = e \cdot P \cdot ED - AC \cdot ED \quad (3)$$

¹ Since there are no data for the change in the world stocks of cobalt we can not make a distinction between consumption and demand for cobalt.

² For both consumption and production of cobalt we are only considering non-communist countries. Production and consumption of cobalt in the centrally-planned economies are assumed to be equal.

where e is Zaire's exchange rate against the US dollar and AC is the average cost of production in Zaire. Since average cost data are not available it is assumed that the average cost of producing cobalt in Zaire is a linear function of Zaire's consumer price index, ZCP , i. e.

$$\pi = e \cdot P \cdot ED - (-b_0 + b_1 \cdot ZCP) \cdot ED \quad (4)$$

Maximizing equation (4) with respect to P and subject to equation (2) yields

$$\begin{aligned} P = & \beta_0 + \beta_1 (Y_{t-1} \cdot P_M) - \beta_2 ((Z + QRW) \cdot P_M) \\ & - \beta_3 \cdot \left(\frac{1}{e}\right) + \beta_4 \cdot \left(\frac{ZCP}{e}\right) \end{aligned} \quad (5)$$

and

$$\begin{aligned} ED = & \alpha_0 + \alpha_1 \cdot (Y_{t-1}) - \alpha_2 \cdot (Z + QRW) + \alpha_3 \\ & \cdot \left(\frac{1}{e \cdot P_M}\right) - \alpha_4 \cdot \left(\frac{ZCP}{e \cdot P_M}\right). \end{aligned} \quad (6)$$

Equations (5) and (6) determine the price and the production of cobalt as set by Zaire.

Equation (5) was estimated with the following modifications: First the supply of cobalt for sources other than Zaire was replaced by a three-year weighted average of that variable. This allows for the fact that since cobalt is produced as a by-product of other metals Zaire cannot be sure whether the change in production of cobalt from other sources is permanent or transitory. Second, during the 1978 - 1980 period there appeared to be a lot of speculative and precautionary buyings in the cobalt market. These extraordinary purchases of cobalt were mainly in response to the expectations of shortages and higher prices of cobalt in the future, which were caused by a brief disruption of production in Zaire.

Therefore, two dummy variables, D78 and D90, were introduced in the price equation. Equation (A1) was estimated with two-stage least squares. The performance of the model is very good. Virtually all variations in the price of cobalt experienced in the sample period are explained by our regression. All the variables have the correct signs and are significant. Our price equation indicates the extent to which cobalt prices went up in response to the special events in 1978 and in 1979-80. Clearly, once the situation gets back to normal cobalt prices are expected to fall drastically.

Equation (A1): Producer Price of Cobalt

$$P = 247.41 + .0278 (Y_{t-1} \cdot P_M) - .00006598 (WRWZ \cdot P_M) \\ (4.58) \quad (5.08) \quad (-3.60) \\ + .3297 \left(\frac{ZCP}{e}\right) - 90.71 \left(\frac{1}{e}\right) + 418.6 (D78) + 1566.1 (D90) \\ (2.14) \quad (-3.49) \quad (9.13) \quad (32.8)$$

$$\bar{R}^2 = .999 \quad D. W. = 1.51 \quad S. E. R. = 17.2$$

SAMPLE: 1958 - 1980

where:

- P - Producer Price of Cobalt; US cents per pound.
 Y_{t-1} - OECD Industrial Production Index; 1975 = 100.
 P_M - US Producer Price Index for Metals and Metal Products; 1967 = 100.
WRWZ - Weighted Average of the Supply of Cobalt from other Sources;

$$WRWZ = \left(\frac{QRW + Z}{6}\right) + \left(\frac{QRW(-1) + Z(-1)}{3}\right) + \left(\frac{QRW(-2) + Z(-2)}{2}\right)$$
Thousand Pounds.
ZCP - Zaire's Consumer Price Index; 1975 = 100.
e - Zaire's Exchange Rate with the US Dollar.
D78 - Dummy Variable for 1978.
D90 - Dummy Variable for 1979-1980.
Instruments: $(P_M \cdot WRWZ)(-1)$;

The elasticity of the producer price of cobalt with respect to $(Y_{t-1} \cdot P_M)$ is .75, while the elasticities with respect to $(WRWZ \cdot P_M)$ and $(\frac{ZCP}{e})$ are -.35 and .1, respectively.

2. Production Equations

Production of cobalt in all other countries, except Zambia and Australia, were found to be insensitive to changes in the price of cobalt. This is not surprising since cobalt is often produced as a by-product of other metals in those countries.

a. Production in Zaire

Zaire's production of cobalt was demonstrated to be influenced by the OECD industrial production, production of cobalt from other sources, and the cost of producing cobalt in Zaire. In equation (A2) production of cobalt in Zaire has an elasticity of 2.2 with respect to the OECD industrial production index. Elasticities with respect to the production of cobalt from other sources and the cost of producing cobalt are -.3 and -.62, respectively. Two dummy variables, D78 and D79, were also included to capture the impact of the sudden increases in demand which were caused by the speculative and precautionary demand for cobalt after the guerilla attack on the cobalt mines in Zaire in 1978 and in 1979.

b. Production in Zambia

Production of cobalt in Zambia was estimated using the deflated price of cobalt and the lagged dependent variable. Since the presence of a lagged dependent variable makes the Durbin-Watson statistic unreliable, this equation was estimated using two-stage least squares adjusted for first order serial correlation.

In equation (A3) production of cobalt in Zambia has a price elasticity of .21 in the short-run and a price elasticity of .35 in the long-run.

c. Production in Australia

Once again, the deflated price of cobalt and the lagged dependent variable were used as explanatory variables. Production of nickel in Australia was also included as an explanatory variable to allow for the fact that cobalt is also produced as a by-product of nickel in Australia.

Production of cobalt in Australia, equation (A4), has a short-run price elasticity of .25 and a long-run price elasticity of .44. According to our estimate about 12 thousand pounds of cobalt are recovered from every thousand metric tons of nickel produced in Australia.

d. Production in the Soviet Union and Cuba

Production of cobalt in the Soviet Union and Cuba did not react to changes in the price of cobalt. Therefore, production of cobalt in these countries (equation (A5)) was estimated using lagged production as the explanatory variable; the fit of this equation is very good.

