

6 Cobalt in Chemicals

Cobalt's oldest uses are chemical. It was not until this century that the metal was used in any other way and, even then, the real growth only occurred when the jet engine was developed and Alnico magnets and cemented carbides appeared. In the history section, we noted that Cobalt Blue has been known since antiquity and cobalt colours are still a large chemical use. The more recent petrochemical and plastic industries have found newer uses for cobalt as a catalyst and the chemical market absorbs around 40% of cobalt produced in one form or another.

All its various uses cannot be dealt with here, but some of the main headings are outlined in the following pages.

6.1 Cobalt Chemistry

Cobalt is not a highly reactive metal and is stable in air at normal temperatures. On heating, it oxidises to Co_3O_4 and 900°C this then breaks down to CoO . It reacts with most inorganic (or organic) acids to form simple CoII salts – CoS_4 , $\text{Co}(\text{NO}_3)_2$, CoCl_2 , etc., and it can also form sulphides, carbonates, halides and a vast range of organic and inorganic compounds; many of which find commercial use. It demonstrates valencies of 1, 2 and 3 but the commonest are 2 and mixed 2/3 with 1 only occurring in a few complex compounds.

Ore	Composition	Locations known
Skutterudite	$(\text{Co}, \text{Ni})\text{As}_3$	Germany, Canada, Morocco
Carrollite	CuCo_2S_4 or CuSCo_2S_3	DRC, Zambia
Linnaeite (Siegenite)	Co_3S_4 (+ Ni or Cu)	DRC, USA Zambia
Cattierite (Nickel-Cattierite)	CoS_2 $(\text{CoNi})\text{S}_2$	DRC only DRC only
Cobaltite	CoAsS	USA, Canada, Sweden
Heterogenite	$2\text{Co}_2\text{O}_3\text{Cu}_{0.6}\text{H}_2\text{O}$	DRC
Asbolite	Mixed Manganese Iron oxides + Co	DRC, New Caledonia, Zambia Zambia
Pyrrhotite	Ni, Cu (Co) Sulphides	Canada
Laterites	Weathered igneous Rock $\text{SiO}_2(40)\text{MgO}(37)$ Ni + Co (20%)	Cuba, Brazil USA, Australia Russia

Cobalt ores are mainly mixed sulphides, either copper or nickel oxide/sulphide mixtures, and occasionally cobalt arsenides. Table 1 attempts to list some of the known minerals and their location in current mining terms. The extraction process varies from ore to ore and also depends on the extractor. In general, cobalt is a by-product of copper or nickel.

The major copper-based operations are in the Democratic Republic of Congo (DRC) and Zambia. The ores there are mixed copper/cobalt sulphides and the process for the Gécamines extraction (DRC) is shown in Figure 1 (for a full description see the monograph Cobalt in Chemicals).

In recent years, nickel-based operations have become more prominent as demand for nickel has increased. This has resulted in the expansion of operations treating nickel sulphide ores and the development of high acid pressure leach processes to treat nickel laterites. The processing of nickel laterites has become more common in recent years such that most new nickel production (and associated cobalt) will arise from these sources in the next decade.

Cobalt metal from the DRC and Zambia is produced as cathode which is broken up into pieces 25 mm square (approx.) and 3 mm thick. From other processes, the final product may be powder – ICCI, OMG; Electrolytic crowns – Inco; electrolytic squares – Falconbridge; ingot – Russia; Briquettes – Murrin Murrin, ICCI, OMG.

