IMPACT OF RECENT COBALT SUPPLY SITUATION ON MAGNETIC MATERIALS AND APPLICATIONS

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ABSTRACT

This paper summarizes the principal viewpoints expressed by members of an invited panel with the above-named title. Five major topics are discussed:
(1) Trends in Cobalt Supply and Demand - Sibley
(2) A Supplier's Viewpoint - Betts
(3) A User's Viewpoint--Telecommunications - Schlabach
(4) A User's Viewpoint--Electrical Equipment - Werner
(5) Possible Substitutes - Martin
The panel was chaired by Chin, who provided the summary. The major sections were authored by the panelists.

SUMMARY

After decades of relative stability, the price of cobalt has jumped nearly four-fold since mid-78, from \$6.85 per pound to \$25.00 in five stepped increases. Moreover, this producers' price is currently some \$15 or so below the so-called free market price. The major reasons for the recent price instability are attributed to the temporary sudden disruption in supply due to the political upheaval in May, 1978, in Zaire (which supplies the bulk of the free world's cobalt). This disruption widened the demand-supply gap which already existed at the time of the Zaire upheaval.

Although proven world deposits of cobalt are considered adequate in the long run, the price of cobalt due to a continuing tight supply-demand situation is not expected to be eased unless production is increased. This is particularly true for production outside Zaire and Zambia in order to avoid cartel control. For the short term, the solution appears to lie in lessened demand for cobalt.

Magnetic materials rank with superalloys at the top of the list of cobalt usage, at more than 20 percent each. Most of the magnetic use of cobalt is in Alnico 5, the most widely used permanent magnet alloy today. Therefore the major solution to the cobalt usage problem in magnetic materials lies in substitutes for Alnico 5.

Alnico 5 contains 24% cobalt. The salient magnetic properties are: B_r = 12500G, H_c = 640 Oe, $(BH)_{max}$ = 5.5 MGOe and a low reversible temperature coefficient of remanence of -0.02 percent per °C. For much of the loudspeaker and magneto applications, redesign with cobalt-free hard ferrites appears the most promising and is already occurring. The ferrites have lower B_r (∿3800 G), higher H_c (∿2800 Oe), lower $(BH)_{max}$ (∿3.5 MGOe), and a higher temperature coefficient. The combination of lower B_r and higher H_c requires operation at a lower load line as compared with Alnico 5, and the lower energy product means bulkier volume. Ferrite parts could be lighter, however, due to decreased density. The higher temperature coefficient is a disadvantage.

A second alternative is to use cobalt rare-earth magnets. At 63% Co, Co_5Sm magnets contain two and a half times the cobalt of Alnico 5 but four times the maximum energy product. Therefore overall decrease of cobalt might be achieved with optimum design using the rare-earth magnets. These magnets, however, are relatively new to the market, and it will take time for designers to evaluate new options.

Two alloys even newer than the rare-earth magnets have shown promise. One is cobalt-free Mn-Al-C. These magnets have energy products equivalent to Alnico 5, but a lower B_r (5600 G) and a higher H_c (2200 Oe). Therefore the magnetic characteristics are more like those of the hard ferrites, except much better. The Mn-Al-C magnets are machinable, and have temperature coefficients between those of Alnico and ferrite. The optimum magnetic properties, however, are presently obtained by warm extrusion. Therefore there is a size and shape limitation along with a relatively costly production technique.

A rather promising family of permanent magnet alloys, but also relatively new, is the Cr-Co-Fe family. These alloys behave metallurgically like the Alnicos. Their magnetic properties in terms of B_r, H_c, $(BH)_{max}$ and temperature coefficient can be made remarkably similar to the Alnicos as well. Recent developments indicate that properties equivalent to Alnico 5 can be obtained in Cr-Co-Fe alloys containing about 12%Co, one-half that of Alnico 5. In addition, the Cr-Co-Fe alloys are ductile and hence could be shaped by conventional plastic forming operations. The optimum magnetic properties can be obtained by either magnetic field treatment as used in Alnico production, or by a suitable deformation-aging sequence without the use of a magnetic field. The substitution of a 10.5% Co Cr-Co-Fe alloy for Remalloy (12%Co) in one type of telephone receiver has promised a savings of 10,000 kg of Co for this item alone.

TRENDS IN COBALT SUPPLY AND DEMAND

In 1978, the cobalt market was thrown into a state of great uncertainty, with soaring prices, limited supply, and accelerating demand. A critical shortage threatened to develop but never really materialized. In order to correctly understand and analyze both the situation as it developed and ensuing events, a review of the industry structure and applications of cobalt is in order.

INDUSTRY STRUCTURE

Production

Because recovery rates vary considerably in different countries, it is best to look at refined metal production in comparing different countries' output. The most important sources of refined metal production are, in order, Zaire, the U.S.S.R., Zambia, Japan (Australian and Philippine origin), Finland, France (Moroccan origin), the United Kingdom (Canadian origin), Norway (Canadian origin), and Canada (mainly Australian origin). Not included is Belgium, but most cobalt processed in Belgium (to powders and compounds) has already been converted or refined in Zaire to metallic form. The network of refining is evidently complex, but it is clear that Zaire, Zambia, Canada, Finland, Australia, and Morocco, in that order, are the most important originating sources of cobalt for the western world. (See Table 1.)