Equation (A2): Zaire's Production of Cobalt

$$ED = -18338.3 + 762.91 (Y_{t-1}) - .4523 (WRWZ) - 19585.6 \\ (-2.13) \quad (7.03) \quad (-1.92) \quad (-4.3) \\ \left(\frac{ZCP}{e \cdot P_M} \right) + 132158 \left(\frac{1}{e \cdot P_M} \right) + 19887.5 (D78) + 8518.48 (D79) \\ (.47) \quad (3.47) \quad (2.41)$$

$$\bar{R}^2 = .89 \quad D. W. = 2.24 \quad S. E. R. = 2277$$

SAMPLE: 1958 - 1980

$$(OAUIS \quad) + 12 \ 35 \ (AUIS)$$

$\rho = .28$

Australia; thousand pounds.

t; US cents per pound.

r Metals and Metal Products;

Australia; thousand metric tons

Health in the Soviet Union and China

$$= 1.69 \quad S.E.B. = 196$$

the Soviet Union and Cuba;

Equation (A6): World Production of Cobalt

$$QW = ED + QZAM + QAUS + QOT + QEB$$

where:

- ED - Production of Cobalt in Zaire; thousand pounds.
- QZAM - Production of Cobalt in Zambia; thousand pounds.
- QAUS - Production of Cobalt in Australia; thousand pounds.
- QOT - Production of Cobalt in other Non-Communist Countries; thousand pounds.
- QEB - Production of Cobalt in Centrally Planned Economies; thousand pounds.
- QW - World Production of Cobalt; thousand pounds.

3. Consumption Equations

Except for the United States, data for the consumption of cobalt in individual countries are not available. Therefore, this part of the model was estimated with the following assumptions:

- (a) The communist countries' production and consumption of cobalt are of equal magnitude¹
and
- (b) consumption of cobalt in non-communist nations, excluding the United States, is equal to the world production of cobalt minus consumption of cobalt in the communist countries minus the consumption of cobalt in the United States plus the release of cobalt from the US stockpile.

¹"There is little trade between Communist block and the rest of the world". See Burrows (1971), P. 5. This probably continued to be the case also through the 1970's, though with some exceptions like in 1978.

Clearly, this is not the real consumption figure because it includes changes in the producer's and consumer's stocks of cobalt, for which no data could be found. Therefore, we refer to this item as the apparent consumption of cobalt in other non-communist countries¹.

a. Consumption of Cobalt in the United States

Detailed data for consumption of cobalt in different end-use categories are available. Unfortunately data for some end-uses were not constantly reported, so that only six end-use categories could be considered for estimation. These are consumption of cobalt in superalloys, magnetic alloys, cutting tools, wear resistant materials, welding and hardfacing rods and materials, salts and driers, and all other uses.

(i) Consumption of Cobalt in Superalloys

Most of the cobalt used in this category is for jet engine parts, industrial turbine engines, natural gas transmission pipelines, and marine equipments. Therefore, two activity variables were used for consumption of cobalt in this category. The first one is the number of jet engines produced and the second one, a dummy variable, is a proxy for the number of gas turbines which have been increasingly used for power generation in the 1970's. This dummy variable has a value of one from 1953 to 1971, and from then on increases by one unit each year. A four-period weighted average of the deflated price of cobalt and two more dummies were also used. D57 was introduced to capture the increase in the production of civilian jets, which began

¹ Some adjustments were made for the 1974, 1975 and 1976 figures to allow for the increase in stocks during the 1974-75 recession and the decrease in stocks in 1976.

on a large scale in 1958. The other dummy, D54S, measures the replenishment of war depleted stocks of material. The results are reported in equation (A7). The short-run price elasticity of consumption of cobalt in superalloys is $-.1$ and the long-run price elasticity of consumption of cobalt in this category is $-.6$. The coefficient of YJET indicates that about 188 pounds of cobalt are used in the production of a single jet engine, which seems quite reasonable¹. The elasticities with respect to production of jet engines and gas turbines are $.5$ and $.25$, respectively.

(ii) Consumption of Cobalt in Magnetic Alloys

The closest activity variable which corresponds with the demand for Alnico magnets is the US production of appliances and television, YTV. A dummy variable, DMA2, was also introduced to reflect the gradual substitution of ceramic magnets for Alnico magnets in loudspeakers. This dummy variable has a value of one from 1953 to 1958, when ceramic magnets were first introduced, it then increases linearly until 1964 and remains constant thereafter. A four-period weighted average of the deflated price of cobalt is also used.

All the coefficients have the right signs and are significantly different from zero. The short-run price elasticity of consumption of cobalt in magnetic alloys is $-.033$ while the long-run price elasticity is $-.2$. The elasticity of consumption of cobalt with respect to production of home appliances and television is 1.16 , which is not significantly different from one. The results are presented in equation (A8).

¹ A finished General Electric J79 engine, a medium-large engine used in the Lockheed F 104, contains about 97 pounds of cobalt; about twice that amount is needed originally, and the remainder is machined away. See Charles River Associates (1976).

(iii) Consumption of Cobalt in Cutting Tool Steels and Wear Resistant Alloys

The appropriate activity variable for demand for cobalt in the cutting tools application seems to be the production of non-electrical machinery. A four-period weighted average of the real price of cobalt was also used to allow for the fact that it will take some time before substitutions for cobalt in this category can be fully implemented. The price elasticities of consumption of cobalt in this category are about $-.1$ in the short-run and $-.6$ in the long-run. The elasticity of consumption of cobalt in cutting tools and wear resistant alloys with respect to production of nonelectrical machinery is 1, which is quite plausible.

(iv) Consumption of Cobalt in Welding and Hardfacing Rods

In this case two activity variables seemed necessary. One is the current production of welding electrodes, YWELD, and the other is the production of jet engines led one year, YJET (+1). A dummy variable, D10, was also included to account for the reduction in the use of cobalt in welding rods. This dummy variable has a zero value from 1953 to 1967 and a unit value from then on. A weighted average of the deflated price of cobalt is also present. All the variables have the correct signs and are significantly different from zero. The price elasticities of consumption of cobalt in this category are $-.06$ in the short-run and $-.36$ in the long-run. The elasticities with respect to the production of jet engines and welding electrodes are 1.2 and .23, respectively.

(v) Consumption of Cobalt in Salts, Driers, Paints and Other Chemical Uses

The activity variable for consumption of cobalt in this category is the Federal Reserve production index of chemicals and allied products. The deflated price of lead, an important ingredient in the production of paints, and a dummy variable, DLD, reflecting the change in regulations concerning the lead content of paints are also included. The elasticities with respect to the index of chemicals and products and the price of lead are about .95 and 1.15, respectively. The own price elasticity is -.55.

(vi) Consumption of Cobalt in All Other Uses

In this equation the Federal Reserve index of industrial production in the United States was used as the activity variable in addition to the deflated price of cobalt. All the variables performed well and the estimated coefficients are both significant. The short-run price elasticity of consumption of cobalt in this category is -.2. The elasticity of consumption of cobalt with respect to the US index of industrial production is about .85.

b. The Apparent Consumption of Cobalt in Other Non-Communist Countries

In addition to a weighted average of the price of cobalt, the OECD index of industrial production and a dummy variable, D56, appear in this equation. The dummy variable was used to account for the change in demand for cobalt used in magnetic alloys. The price elasticities of consumption of cobalt in other non-communist nations are -.096 in the short-run and -.54 in the long-run. The elasticity with respect to the activity variable is 1.08, which is not significantly different from one. All variables performed well, the results are represented in equation (A14).

