INVESTIGATIONS CONCERNING TREATMENT OF CHROMITE ORE FROM BALUCHISTAN, PAKISTAN

A THESIS

By

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INTRODUCTION

It is truly said that the prosperity of a country depends on its mineral resources. This is especially true in newly-formed countries which must depend entirely on their own natural resources for their subsistence, and for obtaining the badly needed dollars and sterling for essential imports needed for the development of their country.

The newly-formed country of Pakistan is not an exception to the above fact and has to depend entirely on her principal natural resources which are agricultural and mineral. Fortunately, nature has endowed Pakistan with an ample supply of both metallic and non-metallic minerals; and the Government of Pakistan, realizing the importance of non-metallic minerals, has taken the necessary steps to establish a reliable and thriving Mineral Industry. Today the Mineral Industry in Pakistan is fast developing and the work in the mines is being done at top speed to increase the output of various mineral and non-mineral deposits. Minerals which are being worked on a commercial scale include coal, petroleum, chromite, antimony, salt, silica, sulphur, gypsum, and limestone.

Of all the above minerals, chromite is the one which shows economic promise because of the following three reasons:

(1) There are huge deposits of chromite in the province of Baluchistan which have been producing since the beginning of the century.

(2) Chromite is the only mineral which has a favorable world market because larger chromite-consuming countries like United States, England, and Sweden have to depend entirely on other countries for their required supply of chromite. The above countries are the principal sources from which Pakistan can acquire

the badly needed dollars and sterling by exporting chromite.

(3) Pakistan chromite can be exchanged for Indian iron and steel, as the former does not possess a steel industry of its own.

In Pakistan chromite occurs in the Hindubagh area of Baluchistan. Mining of the ore was started in 1914 by Messrs. Baluchistan Chrome Company which held 97 leases covering an area of 3,380 acres. The total production has varied from year to year, the highest being in 1942 (about 40,000 long tons). In 1948 the production was only 18,000 tons and during the first half of 1949 about 8,000 tons. The entire quantity produced is exported at present to various countries, such as England, United States, Sweden, etc., as there are no facilities in Pakistan for refining it.

The recent decrease in the production of chromite in Pakistan can be attributed to two main reasons, which are: uncertain political conditions during the last few years, and depletion of high-grade chromite deposits. Since the revival of the Mining Industry in Pakistan, the first cause of uncertain mining conditions has been definitely taken care of, but no provision has been made for the treatment of low-grade chromite deposits. If the chromite industry of Pakistan is to thrive, it has to consider this problem as soon as possible, and find a logical solution.

It is for this reason that the thesis-problem "Investigations Concerning Treatment of Chromite Ore from Baluchistan, Pakistan," was undertaken, the principal aim being to investigate the possibilities of treating the above low-grade chromite ore by the usually feasible concentration methods to obtain the required commercial grade of product.

It is greatly regretted that sufficient information on the geological and commercial aspects of this particular ore was impossible to obtain, as the newly formed Pakistan Geological Survey has started its investigations very recently and no reports have as yet been published. Also, since the records of the Geological Survey of United India after the partition of India remains disputed between the two new-born Dominions, no information was available from that source. No metallurgical information is available because no concentration treatment of any kind has been attempted on this particular ore, except for hand sorting.

PART I

GEOLOGICAL AND COMMERCIAL ASPECTS OF CHROMITE

Mineralogy, Occurrence and Distribution: Of all the minerals containing chromium, chromite is the only one of commercial importance as an ore of chromium. Chromite is black to brownish, sometimes yellowish red in color; it has a brown streak, is translucent to opague, has a submetallic lustre, and is sometimes feebly magnetic. The hardness of chromite is 5.5, its specific gravity is 4.32 to 4.60, it is brittle and has an uneven fracture. Chromite is infusible and gives a definitely green borax-bead test in both the oxidizing and reducing flames. With salt of phosphorus in the oxidizing flame, it gives a yellow color when hot, but on cooling changes to a fine emerald green tint. With soda and nitre on platinum it fuses to a magnetic mass, which is yellow in color when cool. Chromite is insoluble in acids, but it is decomposed by sodium carbonate with the formation of water-soluble sodium chromate.

Chromite ($Cr_2O_3 \cdot FeO$) has a theoretical composition of 68 percent of chromium sesquioxide (Cr_2O_3) and 32 percent of ferrous oxide (FeO), but chromite of the above theoretical composition is extremely rare. The naturally occurring material contains more or less magnesium and aluminum, corresponding to the formula $(Fe,Mg)O(Fe,Al,Cr)_2O_3$, because of the partial replacement of ferrous iron by magnesium, and of chromium by ferric iron and aluminum. So wide is the range in chemical composition in this group that chrome ore consisting entirely of the mineral chromite may range from less than 30 percent to more than 60 percent Cr_2O_3.

The most comprehensive published data on the chemical composition of chromite are by Stevens 1/, who made a complete analysis of more

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1/ R. E. Stevens: "Composition of Some Chromites of the Western Hemisphere." Amer. Mineralogist (1944) 29, pp 1-34.

than 50 samples of chromite concentrate from many localities throughout the Western Hemisphere.

Figure 1. shows the predominant zone of isomorphism, within the triangular prism of composition defined by the mineralogical end members of the series, wherein his analyzed samples fell.

Figure 2. shows the distribution of Stevens' samples in a triangular diagram of chemical composition divided into fields to which mineralogical names have been given.

Metallurgical-grade chromite occupies a small part of the "aluminian chromite" field near the $(Mg,Fe)O \cdot Cr_2O_3$ apex of the triangle, and refractory chromite extends down toward the $(Mg,Fe)O \cdot Al_2O_3$ corner in the "chromian spinel" field.