Table 1
Principal world production of refined cobalt metal in 1978 (Estimated)

Rank	Country	Origin	Percent of total	Cumulative
(1)	Zaire	Domestic	55	55
(2)	U.S.S.R.	Domestic	10	65
(3)	Zambia	Domestic	8	73
(4)	Japan	Australia, Philippines	6	80
(5)	Finland	Domestic	5	85
(6)	France	Morocco	4	89
(7)	United Kingdom	Canada	4	93
(8)	Norway	Canada	4	97
(9)	Canada	Australia	2	99

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The most significant expansion of capacity in 1979 is expected to occur in Zambia, where an increase from about 4 to 8 million pounds per year is projected. INCO, Ltd., of Canada announced plans to double cobalt production from 1.7 to 3.4 million pounds per year, but implementation has been delayed because of a labor strike. Societe Le Nickel in France had planned to produce close to 1 million pounds per year, but a fire destroyed a new nickel-cobalt refinery at Le Havre and production there will be delayed, probably until early 1980. Aside from these and relatively minor expansions in Finland and Australia, there appear to be few prospects for greatly increased production worldwide over the next few years. Despite these problems with production and capacity, the potential supply of primary cobalt in the world from reserves only (at 1977 prices) is estimated at 3.3 billion pounds, easily adequate to meet the world probable cumulative demand to the year 2000 of 2.7 billion pounds.

Imports

In 1978, the United States relied on southern Africa for about 75% of its imports of cobalt. This includes 60% from Zaire (42% directly from Zaire and 18% transshipped through Belgium for processing), 11% from Zambia, and about 4% from Botswana and the Republic of South Africa. The foreign sources, in order of importance to the United States, are shown in Table 2.

Table 2
Distribution of U.S. import dependence in 1978
(Preliminary)

Rank		Percent of Total Imports	Cumulative
(1)	Zaire-------	42	42
(2)	Belgium-----	18 (Zairian origin)	60
(3)	Zambia------	11	71
(4)	Canada------	7 (Australian origin)	78
(5)	Finland-----	5	83
(6)	Norway------	3 (Canadian origin)	86

Demand

Cobalt demand in 1978 is estimated at about 21 million pounds, distributed among the following: Transportation (aircraft), 23%; electrical (magnets), 22%; machinery (principally cutting tools), 16%; paints (mainly driers), 16%; ceramics, 13%; chemical (catalysts), 8%; and other, 2%. For about the last 15 years, magnetic materials held the lead over superalloys as the largest end use area. However, because of the unusually high demand for commercial aircraft since early 1978, usage in superalloys exceeded that in magnetic materials for the year. Loudspeakers and telephones are two of the largest single end use items in magnetic materials. Superalloys for jet engines, metal-cutting tools, hardfacing, and some magnetic applications are areas of usage considered critical for defense and defense-related use.

While demand increased about 15% over that of 1977, imports remained about the same. Therein lies the shortfall in supply versus demand. Moreover, demand is likely to remain strong over the next several years. The supply deficit in 1978 was apparently largely met by a drawdown of major dealer stocks through May 1978. This led to the major supplier imposing a 70% allocation system, which is currently in effect. The uncertainty in the market that this allocation created was heightened significantly in mid-May, when insurgents disrupted cobalt mining and refining activity in the Kolwezi area of Shaba Province, Zaire. However, following the occupation of the town, which lasted only about 2 weeks, production of cobalt resumed at pre-invasion levels (well below capacity). This was not sufficient to result in a relaxation of the supplier's allocation system. A Pan-African security force was established in Kolwezi to protect the area from a recurrence, but this force appears likely to be withdrawn sometime this year. Insurgent attacks in the mining region of Shaba Province, Zaire, occurred in both 1977 and 1978, and the possibility of a recurrence of such attacks and an occupation of greater duration remains a very real concern, especially if the security force is withdrawn.

Price

Although supply and demand are relatively insensitive to price in the short run, the great leap in price from $6.85 to $25.00 per pound for cobalt in one year resulted in a dramatic change in the relative share of total revenue to copper and nickel producers. For example, in the last half of 1978, cobalt was reported to account for fully one-third of the earnings from metal production out of Australia's Greenvale nickel-cobalt mine and about the same for copper mines in Zaire and Zambia. In 1979, cobalt could account for as much as 50% of earnings for some operations, thereby achieving the status of a genuine co-product in the short span of one year. Historically, this situation is almost without parallel in the mining of byproduct and accessory metals. (See Table 3.)

Table 3
Time-price relationship for cobalt 1/

	Average annual price, dollars per pound	
Year	Actual Prices	Constant 1978 dollars
1957	2.03	4.75
1958	2.00	4.60
1959	1.77	3.99
1960	1.54	3.41
1961	1.50	3.29
1962	1.50	3.23
1963	1.50	3.19
1964	1.50	3.14
1965	1.62	3.32
1966	1.65	3.27
1967	1.85	3.56
1968	1.85	3.41
1969	1.89	3.31
1970	2.20	3.66
1971	2.20	3.48
1972	2.45	3.73
1973	3.00	4.31
1974	3.46	4.54
1975	3.98	4.76
1976	4.44	5.05
1977	5.58	5.99
1978	11.53	11.53
1979 (May)	25.00	--

1/ Prices are weighted averages for each year. (Based on African Metals Corp. price list.)