Equation (A7): US Consumption of Cobalt in Superalloys

$$\begin{aligned} \text{CSA} = & 2306.96 - 829.34 (\text{PCORW}) + .188 (\text{YJET}) + 696.27 (\text{DTURB}) \\ & (3.43) \quad (-2.47) \quad (8.09) \quad (7.55) \\ & - 1214.94 (\text{D54S}) + .941.9 (\text{D57}) \\ & (-5.04) \quad (1.93) \end{aligned}$$

$$\text{D. W.} = 2.40 \quad \text{S. E. R.} = 293.98$$

SAMPLE: 1953 - 1974

where:

$$\text{PCORW} - \left(\frac{\text{PCOR}}{6} + \frac{\text{PCOR} (-1)}{3} + \frac{\text{PCOR} (-2)}{3} + \frac{\text{PCOR} (-3)}{6} \right)$$

PCOR - P/P_M ; Producer Price of Cobalt, Deflated.

YJET - Production of the Jet Engines, Number of Engines.

DTURB - Turbine Demand Dummy.

D54S - War Jet Dummy; 1954, 1968 = 1.

D57 - Civil Jet Dummy; 1953 - 1957 = 1.

Instruments: Y_{t-1}

Z

$$\frac{ZCP}{e \cdot P_M}$$

Equation (A8): US Consumption of Cobalt in Magnetic Alloys

$$\text{CMA} = 1776.92 - 205.439 (\text{PCORW}) - 321.806 (\text{DMA2}) + 34.2048 (\text{YTV})$$

$$(7.63) \quad (-2.89) \quad (-5.42) \quad (7.08)$$

$$\text{D. W.} = 1.71 \quad \text{S. E. R.} = 313.8$$

SAMPLE: 1953 - 1980

where:

PCORW - Weighted Average of the Deflated Producer Price of Cobalt.

DMA2 - Dummy for Magnet Demand Shift.

YTV - US Index of Production of Radio and Television; 1967 = 100.

Instruments: Z (-1)

GS (-1)

D78

WRWZ (-1)

Equation (A9): Consumption of Cobalt in Cutting Tool and Wear Resistant Alloys in the US

$$\text{CCW} = 833.611 - 379.91 (\text{PCORW}) + 16.01 (\text{YNELM})$$

$$(1.52) \quad (-2.02) \quad (6.04)$$

$$\text{D. W.} = 1.29 \quad \text{S. E. R.} = 415$$

SAMPLE: 1953 - 1978

where:

PCORW - Weighted Average of the Producer Price of Cobalt, deflated.

YNELM - US Index of Production of Nonelectrical Machinery; 1967=100.

Instruments: Z

$\frac{\text{ZCP}}{e \cdot P_M}$

WRWZ (-1)

Equation (A10): Consumption of Cobalt in Welding, Hardfacing
Rods and Materials

$$\text{CHR} = 45.22 - 87.78 (\text{PCORW}) + .28353 (\text{YJET } (+1)) + .89876 (\text{YWELD})$$

(.27) (-2.08) (4.28) (5.55)

$$- 541.79 (\text{D10})$$

(-8.89)

D. W. = 2.03 S. E. R. = 71.6

SAMPLE: 1953 - 1974

where:

PCORW - Weighted Average of the Producer Price of Cobalt, de-
flated.

YJET - Production of Jet Engines; number of engines.

YWELD - Production of Welding Electrodes in US; million pounds.

D10 - Hardfacing Structure Change, 1953 - 1967 = 0.

Instruments: WRWZ (-1)

$$\frac{\text{ZCP}}{\text{P}_M \cdot e}$$

Equation (A11): Consumption of Cobalt in Salts, Driers, Paints
and Chemicals

$$\text{CSD} = 252.106 - 399.599 (\text{PCOR}) + 17.386 (\text{YCH}) - 791.17 (\text{DLD})$$

(.21) (-3.87) (3.43) (-1.63)

$$+ 10347 \frac{(\text{PLD})}{\text{P}_M}$$

(1.53)

D. W. = 2.07 S. E. R. = 584.2

SAMPLE: 1953 - 1980

where:

YCH - Production of Chemicals and Products in US; 1967 = 100.

DLD - Dummy Variable for the Change in Regulations Affecting
the Lead Content in Paints.

PLD - Price of Lead; US cents per pound.

P_M - US Producer Price Index for Metals and Metal Products.

PCOR - Producer Price of Cobalt, deflated.

Instruments: Z (-1)

GS (-1)

D78

D90

WRWZ (-1)

Equation (A12): Consumption of Cobalt in the US in All Other
Uses

$$\text{COT} = -55.91 - 236.53 (\text{PCOR}) + 38.426 (\text{YUS})$$

(-.099) (-2.52) (5.81)

$$\text{D. W.} = 1.96 \quad \text{S. E. R.} = 463 \quad \rho = .45$$

(2.67)

SAMPLE: 1953 - 1980

where:

PCOR - Producer Price of Cobalt, deflated.

YUS - US Index of Industrial Production; 1967 = 100.

Instruments: Z (-1)

D78

GS (-1)

WRWZ (-1)

Equation (A13): Total Consumption of Cobalt in the US

$$CUST = CSA + CMA + CCW + CHR + CSD + COT$$

Equation (A14): Apparent Consumption of Cobalt in Other Non-Communist Nations

$$COW = 10551.6 - 6175.15 (PCORW) + 378.15 (Y (-1)) + 4372.5 (D56) \\ (1.88) \quad (-2.589) \quad (12.106) \quad (1.28)$$

$$D. W. = 1.50 \quad S. E. R. = 3173.1$$

SAMPLE: 1953 - 1977

where:

PCORW - Weighted Average of the Producer Price of Cobalt, deflated.

D56 - Dummy for the Change in Demand for the Cobalt Used in Magnets.

Y - OECD Industrial Production; 1975 = 100.

Instruments: $\frac{ZCP}{e \cdot P_M}$
GS (-1)

Equation (A15): World Consumption of Cobalt

$$CW = COW + QEB + CUST$$

Table (3) - Non-Communist Nations' Elasticities of Demand
for Cobalt

	Short-run	Long-run	Weights*
1. United States			
a. Superalloys	-.1	-.6	21.5
b. Magnetic alloys	-.033	-.2	18.9
c. Cutting and wear resistant alloys	-.1	-.6	11.1
d. Hardfacing rods and welding	-.06	-.36	3.6
e. Salts and driers	-.55	-.55	27
f. Others	-.2	-.2	17.9
Total United States	-.24	-.43	40
2. Other Non-communist Nations	-.09	-.54	60
3. All Non-communist Nations	-.15	-.50	100

* All weights based on 1978 consumption figures.