Table 1. illustrates the wide range in chemical composition from aluminian chromite containing more than 61 percent Cr_2O_3 to chromian magnetite containing only 13.7 percent.

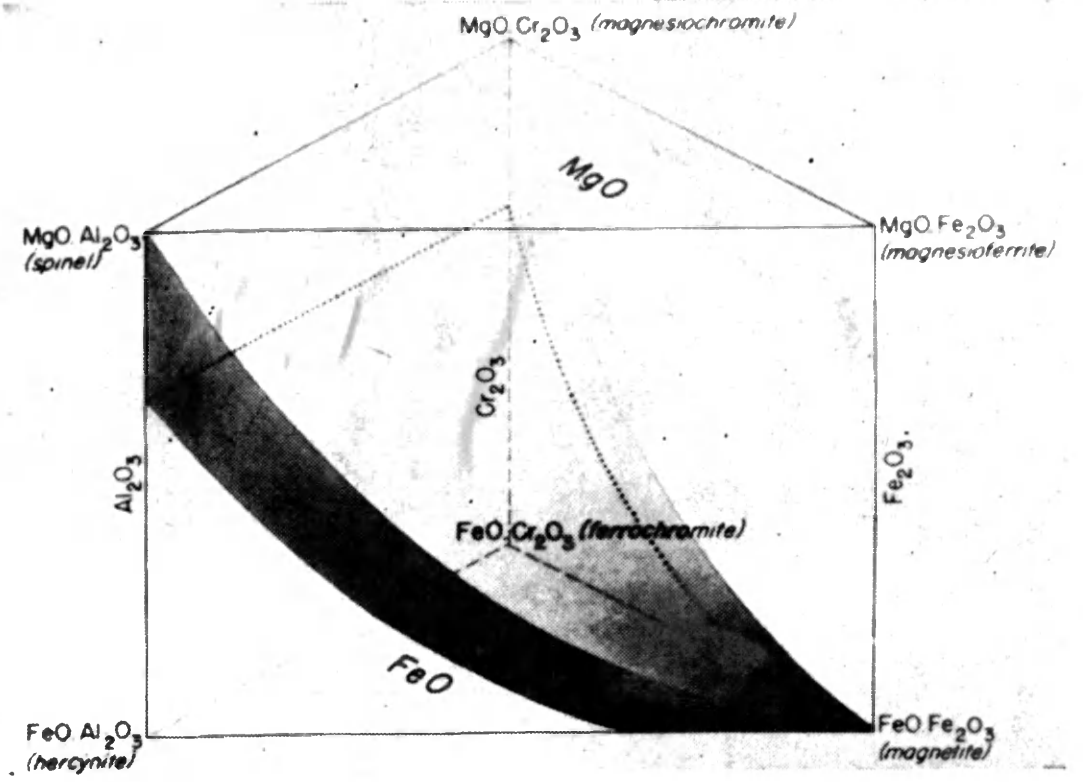

FIG 1—TRIANGULAR PRISM OF COMPOSITION SHOWING END MEMBERS AND PREDOMINANT ZONE OF ISOMORPHISM OF MINERAL CHROMITE (*After Stevens*).