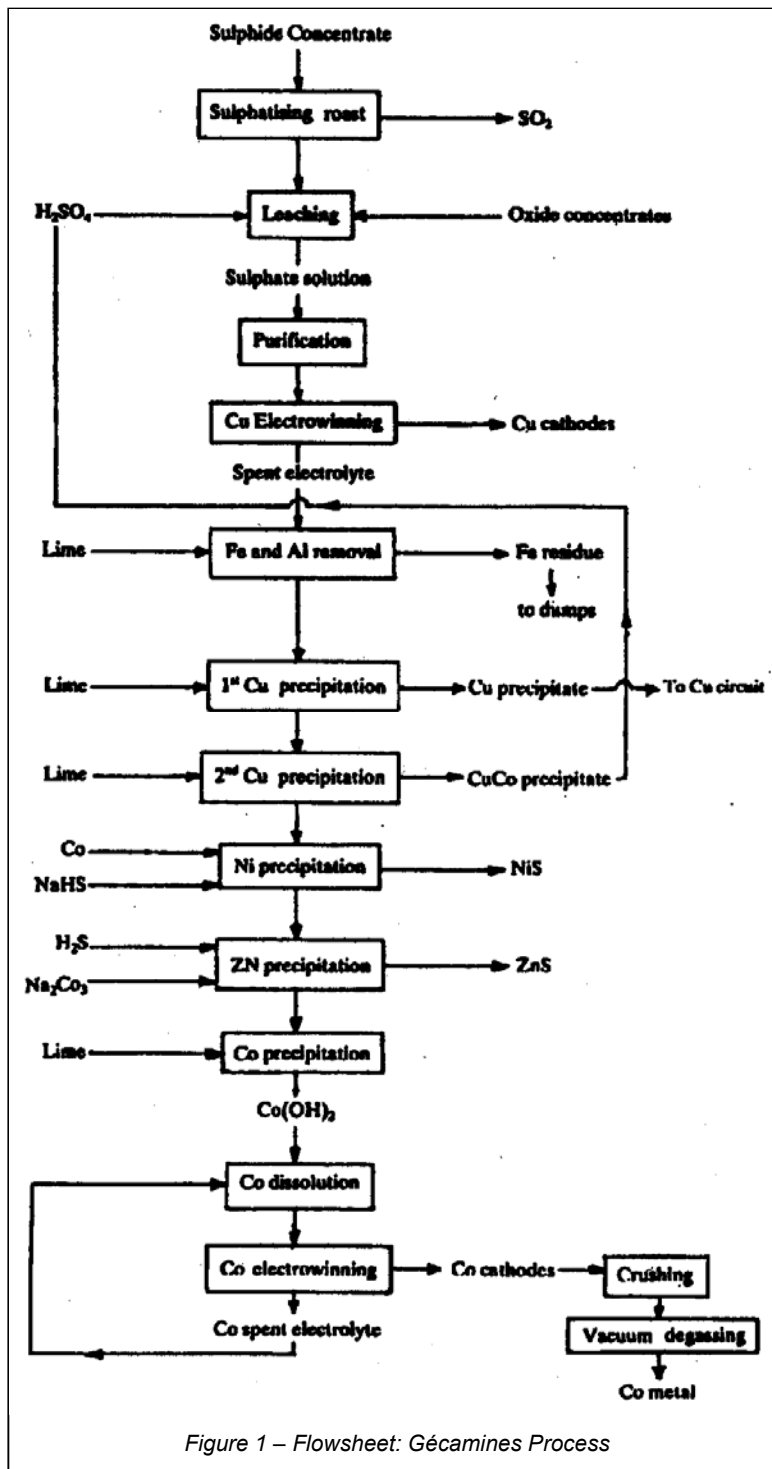


Figure 1 – Flowsheet: Gécamines Process

Traditionally, other chemicals were then produced by specialist companies from the metal by dissolution and reaction. Over the past decade, there has been an increasing tendency for companies to manufacture cobalt chemicals direct from ores, concentrates and slags without passing through the metal stage.

6.2 Cobalt in Pigments

The ability of cobalt-containing minerals impart colour has been of importance for thousands of years going back to the Egyptians and Persians. This property has been used in glass, porcelain, ceramics, paints, inks and enamelware.

The pigments used include cobalt in many formulations. In general, the pigments are prepared by mixing the ingredients as oxides or other decomposable salts (sulphates) and then calcining them at 1100°C-1300°C and grinding back to a fine powder. The colour will depend on the use. In a glaze, further firing occurs which will modify the colour, whereas in paint, what you see is what you get.

Colour	Composition (wt%)								
	Co ₃ O ₄	Cr ₂ O ₃	Fe ₂ O ₃	MnO ₂	Al ₂ O ₃	MgO	ZnO	SiO ₂	CaCO ₂
Blue-violet	15.0			57.0	28.0				
Mazarine blue	68.0							12.0	4.0
Willow blue	33.3							16.7	50.0
Dark Blue	44.6			55.4					
Matt blue	20.0			60.0			20.0		
Blue-green	26.0	8.2		66.0					
Dark blue-green	41.8	19.2		39.0					
Blue-black	11.3	43.3	45.4						
Black	20.6	32.4	41.1	5.9					

Table 1 shows ceramic colours, the colours given being the fired colours and Table 2 shows pigments used in paints, the final colours are given.

Colour	Compounds
Purple-blue	CoO/SiO ₂ /K ₂ O
Blue	CoO/Al ₂ O ₃
Violet	CoO/P ₂ O ₅
Green	CoO/ZnO
Light blue	CoO/SnO ₂ /SiO ₂
Turquoise	CoO/Cr ₂ O ₃ /Al ₂ O ₃
Pink	CoO/MgO
Brown	CoO/FeO
Yellow	K ₃ Co(NO ₂) ₆

Cobalt is also added to glass as a colour or as a decolouriser. Even 2 ppm gives a tint and 200 ppm produces a dark blue. As a decolouriser, at very low levels, it suppresses the yellowish tint glass would otherwise have as a result of iron contamination.

Paintings with Cobalt Blue are common and range from blue to yellow, blue being the popular colour with the French Impressionists.

6.3 Cobalt in Driers

It is obvious that, with paints, inks, etc., how fast they dry is of vital importance. Too quickly or too slowly could both be disastrous. Cobalt salts of the higher carboxylic acids (the Cobalt Soaps) are used to accelerate drying in oil-based paints, varnishes and inks. The salts used for this include the oleate [Co(C₁₀H₃₃O₂)₂], ethylhexanoate [Co(C₈H₁₅O₂)₂], naphthenate [Co(C₁₁H₁₉O₂)₂], linoleate [Co(C₁₈H₃₁O₂)₂].

Metal	Air-Dry System (Hours)	Baked System (Hardness)
Cobalt	1.5	36
Vanadium	6.0	46
Manganese	7.0	54
Rare Earths	10.5	48
Iron	36.0	52

These salts are either soluble in the oils or react to form soluble compounds. Either way, these compounds act as accelerator of the oxidation of the oil and catalysts for polymerisation. The paint, varnish and ink films formed have increased stability, resistance and flexibility as a result of using cobalt driers.

Other metal soaps can be used but as Table 1 shows, cobalt salts are unique.

6.4 Cobalt in Catalysts

In the previous section on driers, much of the action of the cobalt salts may be regarded as homogeneous catalysis. But cobalt has major uses in the petrochemical and plastic industries, as both a hetero and homogeneous catalyst. We can deal here with the three main uses which, between them, accounted for about 5,000 tonnes of cobalt (contained) in 2005.