IV. Model Simulation

The present model can be used in a number of ways to study the impact of future exogenous changes in the cobalt market. For example, one can study the effect of the imposition of a high tariff by the US government, or, alternatively, the impact of disposing or stockpiling of cobalt by the US government. Other exogenous shocks to the supply side of the model, such as the start of seabed mining or a major strike at one of the major producers of cobalt can also be investigated. Finally, it might be of some interest to investigate what will happen if the structure of the model is altered, e. g. if the cobalt market becomes more competitive.

But before the results of our ex ante simulation are presented, it is useful to look at the historical simulation of the model in order to assess the ability of the model in forecasting the sample period.

1. Dynamic Historical Simulation of the Model

A dynamic simulation¹ was performed from 1965 to 1980. The performance of the model is very good. The simulated values of the key variables in the model, e. g. the producers price of cobalt and production of Zaire are very close to their actual values and most of the turning points are reproduced by the simulated values.

The actual and simulated values of the price of cobalt and production of cobalt in Zaire are presented in Table (4). The accuracy of the model in producing the values of the key endogenous variables

¹ Dynamic simulation uses previously solved values of the lagged endogenous variables whereas static simulation uses the actual values. In the former case, the initial values of the endogenous variables must, of course, be given.

over the 1965 - 1980 period is evident from the calculated root-mean-square percent errors¹.

2. Ex Ante Simulations

Now that the model was demonstrated to show a satisfactory performance in the sample period it can readily be employed for ex ante simulations².

First, the model was simulated from 1981 to 1990 without any exogenous shock to the system (base case). Then, two hypothetical scenarios were simulated:

- stockpiling of cobalt by the US government from 1985 to 1988 and
- the start of seabed mining in 1988.

The values of the exogenous variables appear in Appendix III. In general, the most recent information and historical growth rates were combined to obtain the forecast values of the activity and price variables.

a. Forecast of the Cobalt Market for 1981 - 1990

The most noticeable change is in the price of cobalt. From the high price of 25 dollars per pound in 1980, the price falls sharply to about 9.5 dollars per pound in 1982. From then on the price of cobalt will increase up to the end of the simulation period, where it reaches to about 19 dollars. Most of the increase is due to inflation. The deflated price of cobalt, PCOR, increases by 25 percent during the same period.

¹ The root-mean-square percent error is defined as

$$\text{rms percent error} = \sqrt{\frac{1}{T} \sum_{t=1}^T \left(\frac{Y_t^s - Y_t^a}{Y_t^a} \right)^2}$$

where T is the number of simulation periods, Y_t^s is the simulated value of variable Y in period t and Y_t^a is the actual value of variable Y in period t.

² The only adjustment made was to reduce the production of cobalt in Zaire by about 8500 thousand pounds in 1981 and 1982 and by 4200 thousand pounds from 1983 to 1984. These adjustments are necessary if we are to take into account the huge stocks of cobalt held by Zaire in 1980.

Table (4) - Actual vs. Simulated Values of the Key Endogenous Variables, 1965 - 1980

	Producer Price of Cobalt, ¢/lb		Production of Cobalt in Zaire, 1000 pounds	
	Actual	Simulated	Actual	Simulated
1965	162	164.59	18492	21760
66	165	168.93	24906	24657
67	185	175.41	21424	24523
68	185	181.34	23256	21166
69	189	184.72	23360	23689
1970	220	217.14	29464	28820
71	220	230.33	32006	29898
72	245	267.46	28754	30160
73	300	291.99	33184	32508
74	346	351.86	38680	37358
1975	398	357.79	31000	32838
76	444	418.90	23560	24338
77	558.8	560.15	22520	21709
78	1153	1128.5	28930	28771
79	2458	2416.81	31090	30861
1980	2500	2479.39	31960	33034
Root-Mean-Square Percent Error	.0437		.0686	

Production of cobalt in Zaire, Zambia and Australia are expected to fall in the early 1980's and start their recovery around 1985. By 1990 Zaire is likely to account for about 65 percent of the world output of cobalt.

Consumption of cobalt in the early 1980's will be well below its 1978 level. This was to be expected because of the current world recession and the high cobalt prices of the late 1970's which are now showing their full impacts on the quantities of cobalt demanded. But with the world economy recovering in the mid-1980's and the recent lower prices of cobalt showing their impacts, world consumption of cobalt is expected to reach its 1978 level by 1984 and then increases to about 82 million pounds in 1990.

Among the end-uses of cobalt super-alloys show the highest rate of growth, while consumption of cobalt in magnetic alloys and salts and driers shows little increase over the 1978 level. The cobalt market is expected to be oversupplied in the early 1980's. But from 1983 to 1987 world consumption will exceed production, thus allowing the early excess supplies to be depleted. For a complete list of the simulated values see Table (5).

b. The Impact of Stockpiling by the US Government

The US government's stockpile objective for cobalt is 85.4 million pounds, and the inventory in storage was 40.8 at the end of 1979¹. The United States started the stockpiling program in 1981 with a planned purchase of 5.2 million pounds which is expected to be spread over 1981 and 1982. In this section the model was simulated assuming that 5 million pounds of cobalt will be bought annually from 1985 to 1988.

¹ Sibley (1979), P. 1.

Table (5) - Forecasts of the Future Price, Consumption and Output of Cobalt from the Land-Based Sources Without any Exogenous Change⁺

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
P	1698.5	957.5	1004	1082	1166	1279	1394	1529	1677	1863
PCOR	5.63	3.08	3.13	3.23	3.27	3.38	3.48	3.55	3.64	3.72
QW	60390	56964	56796	57999	64960	68009	70474	74135	77128	81347
ED	28903	29893	28485	30130	37453	40295	42539	45995	48778	52884
QZAM	6451	5196	4751	4619	4586	4613	4660	4704	4752	4799
QAUS	2851	2116	2238	2371	2492	2628	2763	2890	3022	3262
QOT	14000	13500	13000	12500	12000	12000	12000	12000	12000	12000
QEB	8184	8257	8321	8378	8428	8472	8510	8545	8574	8601
CW	29958	38940	54441	66772	72073	73945	75804	77771	79742	82015
COW	8907	14781	25045	34362	38153	39220	40220	41370	42513	43886
CEB	8184	8257	8321	8378	8428	8472	8510	8545	8574	8601
CUST	12886	15901	21074	24031	25491	26251	27073	27855	28653	29528
CSA	4281	5323	7210	8695	9386	9693	10010	10303	10595	10893
CMA	2026	2222	2797	3240	3453	3541	3626	3711	3795	3914
CCW	480	841	1645	2205	2409	2446	2478	2524	2570	2634
CHR	188	266	481	648	728	772	866	915	973	1021
CSD	1475	2653	3974	4144	4273	4429	4591	4727	4874	5008
COT	4413	4593	4965	5097	5240	5368	5498	5673	5844	6055

+ A list of the variables used in this and subsequent tables is provided in the Appendix.