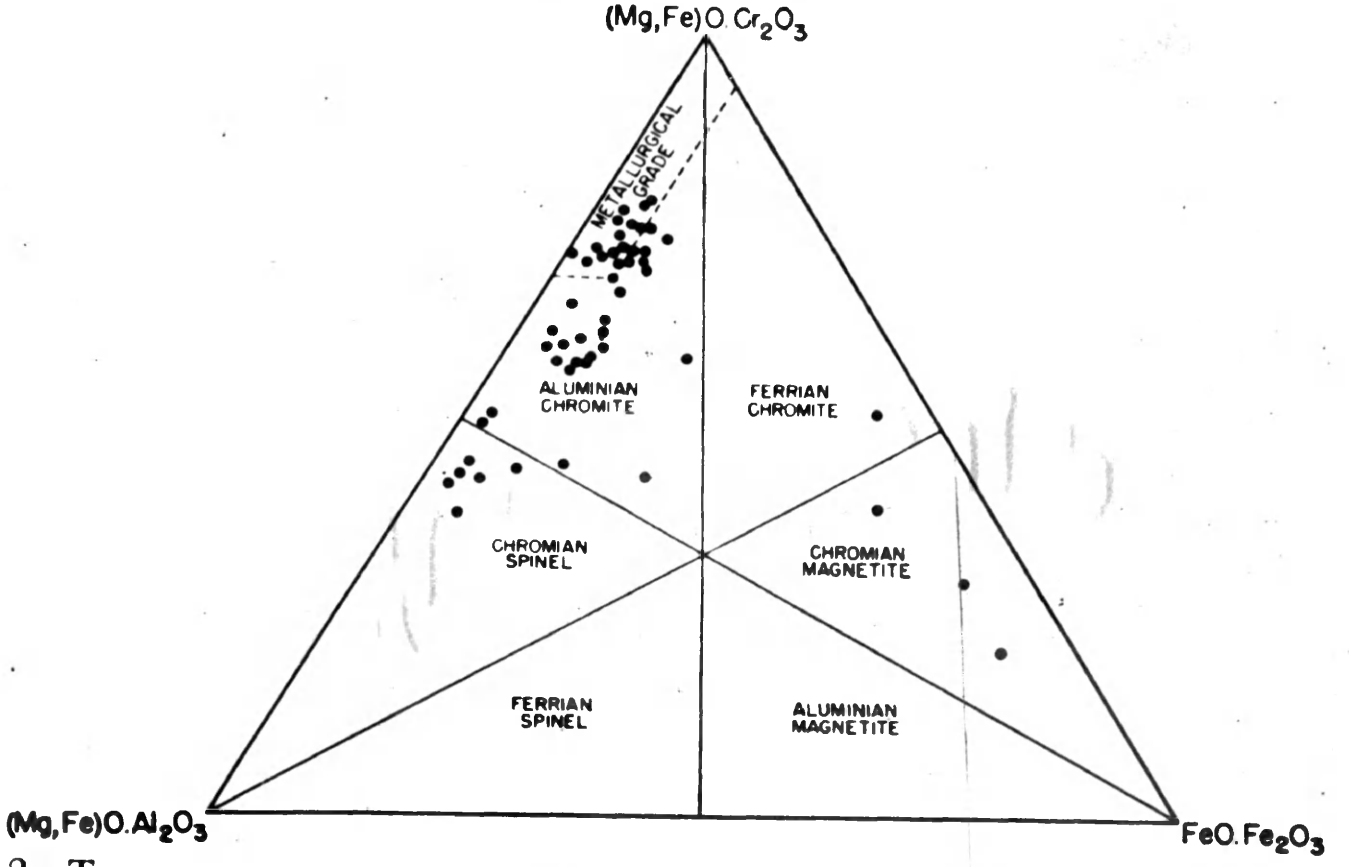

FIG 2—TRIANGULAR DIAGRAM SHOWING COMPOSITION OF CHROMITES AND RELATED MINERALS OF THE SPINEL GROUP IN MOL PER CENT (*After Stevens*).

Table 1 -- Analyses of Chromite Concentrates

Rollin E. Stevens, Analyst

Constituent	Composition, Percent[a]							
	1	2	3	4	5	6	7	8
Cr_2O_3	61.10	59.40	56.24	50.99	41.63	43.71	22.31	13.7
Al_2O_3	8.40	10.28	12.42	16.21	25.20	17.34	44.73	3.4
Fe_2O_3	4.31	3.30	4.44	3.44	3.38	7.22	7.04	53.0
FeO	10.56	14.09	12.72	14.65	12.29	19.27	7.22	27.4
MgO	14.86	12.62	12.47	13.40	16.19	11.00	17.04	1.2
MnO	0.15	0.14	0.37	0.23	0.13	0.21	0.16	0.2
CaO	0.10	0.14	0.12	0.14	0.16	0.34	0.14	0.3
TiO_2	0.11	0.14	0.21	0.17	0.30	0.79	0.20	0.5
SiO_2	0.28	0.12	0.38	0.42	0.36	0.34	0.60	0.3
H_2O^+	0.04	--	0.44	0.34	0.24	0.08	0.86	
	99.91	100.24	99.81	99.99	99.88	100.30	100.30	100.00
Cr/Fe ratio..	3.73	3.07	2.98	2.53	2.40	1.49	1.45	0.16

[a]Samples from: (1) Jalapa, Guatemala; (2) Twin Sisters Mountains, Washington; (3) Campo Formosa, Bahia, Brazil; (4) San Luis Obispo, California; (5) Paraguana Peninsula, Venezuela; (6) Stillwater, Montana; (7) Camaguey, Cuba; (8) Casper Mountain, Wyoming.

Chromite is usually found in ultra-basis igneous rocks or their metamorphic equivalents such as serpentine--the most common gangue rock. It occurs disseminated or in compact masses, lenses, or stringers. Its origin has generally been ascribed to magmatic segregation, but recent

studies by Sampson 2/ and Ross 3/ indicate that some chromite may not

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2/ Edward Sampson: Chromite Deposits, in Ore Deposits as Related to Structural Features, Princeton Univ. Press, 1942, pp 110-125.

3/ C. S. Ross: The Origin of Chromite, Econ. Geol. (1931) 26, pp 540-545.

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be due to this, but may have been introduced after solidification of the rock magma or during its later stages.

Sampson recognizes the following structural types of chromite occurrences: (1) The "evenly scattered" type which never forms ore, but consists of accessory chromite disseminated through the rock; (2) The "schlieven-banded" which shows bands of concentrated chromite grains; (3) The "stratiform" class which is best represented by the Bushveld, where the chromite forms persistent bands; (4) The "sackform" type which consists of irregularly rounded ore bodies, commonly of nearly pure chromite grains interlocking, and (5) The "fissureform" type in which the introduction of chromite has been controlled by pre-existing fissures.

Thayer 4/ finds a correlation between the composition of the chromite

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4/ T. P. Thayer: Preliminary Chemical Correlation of Chromite with the Containing Rocks, Econ. Geol. (1946) 41, pp 202-217.

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and the associated rocks. According to him, high-alumina chromites occur in peridotitic masses which contain feldspathic members, while high-chrome chromites occur in feldspar-free periodotites low in alumina and iron. The high-iron chromites of the Bushveld type apparently resulted from crystallization in pyroxenic environments deficient in alumina and relatively rich in iron.

According to Coulson 5/ the chromite deposits of Baluchistan occur

5/ A. L. Coulson, Chromite, Bulletins of Economic Minerals No. 2, Records of the Geological Survey of India, 1945.

as veins and irregular segregations in serpentine formed by the alteration of enstatite-peridotites (saxonites) of Upper Cretaceous age. The saxonites are traversed by numerous doleritic dikes which, when very thick, approximate in their central parts to gabbros. The saxonites themselves are rarely found fresh, and the abundant olivine they contain is serpentinised. Besides enstatite, altered to bastite, the saxonites contain picotite, the chrome spinel, which fact indicates a genetic connection between the saxonites and the chrome-ore deposits. The chromite is regarded as a magmatic segregation from the saxonitic magma.

Chromite deposits are widely distributed throughout the world and the principal chromite-producing countries of the world are Cuba, Greece, Turkey, Yugoslavia, USSR, Southern Rhodesia, and the Philippines. Countries with smaller production in recent years are Canada, Guatemala, Brazil, Albania, Bulgaria, Cyprus, India, Pakistan, Iran, Japan, Sierra Leone, and Australia.