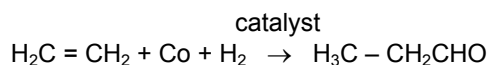
Firstly, **hydro-treating** and **desulphurisation** catalysts for oil and gas. These (CoMOX) catalysts are typically 3-5% cobalt oxide (Co₃O₄) and 14% MoO₃ (molybdenum trioxide), the balance being Al₂O₃ (alumina). Hydrodesulphurisation is a process common to all refineries. In it, the feedstock (or crude oil fraction) and hydrogen are passed over a catalyst at elevated temperature and pressure. The aim is to convert the organic sulphur to hydrogen sulphide (H₂S). All crude oils contain sulphur in quantities varying from .1 to 2.5% depending on their origin. It must be removed for health and safety reasons amongst others. The CoMOX catalysts are universally used for this are very resistant to poisoning and degradation. They can be constantly regenerated and retain their usefulness for several years. They account for the largest amount of cobalt used in this field.

The second major use of cobalt is in the mixed cobalt acetate/manganese sodium bromide homogeneous catalyst for production of **terephthalic acid** (TPA) and **di-methylterephthalate** (DMT). These materials are used to manufacture resin for plastic bottles and also to make the new ultra strong plastics used in recording tapes. It is also the source of the better-known terylene. But anything containing polyester – that's what it is, courtesy of cobalt, PET, polyethylene terephthalate. The TPA or DMT are made from paraxylene by oxidation with nitric acid or air. The process is catalysed homogeneously using cobalt acetate or bromide with manganese present. TPA has a catalyst with a ratio of 1 Co:3 Mn and DMT, a higher cobalt ratio (10:1). However, recycling is easier from DMT spent reactants than TPA and all in all, TPA production uses the same (if not a larger) amount of cobalt. Although demand for recording tapes has decreased in recent years, the switch from aluminium cans to polyethylene terephthalate (PET) bottles has significantly increased the demand for cobalt. In 2005, cobalt demand in these applications was probably of the order of 3,000 tonnes.

The other large cobalt consumer in the catalyst field is OXI synthesis where the end products are alcohols and aldehydes for plastic and detergent manufacture.

Although the cobalt can be introduced to the systems as metal, oxide, hydroxide or as an inorganic salt, the active catalyst species is a carbonyl in a semi-regenerative cycle system [Hco(Co)₄].

The OXO reaction is known as hydroformylation and involves the addition of hydrogen and formyl groups across the double bond of alkenes. The reaction is of the type:



The products being intermediates for a wide variety of chemicals, especially alcohols but also amines and acids.

So these are the 3 main catalysts:

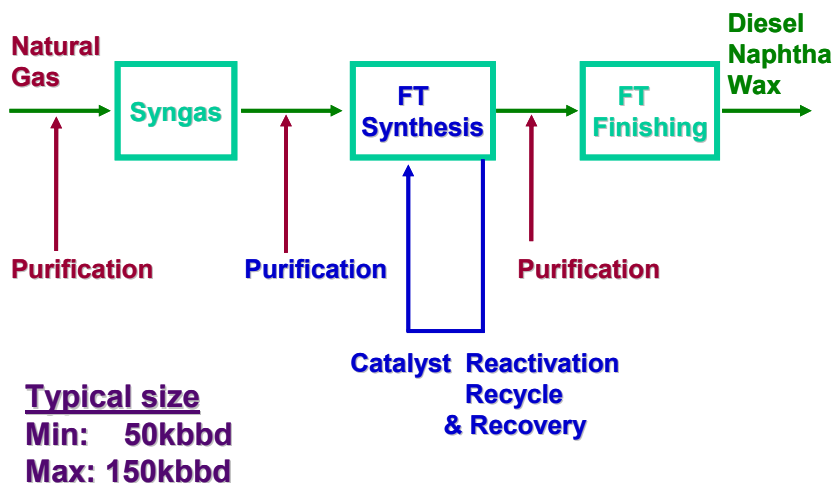
1. Hydro-treating, desulphurisation – cobalt molybdenum oxide – CoMOX
2. Terephthalic acid + dimethylterephthalate – cobalt acetate + manganese
3. OXO catalysts – freshly reduced cobalt metal, carbonyls or cobalt salts (transformed in situ to carbonyl)

Catalysis is a complex subject but cobalt's use in the above 3 situations and in fact in many others, depends on the following facts:

- a) The oxidation-reduction properties of cobalt and its ability to demonstrate several valencies I + II + III with easy electron transfer between these states.
- b) Cobalt's ability to form complexes by accepting atoms from other molecules.
- c) Cobalt chemicals in solution and in polymerisation systems can decompose to give more than one ion to take part in catalysis, i.e. carboxylates – $\text{Co}(\text{RCOO})_2 \rightarrow \text{Co}^{2+} + 2\text{RCO}^{2-}$
- d) Solid cobalt compounds have vacancies in their crystal lattices which can take part in catalysis.

In the past five years, the high price of gasoline, the fact that it originates primarily in politically unstable countries and increasing environmental issues have resulted in the rapid growth in Gas-to-Liquid (GTL) technology. The process enables easily liquefiable hydrocarbons to be formed from natural gas by a chemical process. The process enables the huge stranded gas reserves throughout the world to be transformed into environmentally clean diesel fuel and other products. Since about 35% of stranded gas reserves are located in Europe and Russia, this technology reduces the industrialised countries dependence on the Middle East for their energy requirements.