Market conditions in mid-1978, mainly the unusually high demand and prevailing uncertainty after the allocation and Zairian invasion, provided a convenient opportunity for producers to raise prices. In part, the prices that cobalt commanded on the "free market" induced Zambia to hike its prices. The increases then became self-perpetuating, each pricing tier, producer and free market, encouraging the other to escalate. Zaire also raised its prices. These developments took place against a background of a lack of readily available effective substitutes.

PROBLEM SUMMARY

Given the adequacy of cobalt reserves, it appears doubtful that a serious supply problem would result from depletion of world resources. In addition to the economic problem of prolonged weak markets in copper and nickel, the existence of insecure supplies is of principal concern. Supplies are insecure because the few high-grade deposits are located, unfortunately for the United States, in a region of instability, distant from U.S. shores. Therefore, the possibility of political and military action poses a significant threat of disruption of supply. Although the current shortage of cobalt at the producers' price is primarily the result of unusually high demand combined with lack of efficient recovery in Zaire and generally limited production worldwide because of weak markets in copper and nickel, the incursions into Zaire underscored U.S. vulnerability to supply disruption. Insecurity and financial instability in turn have led to serious problems in maintaining facilities and retaining competent managers and technicians. In addition, this highly centralized source of supply has provided the producing countries with leverage whereby prices may be artificially increased, far out of proportion to increased costs. This revenue is now being used to recoup the losses incurred in the mining and processing of copper and nickel.

SOLUTIONS

Broadening the U.S. base of supply through development of domestic and foreign laterites, sulfides, and ocean nodule resources is one measure that will increase security of supply. The focus of Bureau of Mines research is on development of domestic land-based reserves. Two companies have announced plans to begin domestic production within the next two years. Research into effective substitutes and increasing recycling would also be ameliorating measures. However, until these options have been fully exercised, maintenance of adequate stocks is absolutely essential.

Since World War II, cobalt has been held in the national stockpile under authority of the Strategic and Critical Materials Stock Piling Act. Objectives for material in the stockpile were based on a 5-year emergency from 1946 to 1958, a 3-year emergency from 1958 to 1973, and a 1-year emergency after 1973. Purchases of cobalt were made over about a 15-year period through 1962; sales of material declared in excess of the objective took place from about 1966 through 1976, averaging about 6 million pounds per year. This brought the inventory in storage down to 40.8 million pounds, its current level. In 1976, the objective was raised back up to a 3-year emergency period base, raising the goal, as it is now called, to 85.4 million pounds. Therefore, there is no longer any quantity in excess and sales have been halted. By law, the stockpile is to be used for defense purposes only, and sales or purchases may not be made that might adversely affect the market.

CONCLUSION

Barring any unforeseen developments that greatly reduced the available supply, such as recurrence of military action in Zaire that resulted in a production shutdown lasting several months, the supply of cobalt is likely to remain tight, but not critically short, for the next several years. Prices are expected to remain relatively high. The greatest potential for an easing of the situation appears to be additional production from a number of smaller producers, combined with a possible slackening of demand in one of the major areas--for example, the use of barium or strontium ferrites in the place of Alnico magnets. Over the long term, 1985 and beyond, prospects are good for more readily available cobalt at more reasonable prices. Domestic production of cobalt and mining of cobalt-bearing nodules could satisfy demand and eventually result in lower prices. Thus, the short term outlook is rather pessimistic, but over the long term the present precarious situation could be reversed.

A SUPPLIER'S VIEWPOINT

Like all other users of cobalt, we have experienced both the drastic increase in the cost of the material and the curtailment of supply imposed by the primary domestic source of cobalt.

For many years the producer price of cobalt remained relatively stable. Since early 1978, however, the price of cobalt has soared well beyond the normal inflationary and dollar devaluation influences. Compounding this increase in cobalt prices, and perhaps a justification for the increase, in May 1978, African Metals imposed a 70% allocation to all users based on their 1977 purchases. With an expanding economy in 1978, this allocation was not sufficient to meet the demands of the free world needs and additional material was required over that obtainable from the primary producers. Thus entered the "free" or "gray" market availability of cobalt at $15/lb premium pricing levels over producer prices. Much of the free market cobalt obtained since the allocation was imposed surprisingly is in the same form and in the same packaging as that obtained from the primary producer. I might add that during the entire past year of cobalt procurement there has never been a situation where Hitachi Magnetics has not been able to purchase all of our cobalt needs if we were willing--and we were--to pay the price required.

In early 1978 Hitachi Magnetics Corp. was maintaining its normal inventory of cobalt which never exceeded 2 months and often decreased to a two week period based, of course, on normal availability of material. When the allocation was imposed we found ourselves in a situation of low cobalt inventory, an expanding need for the material over and above 1977 requirements, and much talk of limited cobalt availability which appeared justified on the basis of the 70% allocation and the political/military environment of Zaire.

Confronted, therefore, with limited producer cobalt availability, rumored scarcity situations, increasing producer pricing actions and even higher free market prices, how did Hitachi Magnetics respond? The following steps were taken to counteract the situation.