World Production and Consumption: In response to increased demand from the iron and steel industry, world production of chromite expanded greatly, rising to nearly 190,000 metric tons as early as 1914. This was more than treble the output in 1900. In 1929, more than 600,000 tons were mined. Production naturally fell off during the depression years, but subsequent recovery was so rapid that by 1934 the output was again at a high level. Since that time the world production of chromite has been continuously increasing from year to year, especially

during the war years. In 1943, world production reached the all-time high of 1,973,000 metric tons. Table 2 on the next page shows the world production of chromite in 1941-48 by countries in metric-tons.

Whereas, many of the steel-alloying elements are found in commercial deposits in only a few countries, chromite supplies are distributed rather widely. The world sources of chromite have moved from locality to locality, usually following the discovery and development of newer deposits or the depletion of the old ones.

In historical order the major production has shifted from the United States to Russia, to Turkey, to Russia, to New Caledonia, to Southern Rhodesia, and back to Turkey.

The United States, the largest consumer of chromite, depends entirely on foreign sources, as domestic production is insignificant.

The following Table 3 shows the amount and tenor of ore consumed in the United States.

Table 3 -- Quantity of Chromite and Tenor of Chromite Ore Used by Primary Consumer Groups in the United States in 1940-1948[a]

Year	Total Chromite Consumed		Tenor of Ore Pct. of Cr_2O_3		
	Gross Weight Short Tons	Average Tenor pct. of Cr_2O_3	Metallurgical	Refractory	Chemical
1940	562,915	45.0	50.5	35.8	47.2
1941	800,290	44.3	50.1	34.8	46.3
1942	891,950	43.2	48.5	34.0	44.8
1943	964,600	43.8	48.5	34.0	44.7
1944	848,449	44.1	49.4	34.2	45.7
1945	808,120	43.8	49.1	34.2	45.0
1946	734,759	43.3	49.1	34.2	44.9
1947	833,357	41.1	47.4	35.2	44.7
1948	875,033	42.7	48.2	33.8	45.5

[a] Mineral Yearbook 1948

Table 2. World Production of Chromite 1941-48, by Countries, in Metric Tons
(Compiled by B. B. Mitchell: From Mineral Yearbook 1948)

Country	1941	1942	1943	1944	1945	1946	1947	1948
North America:								
Canada	2,152	10,393	26,846	24,543	5,221	2,821	1,961	1,467
Cuba	163,175	286,470	354,152	192,131	172,626	174,350	159,209	116,624
United States	12,935	102,400	145,259	41,394	12,676	3,726	860	3,283
South America:								
Brazil	5,944	5,776	7,813	4,721	1,490	a	a	1,626
Europe:								
Albania	20,000	5,000	a	a	a	a	a	16,500
Greece	16,240	24,300	15,500	18,295	2,413	9,062	8,000	1,500
Yugoslavia	a	100,000	65,000	a	a	a	a	a
Asia:								
Cyprus	4,816	2,936	7,986	469	1,070	1,158	5,283	6,899
India	50,940	50,380	33,789	40,190	31,642	45,511	35,274	a
Japan	54,510	67,540	58,520	71,135	28,539	7,079	2,347	9,340
Philippines	329,243	50,000	60,000	70,000	a	57,000	195,185	256,854
Turkey	135,714	116,342	154,512	182,108	146,716	103,167	102,875	285,353
USSR	a	400,000	325,000	a	a	a	a	a
Africa:								
Sierra Leone	13,907	10,726	16,306	9,851	578	10,301	16,769	7,886
Southern Rhodesia	322,123	348,314	287,453	277,051	186,318	151,433	155,149	230,703
Union of So. Africa	141,884	337,620	163,232	88,909	99,090	212,253	373,094	412,783
Oceania:								
New Caledonia	64,509	67,610	46,952	55,229	40,826	24,946	50,530	75,021

[a] Data not Available

It is of interest to note that the principal world reserves are of refractory and high-iron chemical grades whereas the present world consumption is mainly of the high-chrome types of ores. This fact implies the future necessity for a more extensive use of high iron chromite where such ores can be substituted for high-chrome types.

Grades, Specifications, and Prices: The three principal uses of chromite are (1) metallurgical (2) refractory, and (3) chemical; and the chrome ores and concentrates are usually identified and graded with regard to their suitability for these uses.

The following Table 4 gives representative analyses of marketable ores from various countries.

[a]Table 4. Representative Analyses of Chromite from Various Countries

Country	Pct. of Principal Constituents					Cr:Fe Ratio	Grade
	Cr_2O_3	Fe	Al_2O_3	MgO	SiO_2		
Cuba	36.03	10.93	27.85	17.02	3.31	2.25	Refractory
Greece	41.83	11.74	11.60	--	8.98	2.46	Refractory
India	51.04	18.2	9.32	12.00	4.88	2.50	Chemical
Pakistan	53.40	12.2	17.32	16.40	1.86	3.20	Metallurgical
Turkey	48.76	11.01	12.54	16.80	4.39	3.03	Metallurgical
Yugoslavia	52.59	11.14	9.90	16.79	4.58	3.23	Metallurgical
USSR	52.47	10.91	9.52	12.36	6.85	3.27	Metallurgical
Southern Rhodesia	49.87	11.50	11.11	15.94	6.39	3.00	Metallurgical
Union of So. Africa	43.97	19.55	15.69	9.99	3.23	1.54	Chemical
New Caledonia	46.42	9.83	16.03	17.84	4.56	3.23	Chemical
Philippines	34.72	11.61	11.38	15.93	3.72	3.05	Refractory

[a] Industrial Minerals and Rocks, A.I.M.E. 1949 page 202.