The process originates from Fischer-Tropsch chemistry first developed in the 1920s and used in Germany in the 1930s and 1940s and a variation using coal to liquid technology in South Africa since the 1950s. A schematic of the process is as follows:



Major developments in GTL by the national oil companies have been made in the past couple of decades and in the last three years a number of new major GTL projects have been commissioned. Dubai became a major GTL technology processing country in 2006. Other countries are set to follow this lead in the next few years. GTL projects currently under development are projected to produce about 525,000 bpd diesel by 2014. Although this is very rapid growth, the total production will be a fraction of the worldwide demand for diesel which currently stands at about 13m bpd.

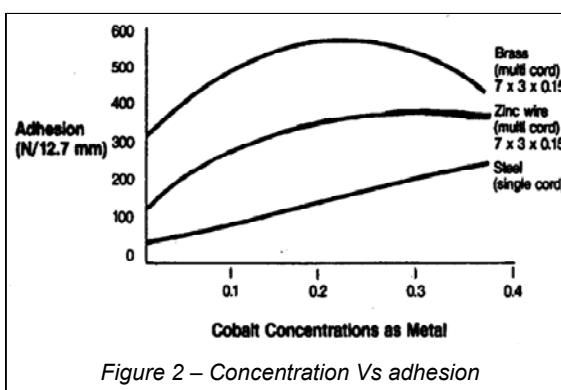
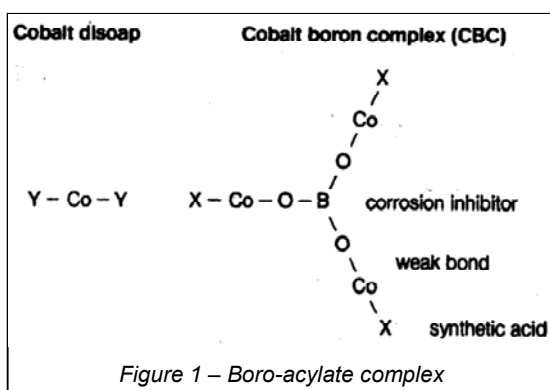
Cobalt is used as the catalyst in the GTL process. It allows a high selectivity to desired products, has a high mechanical resistance and a high sustained activity with long-term low deactivation rates. Typically, the catalyst comprises 20% cobalt as metal, a promoter metal (<1%) supported on an oxide base. As a rule of thumb, 100-200 tonnes of cobalt are required per 10,000 bpd production. However, this is not a fair indication of cobalt requirement for GTL as catalysts are projected to last four years and to be regenerated for further use or recycled. However, the properties of cobalt as a catalyst will ensure its use in GTL technology in the foreseeable future.

Estimates of annual cobalt demand vary widely dependent on the technical issues noted above and the speed of development of new GTL operations throughout the world. In 2005, it is estimated that about 1,000 tonnes of cobalt were used in GTL technology.

6.5 Cobalt in Adhesives

The adhesion in question for cobalt is the one between rubber and brass plated steel cable. The importance of this is in the steel braced radial tyre which has revolutionised tyre production and eliminated the older cross-ply tyre. The essence of the radial tyre is in the sidewall strength of the steel bracing. In the early tyre, one occasionally saw debonding of the rubber from the steel and anyone driving in the early 70's may well remember the odd bubble/bulge on their tyres. You don't see them now because cobalt complex adhesives have cured the problem and created a large market for cobalt (1,000 tonnes world-wide).

The early compounds used were cobalt naphthenate and stearate and these were shown to improve rubber adhesion by 60% when added to the bond layer. Moreover, pull tests now showed failure in the rubber and in the bond. Only small additions are required < .5%.



Since the initial work, more complex boro-acylate complexes of the type shown in Figure 1 have been developed. Figure 2 shows how effective cobalt is.

6.6 Cobalt in Electro-Plating

Cobalt can easily be deposited from a number of electrolytes. However, it must be said that in the main, pure cobalt plated layers are not of great commercial interest. The interest lies in plating wear resistance coatings and those used in the magnetic recording industry.

Cobalt can be deposited from a bath containing non-metallics such as alumina, SiC, CrC, etc. These can be encased in the plated layer to a volume of 30% producing a hard, wear-resistant coat even at elevated temperatures. These find application in the aerospace, aircraft and automobile industries.

Coatings with Co/Ni and Co/W being simultaneously deposited and hardened by suspended non-metallics are also possible.

Table 1 – electrolytes and Operating Conditions for Cobalt Electroplating

Electrolyte	pH	Temperature °C	Current Density Adm^{-2}	
(1) Cobalt sulphate ($\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$) Boric acid (H_3BO_3)	332g/l 30g/l	1-4	20-50	0.5-5
(2) Cobalt chloride ($\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$) Boric acid (H_3BO_3)	300g/l 30g/l	1-4	20-50	0.5-5
(3) Cobalt ammonium sulphate ($\text{Co}(\text{NH}_4)_2(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$) Boric acid (H_3BO_3)	200g/l 25g/l	5.2	25	1-3
(4) Cobalt sulphamate ($\text{Co}(\text{SO}_3\text{NH}_2)_2 \cdot 4\text{H}_2\text{O}$) Formamide (HCONH_2)	450g/l 30ml/l	–	20-50	1-5
(5) Cobalt fluoborate Boric acid (H_3BO_3)	116-154g/l 15g/l	3.5	50	5.6

Nickel plating for decorative and industrial applications (electroformed moulds for glass and plastic) is perhaps more common than cobalt. Adding cobalt as chloride and sulphate produces a bright nickel deposit, typically:

Nickel sulphate ($\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$)	240 g/l
Nickel chloride ($\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$)	45 g/l
Cobalt sulphate ($\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$)	3-5 g/l
Boric acid (H_2BO_3)	30 g/l
Sodium formate (NaCHO_2)	35 g/l

This bath produces bright nickel coats with 18% cobalt in them.