1.) Obviously, as cobalt producer prices rose we had no alternative other than to pass that increase along to our customers. The question under contention was when those price increases should be applied based on a manufacturing cycle of from four to eight weeks. One could argue that since the higher priced cobalt would not be shipped in product until an average six weeks after purchase of the material, our price increases in cobalt bearing permanent magnet product offerings should not be levied until six weeks after cobalt producer prices were increased. From a customer viewpoint this is a very valid argument. From a user standpoint, however, cash flow problems become extremely critical.

Recognizing, therefore, that monthly cash purchases of cobalt increased the cash required to pay for that cobalt by roughly $1,000,000 we found it necessary to institute our price increase on product as quickly as possible after the announced producer price increase.

2.) Also, since our 70% allocation of cobalt was not sufficient to provide the necessary amount of material for our higher production levels, we were forced to purchase additional cobalt from the free market. This additional purchase at the before mentioned premium price of $15/lb. was covered by initiating a cobalt surcharge which could vary from month to month based on free market purchased quantity and the price paid for that purchase.

3.) The cobalt scarcity rumors previously mentioned contributed to another marketing innovation providing an additional option to our customers. We offered the option of the customer either supplying us their cobalt needs for their permanent magnet requirements or providing us the authority to purchase their needs on the free market for which they would reimburse us at the time of our purchase. If they elected to exercise this option we would guarantee 100% of their magnet requirements with an appropriate pricing revision to allow for their cobalt purchase. We further offered 100% of their requirements if they purchased 50% of their cobalt needs and if the cobalt allocation did not decrease below the 70% level. Several of our larger customers exercised these options.

4.) Due to the critical cash flow problems created by the excessive increases in cobalt pricing we took a relatively hard line in our credit policies and are maintaining and intend to continue to maintain this policy in the future. Our terms specify that net payments are required within 30 days of invoice. We are insistent that the 30 day payment policy is adhered to and our present receivable days reflect this insistence. With the present cash flow requirements we cannot do otherwise even though it does create some customer agitation.

The next question we as magnet producers must address ourselves to is what effect the increase in cobalt bearing magnet pricing and the threat of cobalt scarcity will have on the permanent magnet market? We believe the following actions will transpire, and, in fact, some already have transpired or are in the process of transpiring.

1.) We have seen and are seeing a switch from Alnico to non-cobalt bearing ceramic permanent magnet materials in the loudspeaker and magneto application areas. We are predicting that 70% of speaker applications which were served by Alnico in the first half of 1978 will switch to Ceramic by '79 year end. Much of that transition has already taken place. We also project that 100% of the magneto market will also switch. Collectively this represents approximately 30% of the 1977 Alnico pounds produced. Similar transfers will take place in other application areas where temperature parameters, lower inductions, lower energy material capabilities, and increased physical volume will allow the transfer.

2.) Where this switch is not practical from a performance or physical volume basis we anticipate that hybrid designs will be considered; designs that combine the coercive properties of ceramic material coupled with the induction capabilities of the Alnicos to provide lower cost solutions as a result of lower volume usage of the high priced Alnico material.

3.) We may very well see random grain Alnico material designs being redesigned to incorporate the higher energy, higher induction capabilities of their Alnico columnar counterparts such as Alnico 5-7 and Alnico 9. Even more practical is the complete redesign of structure to utilize the very high energy and coercive characteristics of the cobalt rare-earth materials. Even though Co_5Sm consists of 65% cobalt as compared to 24% for Alnico 5, the volumetric material decrease of 1/4 the Alnico 5 volume based on respective energy products provides an end solution which consists of less than 2/3 the amount of cobalt in Alnico 5. As compared with Alnico 8, the relationship is even more dramatic, the rare earth material utilized representing less than 50% of the cobalt in the equivalent amount of Alnico 8. Obviously, as property improvements are made in the rare-earth family of permanent magnet materials, these advantages will be even more dramatic and substantial.

4.) Finally, and certainly the least palatable from a magnet producers viewpoint, is the undeniable reality that some applications will revert to an electromagnetic design. Much as we hesitate to accept this alternative we must acknowledge that the economics of a magnetic circuit will dictate the final design decision if that design fulfills the application need.

And lastly, we must address ourselves to a prognosis of what the future holds relative to cobalt pricing, availability and sourcing. We believe the present situation will persist for the immediate future. The restless political/military conditions in Zaire probably will not change for some time. However, other cobalt users are also striving to substitute that material with more available replacement elements. Coupled with alloy replacements similar to that which we are experiencing in the permanent magnet industry, these other substitutions will substantially reduce the short term demand for cobalt. In addition, Zambia is in the process of increasing their cobalt output which should further ease the supply problem short term. These activities hopefully will equalize the present differentials between supply and demand and create a supply situation where the allocation will no longer be required thus eliminating the premium priced "free" market sourcing. Obviously, if military actions or other problems disrupt mining operations in Zaire, the free world's primary source of cobalt, the supply situation could become even more critical. We doubt that this will happen.

Cobalt pricing poses an additional short term problem. During the recent Gorham conference on cobalt (Cobalt Crisis, Sheraton-Oak Brook, Oak Brook, Ill., April 29-May 1, 1979, sponsored by Gorham International, Inc.), it was acknowledged that cobalt pricing is regulated by a consortium of cobalt producers similar to the OPEC organization regulating oil prices. This consortium was to meet in latter June to determine pricing actions which would be initiated in July. Hopefully, the message given to the producers by the users during that Gorham conference will inhibit the producers from further increases in cobalt prices.