As expected, US government purchases result in higher prices, higher production and lower consumption of cobalt. The producer price of cobalt in 1988 will be about 146 cents higher than without the stockpiling program. World production of cobalt in 1988 increases by about 2400 thousand pounds while world consumption of cobalt falls by 2060 thousand pounds.

About 80 percent of the increase in the world output of cobalt comes from the increased output of Zaire. Due to the inelasticity of world demand for cobalt, the reductions in the US and other Western nations consumption of cobalt is small. The US consumption of cobalt falls by 600 thousand pounds while the consumption of cobalt in other non-communist nations is reduced by 1400 thousand pounds. For a complete list of the forecasts see Table (6).

c. The Impact of Seabed Mining

The purpose of this section is to investigate the potential impact of the start of seabed mining on the future price of cobalt and production of cobalt from land-based sources. To do this we must supply the simulation program with the amounts of cobalt which will be recovered from the seabed nodules.

However, it is very difficult to be exact about the magnitude of the recovery of cobalt from the seabed nodules at the present time. For more than a decade the United Nations Conferences on the Law of the Sea have been unable to come up with a treaty which is acceptable to all parties involved in the negotiations. One of the major issues blocking the ratification of the Law of the Sea is the nature of the regime to govern deep-sea mining and its power to control production.

Table (6) - Forecasts of the Future Price, Consumption and Output of Cobalt
from Land-Based Sources with the Start of the US Stockpiling in 1985 *

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
P	1698	957	1004	1082	1187	1344	1531	1675	1803	1943
PCOR	5.63	3.08	3.13	3.23	3.33	3.55	3.82	3.89	3.92	3.88
QW	60390	58964	56796	57999	65370	69239	72928	76577	79135	82529
ED	28903	29893	28485	30130	37827	41412	44758	48175	50552	53708
QZAM	6451	5196	4751	4619	4607	4684	4811	4882	4917	4918
QAUS	2851	2116	2238	2371	2506	2670	2847	2973	3089	3301
QOT	14000	13500	13000	12500	12000	12000	12000	12000	12000	12000
QEB	8184	8257	8321	8378	8428	8472	8510	8545	8574	8601
CW	29958	38940	54441	66772	71985	73511	74623	75727	77228	79659
COW	8907	14781	25045	34362	38093	38923	39391	39901	40652	42109
CEB	8184	8257	8321	8378	8428	8472	8510	8545	8574	8601
CUST	12866	15901	21074	24031	25463	26115	26721	27281	28001	28948
CSA	4281	5323	7210	8695	9378	9654	9899	10106	10345	10654
CMA	2026	2222	2797	3240	3451	3531	3599	3662	3733	3855
CCW	480	841	1645	2205	2405	2427	2427	2434	2455	2525
CHR	188	266	481	648	727	768	855	895	947	996
CSD	1475	2653	3974	4144	4273	4406	4522	4589	4739	4898
COT	4413	4593	4965	5097	5226	5327	5417	5593	5779	6018

* See Table (5).

The conflict over the nature of production controls involves both consuming countries who wish to ensure the availability of the minerals in question¹, and producing nations who wish to ensure that exploitation does not disrupt the markets of these metals and if it does some kind of compensation will be available².

The present model was simulated assuming that, on an annual basis

- (1) 50 million pounds of cobalt will be recovered under free access to seabed mining,
and, alternatively,
- (2) 30 million pounds of cobalt will be recovered if the access to seabed mining is restricted by a quota system.

The first case allows each of the five big consortia currently involved in ocean mining developments to operate one mining unit with the capacity to recover 3 million tons of nodules. It is estimated that each mining unit will produce about 35 000 tons of nickel, 30 000 tons of copper, 5 000 tons of cobalt and 630 000 tons of manganese³.

The forecasts of the endogenous variables under each of the above-mentioned production quotas are presented in Table (7). The start of seabed mining is assumed to be 1988⁴. The forecasts of the endogenous variables from 1981 to 1987 are the same as the ones in Table (5), because seabed mining is not assumed for those years.

¹ Cobalt is one of the four metals which will be recovered from the seabed nodules. The other metals are nickel, copper and manganese.

² See Art. 150 (g), Draft Convention on the Law of the Sea, UN DOC/Revision 2, A/CON. 62/L. 78, (28 August 1981).

³ United Nations, Economic and Social Council (1979).

⁴ This date is purely fictitious and has been chosen for convenience. Seabed mining, although likely to be technically feasible by 1988, is actually expected to begin in the 1990's or even later, probably not until the property rights issue has been settled. Since forecasts for the exogenous variables reaching well into the 1990's seemed unreliable, it was preferred to restrict the simulation analysis to the 1980's. None the less, our results carry over at least qualitatively to a later period.

Table (7) - Forecasts of the Future Price, Consumption and Output of Cobalt from Land-Based Sources with the Start of Seabed Mining in 1988 *

	With 50 Million Pounds of Cobalt Recovered			With 30 Million Pounds of Cobalt Recovered		
	1988	1989	1990	1988	1989	1990
P	212	289	392	633	732	863
PCOR	.49	.63	.78	1.47	1.59	1.72
QW	46509	49405	54492	59393	62336	66819
ED	26202	29291	33673	32521	35516	39753
QZAM	3624	3257	3178	3947	3727	3694
QAUS	2138	2281	2539	2378	2518	2770
QOT	6000	6000	6500	12000	12000	12000
QEB	8545	8574	8601	8545	8574	8601
CW	81624	92759	102974	80933	89024	96460
COW	43953	51424	59214	43517	48918	54463
CEB	8545	8574	8601	8545	8574	8601
CUST	29125	32759	35158	28871	31531	33395
CSA	10650	11792	12951	10591	11455	12313
CMA	3796	4091	4424	3782	4008	4266
CCW	2683	3118	3577	2656	2964	3285
CHR	952	1100	1239	946	1064	1172
CSD	4644	6098	6213	4727	5707	5828
COT	6397	6558	6751	6166	6330	6529

* See Table (5).

If 50 million pounds of cobalt are recovered from manganese nodules the impact on the 1988 price of cobalt will be drastic. The price of cobalt falls from 1529 cents per pound, in the case of no seabed mining, to about 212 cents per pound; but from then on increases to 392 cents per pound of cobalt. This is so primarily for two reasons:

- (a) World consumption of cobalt has an elasticity of $-.15$ in the short-run. Hence cobalt prices must fall drastically if the additional supplies are to be sold. However, in the span of a few years world consumption of cobalt reacts fully to the lower prices of 1988 and 1989 and the price of cobalt starts to rise again. Similarly, supplies of cobalt take a few years to respond fully to the market price.
- (b) The costs of producing cobalt will be rising

Therefore, a more meaningful interpretation of the impact of ocean mining can be achieved by comparing the 1990 figures given in the Tables (5) and (7).