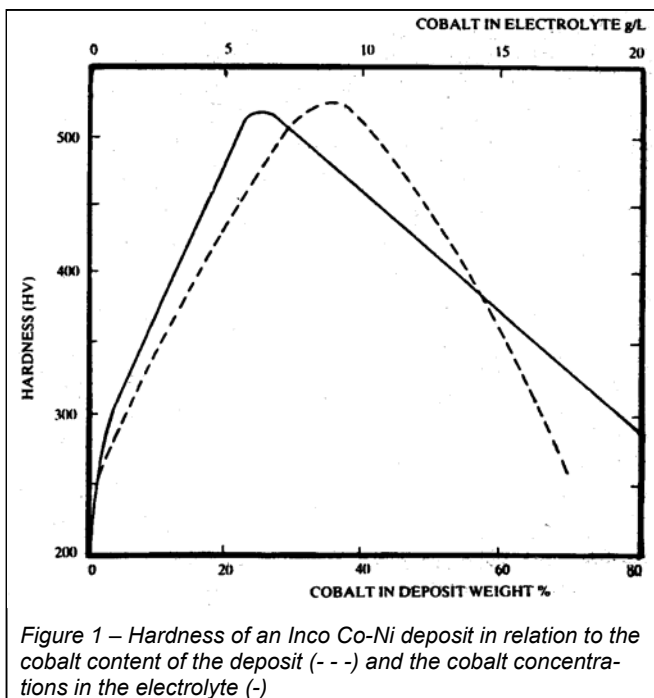


Figure 1 shows Ni/Co electrodeposited coats of varying cobalt levels showing peak hardness at circa 25/30% cobalt.

More recently electrodeposited cobalt has been used in specialised magnetic recording materials. Cobalt from sulphate solutions can be made to deposit as needle shaped crystalline particles with the long axis of the particle and “C” axis of the CPH cobalt crystal (i.e. the easily magnetised direction) at 90° to film axis – perpendicular recording.

Various electroless coatings are also possible – for example, Co/P alloys, Co-Ni-Re-Mn-P, Co-Br, etc. These deposits can form onto non-metallic substrates by chemical reduction.

Whilst the use of cobalt in plating is static, the growth area is in the deposition of recording surfaces.

6.7 Cobalt in Agriculture and Medicine

No section on cobalt chemicals could be complete without looking at cobalt's vital importance in the body through its central place in Vitamin B12 (see also the Environmental section).

The cobalt cycle in Figure 1 shows that the amount of cobalt extracted annually from rocks and soils by biological processes, is approximately the same as the amount extracted by man's mining activities, i.e. 25,000 tonnes.

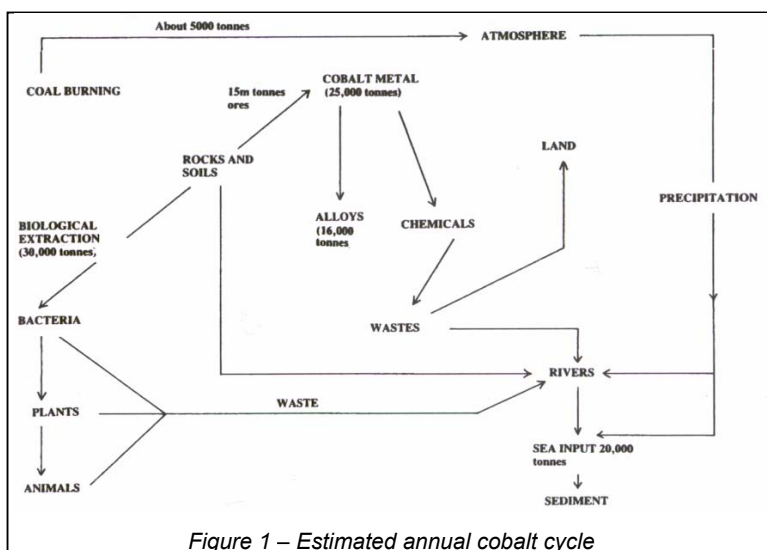


Figure 1 – Estimated annual cobalt cycle

The cobalt available to all living organisms must have its origins in rocks and minerals and been taken up by living organisms via bio-chemical processes. One of the most important routes for the uptake of cobalt from minerals is the biosynthesis of Vitamin B12 by micro organisms.

Living organisms are split into 3 classes depending on their need for Vitamin B12 type molecules and also their ability to synthesise them: i) most plants; ii) most animals and iii) certain micro organisms. Most plants do not require B12 and do not synthesise it, although they do absorb cobalt it is present in the soil. Most animals require the vitamin but

cannot synthesise it themselves and so have to take it from an outside source. The only living organisms that both require and can produce B12 are certain species of bacteria. These can be found in the stomach of ruminant animals, soils, plant nodules and dairy products.

Man falls into category (ii) but not being a ruminant, has to get B12 from animals, dairy products or leguminous vegetables. It is no use eating cobalt. However, this is not true for cattle, sheep, etc., and any feed they have must contain cobalt salts so that their own bacteria can produce B12 for them and for us.