Specification for Metallurgical Grade

The suitability of chromite for metallurgical uses is usually determined by the ratio between iron and chromium in the ore. Iron increases the fusibility of chromite, making it less desirable for refractories; whereas a high-iron content renders chromite less usable for making ferrochromium. The usual ratio of chromium to iron in commercial chromite is about 2.5:1. The ratios of chromium to alumina, to magnesia, and to silica are important also because these constituents increase the amount of slag made in ferrochromium smelting and thus increase the metallurgical loss of chromium.

Specifications for metallurgical chromite normally require a minimum of 48 percent Cr_2O_3, with a Cr:Fe ratio of 3:1. Penalties and premiums on Cr_2O_3 and the Cr:Fe ratio usually are based on these minima. Silica is usually limited to 5 percent, as it is undesirable in ferrochromium except for making a few special alloys. Generally a hard, lumpy ore is specified, but certain metallurgical practices permit the use of a soft ore or chromite concentrates. Usual specifications call for 6-inch maximum size, with not more than 10 to 15 percent through a 1/2-inch screen.

Specifications for Refractory Grade

The quality of refractory ore depends not only on the percentage of chromic oxide present, but also on the percentage of other constituents present. Refractory ores should be high in Cr_2O_3 plus Al_2O_3, and relatively low in Fe and SiO_2. They are used in making chrome brick, chrome-magnesite brick, plastic cement, and other refractory products. The principal limiting factor in the refractoriness of chrome brick is the silicate binder rather than the chrome itself.

Therefore the amount of silica and fluxes such as lime must be kept to a minimum. A typical analysis of chromite refractories is as follows: SiO_2 9.36 percent, FeO 21.06 percent, Cr_2O_3 43.97 percent, and MnO 0.80 percent. In industrial practice, an excess of MgO is added to all chrome ores to combine all the silica in forsterite during firing. The following specifications are in use in the United States for refractory chromite (Specifications, American Ceramic Society).

		Percent
(1)	Cr_2O_3	40-50
	Fe_2O_3	15 (maximum)
	SiO_2	8 (maximum)
(2)	Cr_2O_3	40 (minimum)
	Fe_2O_3	15 (maximum)
	SiO_2	6 (maximum)

Specifications for Chemical Grade

Chemical-grade ore should be as high in Cr_2O_3 and as low in SiO_2 and Al_2O_3 as possible. In this case specifications are more variable than for the other grades and generally are determined for each ore on a basis of price, availability, and past experience. Ore that contains about 47 percent Cr_2O_3 and that is free of sulphur is usually desired for this grade. The silica content should be under 8 percent and preferably under 5 percent. High silica results in the formation of excessive amounts of sodium silicate, which is a waste product in the manufacture of some chromium salts. The use of low-grade ores is objectionable because of increased bulk of ore to be handled, lower furnace efficiencies, and increased loss of other chemical re-

agents due to combination with impurities. Fine ore is slightly more desirable than massive ore on account of the slight saving in crushing, and for this reason fine concentrates of chromite are acceptable to the chemical industry.

Prices

In United States prices of imported chromite are quoted on the long-ton basis, f.o.b., at eastern or southern ports, with freight differentials for delivery to the west coast. The quoted prices are subject to penalty if specifications are not met. Refractory and chemical ores sell for about half to two-thirds the price of standard metallurgical ores. Since 1930, the base price of 48 percent Cr_2O_3 with a Cr:Fe ratio of 3:1 has ranged from $18 to $52.80 per long ton. Between 1941 and 1945, prices were stabilized by OPA ceilings and Metal Reserve purchases, with refractory ores at $36.50.

Table 5 shows the price quotations for various grades of chromite in 1948, as given by the magazine Steel.

Table 5. Price Quotation for Various Grades of Chromite in 1948 (Steel)

Source	Cr_2O_3 pct	Cr:Fe ratio	Prices per long ton[1]	
			Beginning of year	End of year
Indian and African	48	3:1	$39.00	$39.00
Do	48	2.8:1	37.50	37.50
Do	48	--	31.00	31.00
South African (Transvaal)	50	--	29.50	29.50-30.50
Do	48	--	28.50	29.00-30.00
Do	45	--	26.50	26.50
Do	44	--	25.50-26.00	25.50-26.00
Rhodesian	48	[2]3:1	39.00	39.00
Do	48	--	30.00	30.00
Do	45	--	27.00-27.50	27.00-27.50
Brazilian	48	[2]3:1	43.50	--
Do	44	[2]2.5:1	33.65	33.65
Domestic (Sellers nearest rail)	48	3:1	39.00	39.00

[1] Gross ton f.o.b. cars, New York, Philadelphia, Baltimore, Charleston, S. C., plus ocean freight differential for delivery to Portland, Oreg., and for Tacoma, Wash.

[2] Lump

In 1948 the chrome brick were quoted at $69 per short ton and chrome-magnesite brick at $80 per short ton, f.o.b. at the plant.

The price of chrome ore at present (according to Eng. and Min. Jou. Aug. 1950) is $17.30 at $18.30 per long ton, f.o.b. cars Atlantic ports for a grade of 45 percent Cr_2O_3 without specifying the Cr:Fe ratio; while for a grade of 48 percent Cr_2O_3 with a Cr:Fe ratio of 3:1 the price is $35.00 at $30.00 per long ton.