With the recovery of 50 million pounds of cobalt from seabed nodules, the price of cobalt in 1990 will be 78 percent lower than in the case without seabed mining. When demand is inelastic and there is a 60 percent increase in supply, such a result is a natural outcome. The cobalt output of the current land-based producers is expected to fall from 81347 thousand pounds, in the case of no seabed mining, to 54490 thousand pounds. Production of cobalt in Zaire, Zambia, Australia, and other non-communist nations fall by about 33 percent¹.

¹ Production and consumption of cobalt in the centrally planned economies are not affected because they were assumed not to respond to price changes.

On the other hand, world consumption of cobalt in 1990, will be about 25 percent higher than in the case without seabed mining. This is the result of lower cobalt prices in the late 1980's. Once again, since world demand for cobalt is inelastic the percentage increase in consumption of cobalt is less than the percentage decrease in cobalt prices. World consumption of cobalt is 102974 thousand pounds in 1990 while the output of the land-based producers of cobalt is only 54490 thousand pounds. The difference, about 48 million pounds, is roughly equal to the output of cobalt from seabed nodules. Therefore no excess supply or demand will be felt¹.

Consumption of cobalt in the US increases by 20 percent, compared to the case with no seabed mining, while consumption of cobalt in other non-communist nations increases by 32 percent. This was also expected since demand for cobalt in the US had a lower price elasticity. Among the consumption of cobalt in different end-uses the categories with higher price elasticities, such as superalloys and cutting and wear resistant alloys, experience increases of about 20 percent. Other end-uses with lower price elasticities, e. g. consumption of cobalt in magnetic alloys and other end-uses, show an increase of about 10 percent.

Similar changes, though smaller in magnitude, will appear if 30 million pounds of cobalt are recovered from deep-sea nodules. The producer price of cobalt in 1990 will be 863 cents per pound, i. e. the price of cobalt falls by about 55 percent, compared with the case of no seabed mining. Production of the current land-based sources of cobalt will be 66819 thousand pounds,

¹ The additional 2 million pounds of cobalt are likely to end up in consumers' and producers' inventories. Such increase in stocks will be desirable for smooth operation due to the increase in consumption and production of cobalt.

while world consumption will be 96460 thousand pounds. The difference, once again, is roughly equal to the output of cobalt from deep-sea mining. Production of cobalt in Zaire, Zambia, and Australia is about 20 percent lower than in the case with no seabed mining.

World consumption of cobalt increases by about 18 percent compared with the case where there was no seabed mining. Consumption of cobalt in the United States increases by 13 percent while consumption of cobalt in other non-communist nations increases by about 23 percent. For a complete list of the endogenous variables' forecasts see Table (7).

3. The Potential Decrease in the Export Earnings of the Current Land-Based Producers

One of the major concerns of some of the delegates to the United Nations Conference on the Law of the Sea has been that the recovery of metals from the seabed nodules is likely to reduce metal prices and the output of the land-based producers. Thus their export earnings are certain to be lower than in the case without seabed mining. Therefore, current producer countries advocate some kind of compensation scheme to reduce the adverse effects of seabed mining on their potential revenues. Such compensations, if approved, are likely to be primarily determined by the magnitude of the expected reductions in the export earnings of the countries in question as a result of seabed mining. The purpose of this section is to calculate the potential reductions in the export earnings of the current land-based producers of cobalt. To do this we must compare cobalt prices and outputs of Table (5) with the respective figures in Table (7).

According to the calculated figures the annual reductions in the export earnings of Zaire will be about 849.7 million dollars and 638.6 million dollars with the recovery of 50 million and 30 million pounds of cobalt, respectively. Consequently, the annual export earnings of Zambia will fall by 77 million dollars and 57.6 million dollars under the free and limited production scenarios, respectively. Australia, on the other hand, will face annual reductions of 50.75 million dollars, if 50 million pounds of cobalt are produced from manganese nodules, and of 36.6 million dollars if 30 million pounds of cobalt are recovered. For a complete list of figures see Table (8).

Table (8) - Potential Decrease in the Export Earnings of the Major Western Land-Based Producers of Cobalt in 1990 as a Consequence of Seabed Mining

	Zaire	Zambia	Australia
1. No Seabed Mining:			
Output (million pounds)	52684	4799	3262
Price (\$/lb)	18.63	18.63	18.63
Revenue (\$ million)	981.6	89.4	60.7
2. 50 Million Pounds of Cobalt Recovered from Seabed Nodules			
Output (million pounds)	33673	3178	2539
Price (\$/lb)	3.92	3.92	3.92
Revenue (\$ million)	131.9	12.4	9.95
Reduction in Revenue (\$ million)	849.7	77	50.75
3. 30 Million Pounds of Cobalt Recovered from Seabed Nodules			
Output (million Pounds)	39753	3694	2770
Price (\$/lb)	8.63	8.63	8.63
Revenue (\$ million)	343	31.8	23.9
Reduction in Revenue (\$ million)	638.6	57.6	36.6

Source: Tables (5) and (7).

V. Summary and Conclusions

Cobalt is an essential element in many alloys and chemical compounds. Its main characteristics, such as heat resistance, high strength, wear resistance, and magnetic qualities, have made cobalt a vital element in aerospace and electronic products industries. Cobalt is usually mined as a by-product of nickel or copper. The largest producer of cobalt is Zaire, accounting for about 60 percent of the non-communist world output. Other major producers of cobalt are Zambia and Australia, accounting for 12 percent and 6 percent of the non-communist world production of cobalt, respectively. Among the socialist countries Cuba and the Soviet Union are the major producers of cobalt, each one producing about 6 percent of the world output.

About 25 percent of the world identified resources of cobalt are located in Cuba. Other major body of resources have been identified in Zaire and the United States, which account for 15 and 17 percent of the total identified resources of cobalt. In terms of reserves, i. e. that part of resources which can be economically exploited, Zaire ranks first, followed by Zambia, the Soviet Union, Cuba, and the Philippines.

On the consumption side, the United States have traditionally been the biggest consumer of cobalt. The share of the US in world consumption of cobalt has declined from about 66 percent in the late 1940's to about 30 percent in the late 1970's. Consumption of cobalt in other non-communist nations, on the other hand, has been increasing at a faster rate than the one in the US. Consequently, their combined share has increased to about 55 percent of the world consumption of cobalt. Among the socialist countries China and the Soviet Union are the major consumers of cobalt.