Without vitamin B12, animals and man can suffer from anaemia, though it is more often due to mal-absorption rather than actual diet deficiency.

For cattle, sheep, etc., a level of 0.1 µg/g of cobalt in the feed is sufficient to meet all their needs. In areas where levels are too low, the cobalt can be given in various ways: a) by adding cobalt to the soil as sulphate at a rate of 2 kg/hectare (dose good for 3/5 years); b) by providing licks with 0.1% cobalt in them (oxide or sulphate) and c) with cobalt "bullets", cobalt oxide inserted into the oesophagus and allowed to slowly emit cobalt.

Cobalt salts are used in fairly large proportions in animal feeds, mainly as the sulphate, to provide the cobalt which finally reaches man as vitamin B12 – vital cobalt. Commercial plants are however becoming available which synthesise B12 using bacteria in a controlled manner.

Cobalt deficiency disease in man can be treated by administration of vitamin B12 usually as cyanocobalamin or hydroxycobalamin. Treatment is by small doses over an extended period (1 mg every 2 weeks for 6 months). The preparations go under various trade names depending on the country – Forta B12, Novobdedouze, Dodecavit, etc.

The other main use for cobalt-containing materials other than B12 is as an antidote to cyanide poisoning. Dicobalt ethylenediaminetetraacetate (C₁₀H₁₂N₂O₈Co₂) is used because of the speed with which cobalt forms stable complexes with cyanide ions. It can act as antidote to an amount of cyanide equal to 1/8th of its

own weight. A suggested dose is 300 mg by intravenous injection over 1 minute as 20 ml of 1.5% solution, to be followed by 50 ml of 50% dextrose through the same needle (NB: causes vomiting and other side effects).

Other uses have been made of cobalt salts, but the two above are the only usual ones. Cobalt-60 used for treatment of cancer has already been covered (Metallurgical Uses section).

Further Reading

1. Cobalt in Chemicals – CDI, 1986
2. Cobalt in Catalysts – CDI, 1990
3. Cobalt and its Alloys – Betteridge, Horwood, 1982
4. Ullman's Encyclopaedia of Industrial Chemistry – Vth Edn., p. 281, Vol. A7
5. European Market for Catalysts – Frost & Sullivan, 1985
6. Cobalt in Medicine, Agriculture and the Environment – CDI, 1986

COBALT COMPOUNDS: PROPERTIES AND USES						
Name	Synonyms & Formulae	Mol. Wt.	Crystalline Form Properties & Index of refraction	Density or Spec. Gravity	Solubility in grams per 100 cc Cold water	Uses
Cobalt (III) acetate	Co(C ₂ H ₃ O ₂) ₃	236.07	green, octahedral, hyg.		hydr readily	Catalyst for cumene hydroperoxide decomposition
(II) acetate	Co(C ₂ H ₃ O ₂) ₂ ·4H ₂ O	249.08	red-violet, monocl.	1.705	s	Driers for lacquers & varnishes, catalysts, colourant for oil cloth, mineral supplement, anodising
acetylacetonate	Co(C ₅ H ₇ O ₂) ₃	343.34	monocl., black	1.43		Vapour plating of cobalt
aluminate	(approx) Thenard's blue CoAl ₂ O ₄	176.89	blue, cubic		i	Grain refiner investment casting Ni-/Co-base alloys
ammonium sulfat(ous)	CoSO ₄ (NH ₄) ₂ SO ₄ ·6H ₂ O	395.25	monocl, ruby red 1.490, 1.495, 1.503	1.90	20.5 (20°C)	Catalyst, plating
(II)orthoarsenate	Co ₃ (AsO ₄) ₂ ·8H ₂ O		violet-red, monocl 1.626, 1.661, 1.669	3.178	i	Light blue colour for paint on glass & porcelain, colouring glass
arsenic sulphide	Nat. cobaltite CoAsS		grey-reddish	6.2-6.3		Natural ore
(II) benzoate	Co(C ₇ H ₅ O ₂) ₂ ·4H ₂ O	373.23	grey red leaf		vs	
boride, mono-	CoB	69.74	prisma	7.25	d	
(II) bromate	Co(BrO ₃) ₂ ·6H ₂ O	422.84	red, octahedral		45.5	
(II) bromide	CoBr ₂	218.75	green, hex., deliq.	4.909	60.7 (50°C)	Hydrometers, catalyst for organic reactions
(III) bromide anh	CoBr ₃	298.70				Hydrometers
carbide	Co ₄ C	247.77				
carbonate	Nat. spherocobaltite CoCO ₃	118.94	red, trigonal, 1.855, 1.60	4.13	i	Pigments, ceramics, trace mineral supplement feed, temp. indicator, catalyst
(II) carbonate basic	2CoCO ₃ ·Co(OH) ₂ ·H ₂ O	534.74	violet-red prisma		i	Prep. Of Co compounds
carbonyl tetra	Dicobalt octacarbonyl [Co(CO) ₄] ₂ or Co ₂ (CO) ₈	341.95	orange cr. or dark brown micro cr.	1.73	i	Catalyst
carbonyl, tri	Tetracobalt dodecacarbonyl [Co(CO) ₃] ₄ or Co ₄ (CO) ₁₂	571.86	black cr.		sl s	Catalyst
(II) perchlorate	Co(ClO ₄) ₂	257.83	red needles 1.510, 1.490	3.327	100	Chemical reagent
(II) chloride, anhy	CoCl ₂	129.87				
(II) chloride, hexahydrate	CoCl ₂ ·6H ₂ O	237.93	red, monocl.	1.924	76.7	Barometers, hydrometers absorb poison gas & NH ₃ electroplating, solid lubricant, vitamin B12 prep., catalysts
(II) chromate	CoCrO ₄	174.93	grey black cr.	1.924	i	Green tints in ceramics
(II) citrate	Co ₃ (C ₆ H ₅ O ₇) ₂ ·2H ₂ O	591.04	rose-red		0.8	Vitamin preparation
(II) cyanide dihydrate	Co(CN) ₂ ·2H ₂ O	147.00	buff anhydrous blue-violet powder	anhydrous 1.872	0.00418	Catalyst
potassium cobalt cyanide	K ₃ Co(CN) ₆	332.34	monocl. yellow	1.906	s	Suggested: microwave studies
(II) ferrocyanide	Co ₃ [Fe(CN) ₆] ₂	600.71	red needles		i	
(II) ferrocyanide	Co ₂ Fe(CN) ₆ ·xH ₂ O		grey-green		i	
ethylenediamine di-sodium tetracetate	CoNa ₂ (C ₁₀ H ₁₂ O ₈ N ₂ ·H ₂ O	411.14	amorphous pink powder		s	Support of other chelating cmps in medicinal & tree spray preps.