For the long term we believe that both the supply and pricing situations will be eased. Within five years we believe additional sources of cobalt will come on stream, sources that have relatively low ore concentrations but are not profitable to mine and refine due to cobalt pricing levels. In addition these pricing levels have achieved values that exceed those necessary to mine cobalt per se rather than as a bi-product of copper or nickel. As these additional sources come on stream and the abundance of refined cobalt matches and exceeds demand we anticipate an actual reduction in cobalt pricing. This reduction will never achieve the pricing levels prevalent in early 1978 but should provide a stable price range in the $15 to $18 per pound area.

A USER'S VIEWPOINT--TELECOMMUNICATIONS

Steps taken by the Bell System to deal with recent cobalt cost and supply problems in its equipment have included: 1) ensuring an adequate supply of cobalt through 1979 for its most essential uses, 2) expanding scrap recycling and re-use and 3) carefully examining each application for materials substitution possibilities. The last approach is emphasized here and is further restricted to substitutions that could be effected with essentially no design changes.

Examination of the Bell System's uses of cobalt shows that with the exception of glass sealing, all of the significant applications involve magnetic alloys and that most of these find use in the telephone itself. Telephone receivers account for the largest single application followed by ringers and coin chute magnets. Other significant uses include reed switches and memories. Each is discussed below in terms of the substitution possibilities it offers for decreasing or eliminating our dependence on cobalt.

Telephone Receivers

The current receiver design for the standard telephone handset is of the ring armature type introduced in 1950. It uses a cup-shaped permanent magnet to provide the required bias magnetic field and a high-permeability ring armature to give a high force factor and receiver efficiency. The material used historically for the permanent magnet has been 20 Remalloy (20 w/o Mo - 12 w/o Co - bal. Fe) which has a nominal coercivity of 280 A/cm, remanence of 0.95 T and maximum energy product of $10 kJ/m^3$.

In late 1975, well before the current cobalt problem, the Bell System had already embarked on a program to find a replacement for this Remalloy magnet. In particular, we wanted to find a low-cost, cold-formable material for this cup-shaped magnet to eliminate the slow and costly hot forming required for Remalloy. Attention centered on the Cr-Co-Fe system and two new alloys suitable for this substitution were reported by Chin et al in 1978 (G. Y. Chin, J. T. Plewes and B. C. Wonsiewicz, J. Appl. Phys. 49, 2046, 1978). These had a basic composition of 28 w/o Cr - 15 w/o Co - Fe to which small amounts of zirconium and aluminum or niobium were added to suppress γ phase formation and improve cold formability. Typical properties for the 0.25 w/o Zr, 1 w/o Al alloy (Chromindur I in table), suitably aged, were: $B_r = 0.96T$, $H_c = 365$ A/cm and $(BH)_{max} = 15\ k\ J/m^3$.

Chromindur[1] Permanent Magnet Alloys

Type[2]	Comp.[1] (wt. %)	B_r (T)	$_bH_c$ (A/cm)	$(BH)_{max}$ (kJ/m^3)
I	28 Cr, 15 Co, ¼ Zr, .1 Al	0.96	365	15
II	28 Cr, 10.5 Co	0.98	320	14
II B	"	1.30	380	33
II H	"	1.27	450	40
III	33 Cr, 11.5 Co	1.20	620	42
III C	"	1.18	360	27
IV	33 Cr, 7 Co	1.20	380	27

(1) Chromindur is the name given by the Bell System to the family of Cr-Co-Fe permanent magnet alloys. Under composition, balance is Fe.

(2) Types I and II isotropic; remainder anisotropic.

Subsequently, Jin et al (S. Jin, G. Y. Chin and B. C. Wonsiewicz, IEEE Trans. Mag., to be published), showed that a low-cobalt, simple ternary composition of Cr-Co-Fe (Chromindur II) could be readily processed to avoid γ phase formation, have excellent cold formability, and give reproducible magnetic properties that met Remalloy requirements. Reproducible magnetic properties under normal manufacturing conditions is especially important for commercial use and was achieved by a two-stage, continuous cooling, magnetic aging treatment. A field trial of ring armature receivers with these isotropic Chromindur II magnets is underway and the preliminary results are very promising. Replacement of Remalloy with Chromindur II in these receivers represents a 12.5 percent savings of cobalt for each of the 10 million receivers produced by the Western Electric Company each year. Further substantial savings are realized by the simpler processing and fabrication.