Almost all production of cobalt in the socialist countries is used internally and there is very little trade with non-communist producers. The major industrialized countries of the West produce little cobalt and have to import most of their consumption requirements. Since the danger of supply disruption is often present, some of these nations, the United States in particular, keep big stockpiles of cobalt. Additions to and sales from these stocks have been one of the factors affecting price and production of cobalt.

World production and consumption of cobalt are both inelastic in the short-run and in the long-run. The inelasticity of production is mainly due to cobalt being produced as a by-product of other metals such as nickel and copper. The inelasticity of world demand for cobalt is due to the lack of close substitutes. Other metals such as nickel and tungsten can substitute cobalt in some of its uses, but such replacements often result in a sacrifice of the main characteristics of the end product. Besides, the value of cobalt is generally very small compared to the value of the final product, giving little incentive for such substitutions.

The producer price of cobalt is set by Zaire, the dominant producer in the cobalt market. Cobalt prices have been increasing from 1965 to 1980 mainly due to the increase in demand and to rising production costs. However, the 1979 - 1980 price jump was brought about by a high speculative and precautionary demand, under the impression of guerilla attacks on the cobalt mines in Zaire. Hence this part of total demand is certain to fall once the fear of shortage disappears.

In order to empirically assess the potential effects of seabed mining on the cobalt market an econometric model of the world cobalt industry was estimated and presented in chapter III. The estimated model was then simulated under different scenarios. First, it was assumed that no seabed mining or stockpiling by the US government will take place

until 1990. The most noticeable forecast was the producer price of cobalt. Cobalt prices fell from 25 dollars per pound in 1980 to about 9.5 dollars in 1982. Future cobalt prices are expected to be rising to about 18.6 dollars per pound in 1990. World production of cobalt is expected to exceed world consumption of cobalt in the early 1980's. By mid 1980's world consumption of cobalt would exceed production, allowing previous inventory build-ups to be depleted. Among the producers of cobalt the biggest increase in output would come from Zaire. By 1990, Zaire is expected to account for about 65 percent of the world output of cobalt. Among the end-uses of cobalt consumption of cobalt in super-alloys, salts and driers and chemical and ceramic uses are expected to have the biggest increase.

In the second simulation exercise the impact of the annual purchase of 5 million pounds of cobalt from 1985 to 1988 was investigated. This stockpiling, as expected, led to higher prices and production of cobalt and to a lower consumption of cobalt. By 1988, the producer price of cobalt is expected to be 148 cents higher than in the previous case. World production of cobalt is expected to show an increase of about 2400 thousand pounds while world consumption of cobalt should decrease by about 2 million pounds, with most of the increase in output originating from Zaire.

Finally, the model was simulated under the assumption that seabed mining starts in 1988. Two scenarios were considered. Under the first one it was assumed that an unrestricted access to seabed mining would yield 50 million pounds of cobalt annually. The second scenario assumed that seabed mining will be restricted so that only 30 million pounds of cobalt will be produced each year. In the first case the producer price of cobalt will be 392 cents per pound in 1990, while under the second scenario the price of cobalt will be 863 cents per pound in 1990. The drastic reductions in the producer price of cobalt were expected because of

the inelasticity of the world consumption and production of cobalt. With the recovery of 50 million pounds of cobalt from seabed nodules production of cobalt from land-based sources falls to 54 million pounds and the world consumption of cobalt rises, to about 103 million pounds. The recovery of 30 million pounds of cobalt, on the other hand, results in 66 million pounds of cobalt produced from land-based sources and in world consumption of cobalt amounting to 96 million pounds. Once again, most of the decrease in the output of the land-based producers of cobalt is accounted for by a reduction in Zaire's production of cobalt.

Moreover, the start of seabed mining results in a significant reduction in the export earnings of the land-based producers of cobalt through the decrease in price and production. With the recovery of 50 million pounds the annual export earnings of Zaire, Zambia and Australia are expected to fall by 849 million dollars, 77 million dollars and 50 million dollars, respectively. The reductions in the annual export earnings of Zaire, Zambia and Australia with the recovery of 30 million pounds of cobalt would amount to 638 million dollars, 57.8 million dollars and 36 million dollars, respectively.

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Appendix I The Complete Model

$$\begin{aligned} P &= 247.41 + .0278 (Y_{t-1} \cdot P_M) - .00006598 \\ &\quad (WRWZ \cdot P_M) + .3297 \left(\frac{ZCP}{e}\right) - 90.71 \left(\frac{1}{e}\right) \\ &\quad + 418.6 (D78) + 1566.1 (D90) \end{aligned} \quad (I.1)$$

$$PCOR = P/P_M \quad (I.2)$$

$$PCORW = \left(\frac{PCOR}{6} + \frac{PCOR(-1)}{3} + \frac{PCOR(-2)}{3} + \frac{PCOR(-3)}{6}\right) \quad (I.3)$$

$$\begin{aligned} ED &= 18338.3 + 762.91 (Y_{t-1}) - .4523 (WRWZ) \\ &\quad - 19585.6 \left(\frac{ZCP}{e \cdot P_M}\right) + 132158 \left(\frac{1}{e \cdot P_M}\right) + 19887.5 \\ &\quad (D78) + 8518.48 (D79) \end{aligned} \quad (I.4)$$

$$QZAM = 1687.36 + 362.84 \left(\frac{P}{P_M}\right) + .37 (QZAM(-1)) \quad (I.5)$$

$$\begin{aligned} QAUS &= -39.6 + 138.1 \left(\frac{P}{P_M}\right) + .43 (QAUS(-1)) \\ &\quad + 12.35 (AUS) \end{aligned} \quad (I.6)$$

$$QEB = 1052 + .88 (QEB(-1)) \quad (I.7)$$

$$QRW = QZAM + QAUS + QOT \quad (I.8)$$

$$QW = ED + QZAM + QAUS + QEB + QOT \quad (I.9)$$

$$WRWZ = \left(\frac{QRW + Z}{6} \right) + \frac{QRW(-1) + Z(-1)}{3} + \left(\frac{QRW(-2) + Z(-2)}{2} \right) \quad (I.10)$$

$$CSA = 2306.96 - 829.34 (PCORW) + .188 (YJET) + 696.27 (DTURB) - 1214.94 (D54S) + 941.9 (D57) \quad (I.11)$$

$$CMA = 1776.92 - 205.439 (PCORW) - 321.806 (DMA2) + 34.2048 (YTV) \quad (I.12)$$

$$CHR = 45.22 - 87.78 (PCORW) + .28353 (YJET(+1)) + .89876 (YWELD) - 541.79 (D10) \quad (I.13)$$

$$CCW = 833.611 - 379.91 (PCORW) + 16.01 (YNELM) \quad (I.14)$$

$$CSD = 252.106 - 399.599 (PCOR) + 17.386 (YCH) - 791.17 (DLD) + 10347 (PLDR) \quad (I.15)$$

$$COT = -55.91 - 236.53 (PCOR) + 38.426 (YUS) \quad (I.16)$$

$$CUST = CSA + CMA + CHR + CCW + CSD + COT \quad (I.17)$$

$$COW = 10551.6 - 6175.15 (PCORW) + 378.15 (Y_{t-1}) + 4372.5 (D56) \quad (I.18)$$