Name	Synonyms & Formulae	Mol. Wt.	Crystalline Form Properties & Index of refraction	Density or Spec. Gravity	Solubility in grams per 100 cc Cold water	Uses	
Cobalt							
(II) fluoride	CoF ₂	96.93	pink monocl.	4.46	1.5		
(III) fluoride	CoF ₃	115.93	brown Hex.	3.88	d to Co(OH) ₃	Fluorinating agent	
(II) fluoride tetrahydrate	CoF ₂ ·4H ₂ O	168.99	α: red, rhomb octahedral β: rose cr. powder	2.192	s	Catalyst in organic reactions	
fluosilicate	CoSiF ₈ ·6H ₂ O	309.10	pink trigonal	1.382, 1.387	2.113	118.1	Ceramics
(II) formate	Co(CHO ₂) ₂ ·2H ₂ O	185.00	red cr .	2.129	5.03		Catalyst
(II) hydroxide	Co(OH) ₂	92.95	rose-red, rhomb	3.597	0.00032		Paints, catalysts, inks
(III) hydroxide	Co ₂ O ₃ ·3H ₂ O	219.91	black-brown powder	4.46	0.00032		
(II) iodate	Co(O ₃) ₂	408.74	blue-violet needles	5.008	0.45		
(II) iodide (α) stable	CoI ₂	312.74	black hex., hyg.	5.66	159		Moisture indicator
linoleate	Co(C ₁₈ H ₃₁ O ₂) ₂	617.83	brown, amorphous		i		Drier for paints, varnishes
lithium cobaltite	LiCoO ₂	97.9	dark blue powder		i		Ceramics
naphthenate	Co(CuH ₁₀ O ₂) ₂		purple liquid (6% Co)	0.966			Drier for paints, varnishes
(II) nitrate	Co(NO ₃) ₂ ·6H ₂ O	291.04	red, monocl., 1.52	1.87	133.8		Pigments, hair dyes, feed supplement, catalysts
octoate (ehtylhexoate)	Co(C ₈ H ₁₅ O ₂) ₂		blue liquid (12% Co)	1.013			Driers, whiteners
nitrosylcarbonyl	Co(NO)(CO) ₂	172.97	cherry red liquid		i		
(II) oleate	Co(C ₁₈ H ₃₃ O ₂) ₂	621.96	brown, amorphous				Drier for paints, varnishes
(II) oxalate	CoC ₂ O ₄	146.95	white or reddish	3.021	i		Temperature indicator, in hydrous form for catalysts
(II) oxide	CoO	74.93	green-brown cubic	6.45	i		Glass decorating, colouring & whitener, drier
(II, III) oxide	Co ₃ O ₄	240.80	black, cubic	6.07	i		Enamels, semiconductor, grinding wheels, colours, pigments, catalysts
perchlorate(ous)	Co(ClO ₄) ₂	257.85	red needles	3.327	i		Chemical reagent
(II) orthophosphate octahydrate	Co ₃ (PO ₄) ₂ ·6H ₂ O	510.87	reddish powder	2.769	sl s		Glazes, enamels, pigments, plastic resins
phosphide	Co ₂ P	148.84	grey needles	6.4	i		
potassium nitrite	K ₃ Co(NO ₂) ₆ ·1-1/2H ₂ O	479.3	tetragonal, yellow		sl s		Oil & water pigment, paint for glass/porcelain, rubber colourant, Fishers yellow in Co analysis
resinate	Co(C ₄₄ H ₆₂ O ₄) ₂	1368.81	brown-red amorphous powder		i		Drier for paints, enamels, varnishes, coating for china, pottery, catalysts
(II) selenate pentahydrate	CoSeO ₄ ·5H ₂ O	291.97	ruby red, tricl.	2.512	v s		
selenide, mono	CoSe	137.89	yellow, hex.	7.65			
selenite	CoSe ₂ O ₃ ·2H ₂ O	300.9	blue-red amorphous		i		
(II) orthosilicate	Co ₂ SiO ₄	209.95	violet cr., rhomb	4.63	i		
silicide, di-	CoSi ₂	115.1	rhomb	5.3			
(II) orthostannate	Co ₂ SnO ₄	300.55	greenish-blue, cubic	6.30			
stearate	Co(C ₁₀ H ₃₅ O ₂) ₂	433.83					Driers, tyre adhesives
succinate(ous)	Co(C ₄ H ₄ O ₄) ₂ ·4H ₂ O	237.05	violet cr.		sl s		Vitamin prep., therapeutic agents