The prices of chrome ore prevailing in the British Empire at present (according to the Mining Journal, London, July 21, 1950) are as follows:-

		£	s	d	
Chrome Ore:	Turkish refractory Basis 43 pct Cr_2O_3	13	9	5	ton, ex ship
	Rhodesian refractory	10	19	2	ton, ex ship
	Rhodesian (lumpy) Metallurgical	11	5	2	ton, ex ship
	Transvaal Chemical Basis 48 pct Cr_2O_3	9	6	8	ton, ex ship

Chromite was freed from Government control in 1947 for the first time in seven years. However, the United States Government, under the authority of the Stockpiling Act of 1946 (Public Law 520) is still a potential buyer of both domestic and foreign chromite, but at prices directly competitive with those paid by industry. Stockpiling activities under the above act are the responsibility of the Munitions Board, acting under the direction of the Secretaries of War, Navy and the Interior. Metallurgical and refractory grades of chromite are classified by the Munitions Board as Group A (materials of a strategic and critical nature for which stockpiling is deemed the only satisfactory means of insuring an adequate supply for a future emergency). The Bureau of Federal Supply has no price schedule for the purchase of chromite, and any offers for sale should be accompanied by a statement as to price expected.

Since the United States is the largest consumer of chromite and depends entirely on foreign sources, no tariff is levied on the imported chromite ores.

Uses of Chromite: The world's production of chromite finds its way into the following three heads in the order of their present relative importance:- metallurgical uses, refractory uses, and chemical uses. Table 3 clearly shows the consumption of chromite and tenor of ore used by the above three heads in the United States for the years 1941-47.

Metallurgical Uses: The chief metallurgical uses of chromite are in the preparation of alloys in which the major constituents are chromium and either iron, nickel, or cobalt. Depending upon the percentage of chromium used, and on the other metals present in the alloys, a large range of properties may be obtained as regards strength, toughness, hardness, resistance to wear, chemical corrosion, oxidation and mechanical weakness at high temperatures, and high electrical resistance. The result is that the percentage of chromium varies from a fraction up to more than 60 percent. Ferrochrome, the most important alloy of chromium, iron, and carbon, was originally made from high-grade chromite ores in clay crucibles at a prohibitive cost; nowadays, however, it is produced in electric furnaces much more cheaply. Ferrochrome always contains over 60 percent of chromium; however, it tends to take up large amounts of carbon in its manufacture, which is an undesirable constituent, and the quality and price are determined in inverse proportion to the carbon content.

Chromite and its compounds are used to a small extent in preparation of metallic chromium and in chrome plating. During the last three decades, the chromium plating industry has developed very rapidly because of the three principal characteristics of chromium plate: first, readiness with which it is brightly polished; second, the resistance of chromium to corrosion; and third, its hardness and resistance to abrasion by sliding or rubbing wear.

Refractories: The second largest use of chromite is in the manufacture of refractory materials such as brick and cement. Its use here depends upon its chemical stability and

its neutral character, which permits its use as a parting between silica and magnesite (basic) bricks. Chromite refractories are very resistant to corrosion by metals, slags, and vapors. They have a fairly high melting point, relatively high thermal conductivity, and relatively low electrical resistivity.

The ratios of chromium to iron, alumina, and silica in chromite ores are important in the manufacture of refractories. The normal ratio of Cr_2O_3 to iron varies from 2:1 to 3:1; when the iron content increases in respect to the chromium content, the ore becomes less usable on account of its increased fusibility. Lump ore is preferred by manufactures of chromite bricks.

Chromite bricks have fair resistance to abrasion, but are said to be objectionable for furnace bottoms because of their inability to withstand the severe mechanical erosion encountered there. They are, however, well suited for lining along the slag line of basic open-hearth steel furnaces in which a magnesite refractory bottom and silica brick sides and roof are used. Among the more recent applications of chromite brick is its use as a lining for kilns used for drying sulphite paper pulp. This application is based upon the resistance of chromite to corrosion from the sulphurous gases liberated in the kilns.

Chemical Uses: About one-fourth of the chromite consumed in this world is manufactured into chemicals for the electroplating, dyeing, tanning, and pigment industries.

The chromite used in the chemical industry is the source of chromium for the manufacture of the chromates and dichromates, chromic acid, chromium acetate and chloride, chrome-alum, chrome yellows and

greens, etc. The dichromates are used by alizarine manufactures, chrome-alum manufactures, chemists, and druggists; for purifying certain coal tar products; mordanting and fixing dyes in wool, silk, and also certain printed goods; for purifying and bleaching oils; for oxidizing purposes; for tanning leathers known to the trade as chrome leathers; for battery and other electrical uses; in aniline colour works; in making artificial perfumes; in photography; etc.

Lead chromate is the essential constituent of the various pigments known as chrome yellow, Paris yellow, Cologne yellow, etc. The chrome-yellow colors, mixed with Prussian blue, give the chrome and Brunswick greens. True chrome green is chromic oxide, Cr_2O_3, and with ultramarine green, is used for imparting a green color to glass, porcelain, etc.

Chromates and dichromates are all therapeutically dangerous, being strongly caustic and destructive of the red corpuscles of the blood. They have, however, been used as external caustics and antiseptics for ulcers, etc., with success.

PART II

BENEFICIATION OF CHROMITE ORE

General Aspects of Beneficiation: The response of a chromite ore to beneficiation depends to a great extent on the character and extent of the impurities present. Impurities such as silica, which are purely mechanical, can be removed with little difficulty, but silica as a rule is only a minor impurity. However, impurities which are chemically combined with the valuable mineral cannot be removed by usual mineral dressing processes. For example, when the low Cr_2O_3 content of chromite is due to the partial substitution by Al_2O_3 or Fe_2O_3, rather than to an admixture with other minerals, the ore is not usually amenable to concentration. Where magnetite, however, has been formed by Fe_2O_3, it can sometimes be removed magnetically. Beneficiation is not often practiced with chromite ores because, although it may improve the Cr_2O_3 content, it seldom improves the ratio of chromium to iron.

The pure mineral chromite $FeO \cdot Cr_2O_3$ consists of ferrous and chromium oxides chemically united in equal molecular proportions. Unfortunately, pure chromite, as defined above, appears to be a rare exception. In most chrome ores the mineral may be considered a combination of spinel, $MgO \cdot Al_2O_3$, and chromite, with the latter predominating. The ratios between the four common constituents FeO, MgO, Al_2O_3 and Cr_2O_3 vary greatly, and other minor constituents such as TiO_2 and Fe_2O_3 may also be present.