Central armature receivers are a second type for which we are exploring substitute permanent magnet materials of lower cobalt content. Of two codes now made, one uses an Alnico 6B bar magnet and the other one of Alnico 8. Together, they approximate the number of ring armature receivers made, but use less material. Both have the potential for being replaced with Chromindur III, an anisotropic permanent magnet material containing only 11.5 w/o cobalt. These new, anisotropic permanent magnet alloys, containing from 5 to 11.5 w/o cobalt, depend upon a deformation-aging technique to induce a strong magnetic anisotropy without the need for magnetic field heat treatment (S. Jin, this conference). Chromindur III is made anisotropic by uniaxial deformation (as is Chromindur IIB and IV) while IIIC is made anisotropic by planar deformation and IIH is made by magnetic field treatment (R. C. Sherwood, S. Jin and G. Y. Chin, this conference). Deformation induces the optimum shape anisotropy in the partially spinodally decomposed alloy, and subsequent aging increases the amplitude of the concentration modulation needed to develop maximum coercive force. Depending on composition, deformation and subsequent aging, these anisotropic Chromindurs can exhibit maximum energy products of 16-48 kJ/m^3. Substitution of Chromindur III for Alnico 6B or 8 in these central armature receiver magnets can save 50 to 70 percent cobalt, respectively, and offer further processing savings.

The armature is the other receiver component of concern and for both types the alloy used is 2V-Permendur (49 w/o Co-2 w/o V-bal Fe). It is normally chosen for this use because of its high permeability at high flux levels combined with reasonable ductility needed to make thin strip. A potential substitute is the 27 w/o Co-bal Fe alloy which also has reasonable ductility, comparable magnetic properties and only a somewhat lower electrical resistivity. Such a substitution could save 45 percent cobalt in this application.

Ringers and Coin Chute Magnets

Telephone ringers are another important component where we believe significant cobalt savings can be achieved. Ringers use low-aspect ratio permanent magnet rods to provide a bias flux and define a positive direction in circuit members. One such ringer now uses Alnico 5 and is produced at the rate of about 5 million per year by the Western Electric Company. This can be replaced with Chromindur III which has magnetic properties somewhat superior to those of Alnico 5 while saving 50 percent cobalt and offering further processing savings as already noted. A second type ringer uses Alnico 2H for which we are exploring yet another Chromindur alloy that would result in a 40 percent cobalt savings. Beyond ringers, there are various coin chute magnets now using Alnico alloys for which anisotropic Chromindur alloys could be substituted.

Cobalt Savings in Telephone Station Apparatus

Based on programs now underway in telephone station apparatus, we expect to realize an overall Bell System cobalt savings of 15 percent by the end of 1979. Further possibilities, still based on the adoption of Chromindur alloys, could extend these cobalt savings to 30 percent. And, for the most part, these substitutions do not involve design changes.

Reed Switches

Next to station apparatus, our most important use of cobalt-containing magnetic alloys is found in reed switches, particularly the Remreed (W. E. Archer, K. M. Olsen and P. W. Renaut, B.S.T.J. 55, 511, 1976). These use Remendur alloys containing from 2-5 w/o vanadium with the balance 50/50 Co-Fe as semi-hard magnetic materials having high remanence, high squareness and a coercive force controllable over the range of 16-40 A/cm. The Remreed is the most critical of these applications and uses a Type 27 Remendur alloy with 2.7 w/o vanadium in a miniature, self-latching, dry reed, sealed contact. In addition to stringent magnetic requirements, the alloy must exhibit good mechanical stiffness and formability, controlled thermal expansivity and glass sealing characteristics, be solderable and plateable, have magnetic properties minimally affected by glass sealing temperatures and, preferably, low magnetostriction. Alloys considered for this use have been reviewed by Pinnel (M. R. Pinnel, IEEE Trans. Mag. MAG-12, 789, 1976) and, while some contain less or no cobalt compared to Type 27 Remendur, substitution has not been feasible to date because of needed requirements and the expected development of a silicon crosspoint to replace the Remreed cross point. Other ferreed switches use a soft magnetic alloy reed element (51 w/o Ni - bal Fe) with external Remendur alloy plates or rods to maintain latching in the absence of coil current pulses. These uses, however, are minor and do not warrant attention.

PMT Memory

The permanent magnet Twistor (PMT) memory is a random access, semi-permanent, non-destructive readout memory used as a program store by the Bell System in its No. 1 ESS. It stores information in the form of small Vicalloy I (52 w/o Co - 10 w/o V - bal Fe) permanent magnets carried on an aluminum card and sensed by current pulses in a word solenoid. The Vicalloy is used in the form of 0.025 mm thick foil adhesively bonded to the aluminum carrier card and etched to provide the 4000 bit magnet array. The magnetic requirements of Vicalloy I (B_r=0.88T, H_c =240 A/cm, $(BH)_{max}$=7.96 kJ/m^3) as well as its ductility, bonding and etching characteristics could probably be met with Chromindur II. This possibility is currently being explored.

A USER'S VIEWPOINT--ELECTRICAL EQUIPMENT

The electrical equipment industry manufactures and uses a wide range of products which contain cobalt. However, rather than covering the entire industry, this discussion is confined to the principle uses of cobalt by the Westinghouse Electric Corporation (Ⓦ). The uses of cobalt within Ⓦ are illustrative of the general uses in the electrical equipment industry, but other organizations would, of course, differ in the details of their cobalt use.

In total, Ⓦ annually uses somewhat more than one percent of the United States consumption of cobalt. Over half (about 50,000 kg) of the Ⓦ use is for magnetic materials. Although the total amount used does not appear to be great, it is used in critical applications which place a heavy reliance on the properties of the cobalt-containing materials.