Name	Synonyms & Formulae	Mol. Wt.	Crystalline Form Properties & Index of refraction	Density or Spec. Gravity	Solubility in grams per 100 cc Cold water	Uses	
Cobalt sulfamate(ous) (amino sulfonate)	Co(NH ₂ SO ₃).3H ₂ O	241.04			s	Electroplating	
(II) sulphate	CoSO ₄	155.00	dark bluish, cubic	3.71	36.2	Ceramics	
(II) sulphate heptahydrate	Nat. bieberite CoSO ₄ .7H ₂ O	281.10	red pink, monocl. 1.477, 1.483, 1.489	1.946	60.4	Pigments for porcelain; glazes, plating, feed supplement, catalysts, batteries, drier for inks	
(II) sulphate monohydrate	CoSO ₄ .H ₂ O	173.01	red cr., 1.603, 1.639 1.683	3.075	s	Same as for CoSO ₄ .7H ₂ O	
sulphide, mono	Nat. sycoporite CoS	91.00	reddish, silver-white octahedral	5.45	0.00038	Catalyst for hydrogenation or desulphurisation	
(III) sulphide	Co ₂ S ₃	214.06	black cr.	4.8			
tallate	(varying composition)		purple liquid (6% Co)	0.975		Driers for paints, varnishes	
thiocyanate	Co(SCN) ₂ .3H ₂ O	229.14	violet, rhomb.		s	Humidity indicator	
orthotitanate	Co ₂ TiO ₄	229.76	greenish-blue, cubic	5.07-5.12			
(II) tungstate	CoWO ₄	306.75	blue-green, monocl.	8.42	i	Light sensitive varnishes, drier for enamels, inks, paints, electronic fields	
Cobalt complexes							
Hexamminecobalt ((III) chloride)	Co(NH ₃) ₆ Cl ₃	267.46	wine-red, monocl.	1.710	5.9		
triethylenediamine-cobalt-(III) chloride	Co[C ₂ H ₄ (NH ₂) ₂] ₃ Cl ₃ .3H ₂ O	399.64	brown prisma	1.542	v s		
ammonium tetra-nitrodiammine (III) cobaltate	Erdmann's salt NH ₄ [Co(NH ₃) ₂ (NO ₂) ₄]	295.12	reddish-pale brown rhomb. 1.78, 1.78, 1.74	1.876			
aquapentammine-cobalt(III) chloride (roseo)	[Co(NH ₃) ₅ .H ₂ O]Cl ₃	268.45	brick red cr.	1.7	24.87		
ABBREVIATIONS							
cr.	crystalline	hex.	Hexagonal	monocl.	Monoclinic	tricl.	triclinic
d, dec.	decomposes	hyg.	Hygroscopic	s	soluble		
deliq.	deliquescent	i	insoluble	sl	slightly		

OTHER COMPOUNDS

Acetylene dicobalt nona carbonyl – C ₄ H ₂ O ₂ (Co) ₇	Cobaltic molybdate – CoMoO ₄ H ₂ O
Aluminium-cobalt catalyst Raney type (50% Co)	Cobalt nitride - CoN
Ammonium cobalt phosphate – NH ₄ CoPO ₄ .H ₂ O	Cobalt potassium oxalate
Barium cobaltcyanide – Ba ₃ [Co(CN) ₆] ₂	Cobalt phthalocyanine – (C ₈ H ₄ N ₂) ₄ Co
Cobalamine (cyanocobalamin, Vit. B12) – Co ₆₃ H ₈₈ CoN ₁₄ O ₁₄ P	Cobaltic phosphide – Co ₄ P ₃
Cobalt antimonide – Co ₂ Sb	Cobaltic soyate
Cobalt borate – CoB ₄ O ₇	Cobaltous telluride - CoTe
Cobaltous chromite – CoCr ₂ O ₄	Cobaltidialcylethylene diamine
Cobaltous cobaltcyanide	Cobaltocene – (C ₃ H ₅)Co
Cobalt cyclohexanebutyrate – (C ₆ H ₁₁ (CH ₂) ₃ COO) ₂ Co	Cobaltous acetylacetonate – (CH ₃ CoCHCoCH ₃) ₂ Co
Cobalt cyclopentadienyl dicarbonyl	Cobaltous ferrite – CoFe ₂ O ₄
Cobalt ethylene diamine chloride – Co(NH ₂ CH ₂ CH ₂ NH ₂) ₃ Cl ₃ .3H ₂ O	Cobaltous propoxide-iso – Co(C ₃ H ₇ O) ₂
Cobalt fluoroborate – Co(BF ₄) ₂	Cobaltous sulfamate (aminosulfonate) – Co(NH ₂ SO ₃).3H ₂ O
Cobalt gluconate	Cobaltous titanate - meta
Cobalt glycine	Cobaltous zirconate - meta
Cobalt lactate – Co(C ₃ H ₅ O ₃) ₂ XH ₂ O	Copper cobaltcyanide – Cu ₃ [Co(CN) ₆] ₂
Cobalt laurate	Potassium tiroxalate cobaltate – K ₃ Co(C ₂ O ₄) ₃
Cobalt mercuri thiocyanate	Sodium cobaltcyanide – Na ₃ Co(CN) ₆