In the mechanical concentration of chromite ore, the maximum grade of concentrates that can be produced is then limited by the chemical composition of the chromium mineral present. Pure chromite contains 68 percent Cr_2O_3, but the Cr_2O_3 content of the chromium minerals in commercial chromite ores varies between 40 and 60 percent, and the average is not far from 55 percent. Chromite is usually associated with serpentine.

Other silicates, quartz, lime, dolomite, magnetite, ilmenite, and other iron minerals, are frequently present.

Provided that the chemical composition of the isolated chromite mineral is suitable, its amenability to concentration depends upon the kind and amount of the various gangue minerals present and the amount of crushing necessary to separate the chromite from them.

A relatively small amount of chromite is concentrated by milling. In most cases the main product is simply hand-sorted. This is especially true in those parts of the world where labor is cheap, as for example, India, Pakistan, Africa, Turkey, Russia, etc. Such chromite deposits as are known in the United States can not be worked in this way on account of one or both of the following conditions: high cost of labor and finely disseminated impurities. There are, however, several deposits in the United States, Canada, and Alaska which may compete with imported ores by efficient use of modern ore dressing and milling methods.

Concentration Methods

Tabling: Scarcely any quantitative data on concentration of chromite ores have been published. During the early thirties a limited amount of data was published by Doerner 6/, who carried out table concentrating

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6/ H. A. Doerner, "Concentration of Chromite," U. S. Bureau of Mines, R. I. 3049, 1930.

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tests on samples of chromite ores from several of the more important domestic deposits.

Some of the more important generalizations obtained by Doerner are as follows:

(1) If the mineral is disseminated in rather small crystals and the ore easily crushed, it should be put through a jaw crusher and rolls until it all passes through a 35-mesh screen, and the -100 mesh material should then be removed. By this method of crushing and screening very little chromite is reduced to slimes.

(2) The table does excellent work on the -35 mesh plus 100 and puls 200-mesh products. The minus 200-mesh product, however, is difficult to treat since it does not travel with the table throw. In this case the best solution is to pass the minus 200-mesh material over a small, especially made circular slime table.

(3) When the chromite ore contains a considerable amount of magnetite, ilmenite, zircon, etc., they will collect in the concentrates. These impurities can be removed magnetically. Thus a combination of tabling and magnetic concentration gives a high recovery and valuable by-products.

Chromite settles rapidly and beds well on the tables, but it is sluggish and does not travel. Only a table having a sharp stroke (kick) will successfully separate it from the gangue serpentine. This rapid settling and sluggishness is a characteristic which is noticeable through all operations in the chromite mills.

Experience has shown that the best results are obtained with long tables having a sharp stroke, the length of stroke not being as important. The tables are set flat to keep the ore bed as shallow as possible. Dressing water should commence close to the head end of the table. Raising the concentrate discharge end from 1/2 to 1 inch is beneficial on some tables.

It is general practice to reconcentrate the middlings product from

the first set of tables without regrinding. The reconcentration permits better control of the grade of the concentrate. An extraction of above 65 percent is readily made with the simplest of equipment. To increase extraction and maintain the grade of concentrate required by the consumers means a greatly increased capital expenditure for plant. With a plant equipped for fine grinding and sand and slime concentration, an extraction above 80 percent may be expected.

In general, after proper grinding and classification, tabling will produce a satisfactory separation of chromite from the minerals with which it is usually associated. The presence of low-grade chromite (chrome spinel) is responsible for most of the limitations of concentration. As chromite concentrate is bought on the basis of 45 to 48 percent chromic oxide content, the grade of concentrate is at all times a controlling factor in milling operations. It is, therefore, sometimes necessary to sacrifice somewhat on extraction to permit taking a clean concentrate.

In Canada 7/ the general milling practice on chromite ores in the

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7/ L. K. Fletcher, Concentration of Chromite, The Transactions of the Canadian Mining Institute, Vol. 22, 1919, p. 123.

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past has been to grind the ore between 20 and 30-mesh and to separate this product into sands and slimes which are treated separately. The first set of tables make a concentrate, middling and tailing. The middlings are sent to a second set of tables without grinding, making the final concentrate and tailing. By this above method of concentration it was possible to obtain as high as 80 percent recovery.

In 1936, Koster 8/ of the United States Bureau of Mines, conducted

8/ Koster, Progress Report - Metallurgical Division, R. I. 3322, U. S. Bureau of Mines, 1936.

tests on the Montana Chromite ore, utilizing gravity, flotation, and magnetic separation methods.

The principal conclusions of this investigation were as follows:

(1) By gravity concentration a total recovery of 93 percent is possible producing concentrates containing 44 percent Cr_2O_3.

(2) Flotation of the entire feed will not readily yield as good concentrates or as high recovery as gravity concentration. Flotation, however, may be employed to a limited extent to supplement gravity concentration in order to obtain slightly better recovery.

(3) Magnetic separation does not seem applicable to the improvement of the quality of the gravity concentrates, and it is too expensive to compete with the gravity or the combined gravity and flotation methods for treatment of the entire feed.

Flotation: Various investigators have tried to float chromite commercially, the date of investigation extending as far back as 1932. Some of the milestones in the development of flotation of chromite are as follows:

According to Coghill and Clemmer 9/ chromite is amenable to concen-

9/ Coghill and Clemmer, Soap Flotation of Nonsulphides, A.I.M.E., T.P. 445, 1932.

tration by soap flotation, the reagents being pine oil, sodium oleate, and oleic acid.

An innovation in flotation reagents was patented by Arnold 10/ in

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10/ Arnold, "Method of Producing a Concentrate of Chrome Ores" Patent No. 2,082,817, 1934.