$$CW = CUST + COW + QEB \quad (I.19)$$

Appendix II List of the Variables

<u>Symbol</u>	<u>Units</u>	<u>Title</u>	<u>Source</u>
AUS	1000 Metric Tons	Production of Nickel in Australia	Metal Statistics
CCW	1000 Pounds	Consumption of Cobalt in Cutting Tools and Wear Resistant Materi- als	Bureau of Mines
CHR	" "	Consumption of Cobalt in Hardfacing and Rods	" " "
CMA	" "	Consumption of Cobalt in Magnetic Alloys	" " "
COT	" "	Consumption of Cobalt in Other Uses	" " "
COW	" "	Apparent Consumption of Cobalt in Other Non-communist Nations	Calculated
CSA	" "	Consumption of Cobalt in Superalloys	Bureau of Mines
CSD	" "	Consumption of Cobalt in Salts and Driers	" " "
CUST	" "	Total Consumption of Cobalt in the US	" " "
CW	" "	World Consumption of Cobalt	Calculated

<u>Symbol</u>	<u>Units</u>	<u>Title</u>	<u>Source</u>
D10	1968* to 1980 = 1	Hardfacing structural Change	-
D54S	1954* and 1968 = 1	War Dummy for Jet Engines	-
D56	1953* to 1956 = 1	Dummy for Change in Magnet Demand	-
D57	1954* to 1957 = 1	Dummy for Change in Magnet Demand	-
D78	1978 = 1 *	Dummy Variable for 1978	-
D79	1979 = 1 *	Dummy Variable for 1979	-
D90	1979 - 1980 = 1*	Dummy Variable for 1979 - 1980	-
DLD	1953* to 1968 = 1	Dummy for the Lead Content of Paints	-
DMA2	1953 to 1958 = 1, increases by 1 each year there- after up to 1964	Dummy for Magnet Demand Shift	-
DTURB	1953 to 1971 = 1, increases by 1 each year there- after	Dummy for Turbine Demand	-
e	Zaires per Dollar	Zaire's Exchange Rate with US \$	International Financial Statistics

* Other years equal to zero.

<u>Symbol</u>	<u>Units</u>	<u>Title</u>	<u>Source</u>
GS	1000 Pounds	US Government Stocks of Cobalt	Bureau of Mines
P	US Cents per Pound	Producer Price of Cobalt	" " "
PCOR	1967 Dollar per Pound	Producer Price of Cobalt, Deflated	-
PCORW	-	Weighted Average of the Producer Price of Cobalt	-
PL	US Cents per Pound	Price of Lead	Metal Statistics
P _M	1967 = 100	US Producer Price Index for Metals and Metal Products	Survey of Current Business
QAUS	1000 Pounds	Production of Cobalt in Australia	Bureau of Mines
QEB	" "	Production of Cobalt in Cuba and USSR	" " "
QOT	" "	Production of Cobalt in the Rest of the World	" " "
QW	" "	World Production of Cobalt	" " "
QZAM	" "	Production of Cobalt in Zambia	" " "

<u>Symbol</u>	<u>Units</u>	<u>Title</u>	<u>Source</u>
WRWZ	1000 Pounds	Weighted Average of the Supply of Cobalt from Non-communist Nations excluding Zaire	-
Y	1975 = 100	OECD Industrial Pro- duction Index	OECD Financial Statistics
YCH	1967 = 100	Index of Chemical Products	Survey of Current Business
YJET	Number of Engines	Production of Jet Engines	Charles River Associates
YNELM	1967 = 100	Production of Non- electrical Machinery	Survey of Current Business
YTV	1967 = 100	Production of TV and Appliances	" " " "
YUS	1967 = 100	US Industrial Produc- tion Index	" " " "
YWELD	Million Pounds	Production of Welding Electrodes	Welding Engineer
Z	1000 Pounds	Sales of Cobalt from the US Stockpile	Bureau of Mines
ZCP	1975 = 100	Zaire's Consumer Price Index	International Financial Statistics

Appendix III Forecasts of the Exogenous Variables

	<u>D10</u>	<u>D54S</u>	<u>D56</u>	<u>D57</u>	<u>D78</u>
1981	1	0	0	0	0
82	1	0	0	0	0
83	1	0	0	0	0
84	1	0	0	0	0
85	1	0	0	0	0
1986	1	0	0	0	0
87	1	0	0	0	0
88	1	0	0	0	0
89	1	0	0	0	0
90	1	0	0	0	0

	<u>D79</u>	<u>D90</u>	<u>DLD</u>	<u>DMA2</u>	<u>DTURB</u>
1981	-1	.5	0	7	10.5
82	-1	0	0	7	11
83	- .5	0	0	7	11.5
84	- .5	0	0	7	12
85	0	0	0	7	12.5
1986	0	0	0	7	13
87	0	0	0	7	13.5
88	0	0	0	7	14
89	0	0	0	7	14.5
90	0	0	0	7	15

	<u>z⁺</u>	<u>e</u>	<u>PLD</u>	<u>P_M</u>
1981	-3200	4.2	36.5	301.5
82	-2000	5.8	30	310
83	0	6.3	35	320
84	0	7	40	335
85	0	7.7	44	356
1986	0	8.5	48	378
87	0	9.35	52	400
88	0	10.3	56	430
89	0	11.3	60	460
90	0	12.4	66	500

	<u>QOT⁺</u>	<u>YCH</u>	<u>YJET</u>	<u>YNELM</u>	<u>YUS</u>
1981	14000	198	6000	163	151
82	13500	210	5500	163	140
83	13000	220	5000	166.5	150
84	12500	225	5200	170	154
85	12000	232	5400	174	158
1986	12000	240	5500	178	162
87	12000	250	5700	182	166
88	12000	260	5800	187	171
89	12000	270	5900	192	176
90	12000	280	6000	198	182

	<u>YTV</u>	<u>Y</u>	<u>YWELD</u>	<u>ZCP</u>	<u>AUS</u>
1981	120	123	1350	1800	70
82	120	118	1360	2500	65
83	125	121	1400	3100	70
84	130	125	1450	3700	75
85	134	129	1500	4300	80
1986	137	133	1550	5100	85
87	140	137.5	1660	6100	90
88	143	142	1720	7200	95
89	146	147	1790	8500	100
90	150	152	1850	10200	110

⁺ The forecast values of Zaire changed in the case of stockpiling to -5000 from 1985 to 1988. Forecasts of QOT were reduced to 5000 in the case when 50 million pounds of cobalt are recovered from seabed nodules.