Two materials are dominant: Fe-Co soft magnetic materials used in strip form, and Alnico permanent magnets. Some limited use is made of rare earth cobalt permanent magnets. Although not used for its magnetic properties *per se*, iron-nickel-cobalt controlled thermal expansion alloys rely on their magnetic characteristics to achieve the desired expansion; these glass-to-metal sealing alloys will not be discussed further.

The principle uses and quantities of contained cobalt are shown in Table I. Soft magnetic materials account for 20%, permanent magnets for 80% of the cobalt.

TABLE I--Principle Ⓦ Uses of Co for Magnetic Purposes

Category	Annual Co Use (kg)	Application	Materials
Soft Magnetic	10,000	Aircraft generator laminations	27Co-73Fe 49Co-49Fe-2V
		Power supply and inductor cores	49Co-49Fe-2V
Permanent Magnets	40,000	Generators, motors	Alnico 5
		Meters, instruments	Alnico 5, 8
		Microwave tubes	$SmCo_5$

The cobalt-containing soft magnetic materials are used primarily for aircraft applications where the high saturation induction of iron-cobalt alloys leads to lower weight and volume. Core loss and permeability are other important magnetic properties. The 27% Co alloy has slightly poorer magnetic properties than the 49% Co alloy; however, the saturation (23.6 kG) of the 27% Co alloy is nearly as high, and its sensitivity to fabrication stresses is lower. (D. R. Thornburg, IEEE Trans. Magn., Vol. MAG-13, 995 (1977).) For some applications, then, the 27% Co alloy is very satisfactory, with the advantage that less cobalt is used. Replacement of these materials with presently available cobalt-free alternates would be very difficult because the lower saturation of all practical alternatives leads to added weight and volume.

Rotating equipment uses include permanent magnet generators (PMG) and motors. PMG's are used in conjunction with brushless exciters for aircraft generators and also for turbine-generators for central station electric utility plants. The PMG supplies power to the exciter which in turn supplies power to the field of the generator. The PMG is a reliable source of power, is isolated from the power system disturbances, and eliminates the need for an externally applied field. Alnico magnets perform very well for this application, and alternative materials, or alternative excitation systems, would not be as desirable.

Large Alnico permanent magnet motors are used for such applications as steel mill run-out table DC motors. Permanent magnet motors permit an easier installation to be made. Wound field instead of permanent magnets could be used, but are undesired in many cases by the user.

A wide variety of meters and instruments utilize permanent magnets. In addition to the usually desired high working B, H_c, and BH_{max}, long-time (> 30 years) stability and low temperature coefficient are usually very important; thus, Alnico dominates. In instruments, the permanent magnet is usually stationary, while the coil is attached to the moving element containing the indicating needle.

The biggest single use of cobalt-containing magnetic materials in Ⓦ is the Alnico damping magnet in watt-hour meters. In such a meter the magnet exerts a retarding force proportional to the speed of the disk by inducing eddy currents in the disk. Watt-hour meters must function very accurately for many years over a wide range of ambient temperatures. It would be desirable to use cobalt-free (or at least greatly diminished cobalt content) magnets for this application, but at the moment there is no proven alternate which will satisfy the stringent requirements.

Traveling wave tubes for radar systems now use $SmCo_5$ magnets, typically 60-80 per tube. The high BH_{max} and H_c make these materials very suitable for this application. Some use is made of $SmCo_5$ also in breakers. The use of rare earth cobalt magnets will undoubtedly grow in electrical equipment, as greater consistency is achieved in the material, and as designers and manufacturers learn how to utilize its desirable properties and work around its limitations.

The cobalt "situation" has had a significant effect on electrical equipment manufacturers such as Ⓦ. Supplies have so far generally been adequate, but the nearly four-fold increase in price since January, 1978, has greatly added to costs. There is also a concern about the long-term supply situation since the major sources of cobalt are in a politically unsettled part of the world. Whether an alternative source such as deep-sea nodules becomes viable remains to be seen. We have also intensified our efforts to segregate our cobalt-containing scrap, which is frequently returned to the supplier of the original materials. Although difficult to do, it is important that we reduce the amount of cobalt contained in electrical equipment.

POSSIBLE SUBSTITUTES FOR COBALT BEARING MAGNETIC MATERIALS

Cobalt has been widely used in magnetic alloys. This has been particularly the case for permanent magnet alloys where most of the commercially useful alloys contain cobalt.

The role of cobalt in magnetic alloys is related to one or more of the following:

1) It increases the saturation of iron and nickel alloys. For example, the addition of cobalt to iron increases the saturation from 21500 to 24500 gauss and that of the Fe-Ni-Al alloys from 8000 to over 13000 gauss.

2) Cobalt additions also increase the Curie temperature. This results in a decrease of the reversible temperature coefficient, permits operation at higher temperatures, and in the case of Alnico 5 make it possible to heat treat in a magnetic field to obtain anisotropic properties.

3) Cobalt has a beneficial effect on the phase structure of some alloys. For example, cobalt raises the $\alpha \rightarrow \gamma$ transformation temperature of iron; it promotes ordering in the Fe-Co and Co-Pt alloy systems; and in the cobalt-rare-earth systems results in the formation of the $Co_{17}R_2$, Co_5R and Co_7R_2 hexagonal phases.

4) Cobalt influences the transformation kinetics of some alloys. For example, addition of cobalt to the Fe-Ni-Al alloys (AlNi) slows down the $\alpha \rightarrow \alpha_1 + \alpha_2$ transformation so that a much slower cooling rate from the solution temperature can be tolerated, thus increasing the permissible cross section of the castings that can be heat treated to achieve maximum properties.

Cobalt has had a minor role in soft magnetic materials, where iron and silicon-iron dominate, being limited to special alloys such as Permendur and Perminvar. If a high saturation material is needed then cobalt is required, as there is no known substitute for the high saturation iron-cobalt alloys. In contrast, cobalt has had a very broad role in semi-hard and hard magnetic materials. These will be discussed in the following sections.

Semi-Hard Alloys. The semi-hard magnetic alloys are those with a coercive force in the range 10 to 250 oersteds. They are generally ductile alloys capable of being rolled into strip or drawn into rod or wire, and are used for reed switches, memory applications and hysteresis motors for clocks, timers and gyros. A list of some semi-hard alloys is given in Table I. Note that six out of the ten alloys contain appreciable amounts of cobalt, and that the highest values of B_r and coercive force are for alloys containing cobalt. The alloy carbon steels and Fe-Mn-V alloys offer a choice for a cobalt free alloy with a B_r of 11000 gauss and a coercive force of 60 oersteds, but there are no known commercial, cobalt-free, ductile materials with a B_r >12000 gauss and H_c > 60 oersteds. Additional research and development will be needed to find a replacement for P6, P24, etc.

TABLE I

MAGNETIC PROPERTIES OF SOME SEMI-HARD MAGNETIC ALLOYS

Material	%Co	B_s, gauss	B_r, gauss	H_c, Oersteds
P6	45	19000	14000	60
P24	46	18000	13500	100
Fe-Mn-V	0	-	11400	60
5% W Steel	0	-	10500	70
36% Co Steel	36	14500	10400	230
Co-Fe-Nb	85	11500	10400	50
35% Cr Steel	0	14700	10300	60
Remalloy	12	14200	9700	250
17% Co Steel	17	14000	9500	160
Vicalloy 1	51	12900	8400	240

Hard Alloys. Cobalt has had an important role in many permanent magnet alloys. In particular the Alnico series of alloys containing 20-40% cobalt have had a dominant position for many years. However, in recent years the barium and strontium ferrite permanent magnet materials have been utilized more and more because of their moderately good properties coupled with low materials cost. The sharp increase in price of cobalt has accelerated the shift from Alnico to hard ferrites.

A list of permanent magnet alloys is given in Table II together with their magnetic properties and cobalt content. The Fe-Co-Cr base alloys and Mn-Al-C are newcomers to the list.

TABLE II

PROPERTIES OF SOME PERMANENT MAGNET MATERIALS

Alloy	% Co	B_r, gauss	H_c, Oersteds	$(BH)_{max}$ MGOe
Cobalt-Bearing Alloys				
Lodex 32	11	7300	940	3.5
Fe-Co-Cr-x	15	13000	600	5.0
Alnico 5	24	12800	640	5.5
Alnico 8	35	9200	1550	6.0
Vicalloy II	52	9050	415	2.3
Co_5R	63	8500	8000	18.0
CoPt	77	6450	4450	9.2
Cobalt-Free Alloys				
Ceramic 1	0	2200	1825	1.0
Ceramic 3	0	3350	2350	2.6
Ceramic 8	0	3850	3050	3.5
Cunife	0	5500	530	1.4
Alni	0	7000	470	1.4
Mn-Al-C	0	5500	3000	7.5
ESD Iron	0	9000	700	3.5

The Fe-Co-Cr base alloys contain less cobalt than Alnico 5, have nearly identical magnetic properties, and are workable and machinable. They should be considered a replacement for Alnico 5 in applications where the hard ferrite magnets do not fulfill all requirements; e.g., where a low reversible temperature coefficient is beneficial.

The Mn-Al-C alloys contain no cobalt, have a higher residual induction than the hard ferrite and have a comparable coercive force. Therefore, they should be considered for applications where a high flux density is beneficial. In addition, the Mn-Al-C alloys are machinable. The best properties are obtained in extruded rod; consequently there are size limitations for extruded products and the pieces will have to be sliced from the extruded rods.

The Co_5R and $Co_{17}R_2$ alloys, while high in cobalt are more efficient in the use of cobalt than the Alnicos in terms of energy product and coercive force. Because of their high coercive force the cobalt rare-earth alloys are needed for applications where resistance to demagnetization is a major factor.

The elongated single domain, ESD iron magnet contains no cobalt. It has promise as a substitute for the cobalt containing Lodex magnets and as a substitute for Alnico in some applications. Historically, the cobalt-free ESD material was replaced by the cobalt bearing ESM material on the basis of processing and properties; therefore additional development would be required for a commercial substitute to be produced.

To summarize, the hard ferrites offer the best near term solution as a substitute for Alnico and other cobalt bearing alloys. In the long term, Mn-Al-C and the Fe-Co-Cr-X alloys offer the prospect of cobalt-free alloys or a more efficient use of cobalt in alloys where a higher flux density material is required or where their ductility and/or machinability is an added benefit. However, there are no substitutes for the high coercive force, high B_r cobalt-rare-earth magnet alloys.