1934. He pretreated the ore with a small proportion of a complex acid of the type of phosphomolybdic or phosphotungstic acid.

In 1937, Davis 11/ and his co-workers used soap flotation, in which

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11/ Davis, "Ore Testing Studies," R.I. 3328, U. S. Bureau of Mines, 1937.

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sodium oleate was replaced by another anionic reagent, Ninol 494.

MacDonald 12/ in his paper stated that he found sodium metaphosphate

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12/ MacDonald, "A Useful New Selectivity Modifier in Non-sulphide Flotation," Min. and Met., vol. 18, 1937.

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an excellent chromite activator and limestone depressant, when oleic acid is used as an activator.

Finally, the latest patent has been granted to Havens 13/ for his

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13/ Havens, Froth Flotation of Chromite with Fluoride, Patent No. 2,412,217 - 1946.

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process of floating chromite. This is a process for the beneficiation of chromite ores, which comprises agitating and aerating an acqueous pulp of such an ore in the presence of hydrofluoric acid, and a long-chain fatty acid at a pulp acidity of between 1.5 and 5.5.

In some chromite ores which are hand picked, the amount of gangue present is small, usually not more than 25 percent by weight, and mostly there is complete liberation occurring below 150-mesh. In such cases it is beneficial to treat slimes by flotation, in which the gangue (serpentine, olivine, etc.) is floated instead of the valuable material. The usual process for floating quartz is followed and a very high recovery and efficient operation results. Naturally, in this case the percentage of Cr_2O_3 in the concentrate is not very high, but is good enough to be mixed with higher grade concentrates from other stages of concentration to obtain a marketable product.

Magnetic Concentration: Magnetic concentration methods have been tried to a limited extent in the beneficiation of chromite ores. This is especially true in cases where the Cr_2O_3 content of the ore is low and where minerals having higher permeability -- as for example, magnetite, ilmenite, rutile, zircon, etc. -- are present. The above-stated minerals are then obtained as by-products, and the over-all return from the operation is increased considerably.

It is a usual practice to apply magnetic concentration methods at the last stage of beneficiation, for the following reasons:-

(a) Magnetic treatment involves considerable expense and the tonnage to be treated at the final stage is comparatively smaller than the first or the middle stages.

(b) It is easier to adjust the grade of the concentrate to meet the required specifications at that stage.

(c) The by-products obtained at the final stage are the cleanest and usually do not require further treatment.

Sometimes magnetic concentration methods are applied at the last

stage, even when the above-stated by-product minerals are not present in the ore. In this case the aim is to remove iron in the form of magnetite, hematite, and higher iron-bearing chromite material to reduce the ratio of chromium to iron in the concentrate. This is especially necessary in the ores or concentrate which are marketed as metallurgical grade, in which the chromium to iron ratio should be 3:1.

During World War II, magnetic concentration methods were successfully applied by the Defense Plant Corporation 14/, which set up a proces-

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14/ How Krome Corp. Worked the Black Sand Deposits of the Oregon Coast. Mining World, Vol. 6, Jan. 1944, p. 7.

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sing plant at Beave Hill, Oregon to handle concentrates produced by Krome Corporation as well as those from the Humphreys Gold Corporation. Its primary purpose was to raise the chrome content of the custom concentrates to shipping grade, that is, to 40 percent or better and recover by-product minerals such as magnetite, ilmenite, zircon, etc.

The above process was developed at the laboratory of the Arizona Bureau of Mines and involves treatment of dried concentrates by magnetic separation, flotation, and tabling.

Humphreys Spiral: In recent years an entirely new metallurgical process or method of ore beneficiation which has been applied to many ores and minerals is the installation of Humphreys Spiral. The Spiral has been successfully applied to the beneficiation of chromite ores by the Humphreys Gold Corporation at its property near Bandon, Coos County, Oregon, in 1942 15/. By a simple enough application of centrifugal

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15/ J. S. Hubbard, Spiral Concentration, Mining World, Sept. 1948.

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forces, consisting of passing pulp through a system of spiral launders, metallurgical results have been achieved which equal or surpass those of orthodox methods, and a remarkable degree of simplicity and economy has been maintained.

At the above plant 30 spirals treated 1,000 tons per day of fine chrome-bearing sands averaging 6 percent Cr_2O_3 which was concentrated in the spirals to a product containing about 25 percent Cr_2O_3. Recovery was better than 90 percent.

A detailed theory of operation of the Spiral is given by George W. Gleeson 16/.

16/ George W. Gleeson, "Why the Humphreys Spiral Works," Eng. and Min. Jou., March 1945, p. 85.

Figure 3 illustrates concentrating action and position of products in the Spiral.

Figure 4 is a highly conventionalized diagram of a section of the spiral and the flowing stream.

Since the first plant installation in 1943 on Oregon chrome beach sands, use of spiral in plant operation has steadily broadened into new fields of beneficiation of minerals, which, due to the difference in specific gravity and size range, are amenable to concentration by this method. This growth is due to the recognition of certain outstanding features of spiral concentration which together result in marked economy. These are principally the low initial cost, installation cost, maintenance cost, and operating cost. Another very important factor is the extremely small floor space required for a spiral plant of large capacity.

It seems that the Humphreys Spiral is ideal for concentration of chromite and fits in very well in the flowsheet both from the point of view of economics and ease of operation. It should be clearly understood, however, that spirals alone are not the final answer. To acquire the maximum benefit from the spiral it must be used in conjunction with other gravity methods. The spiral is a comparatively new milling equipment, and it has not yet been tried fully or used extensively; but from the encouraging promise it has shown, it will be one of the most important gravity concentrators. As far as chromite milling is concerned, there is no substitute.

Sink-Float Concentration: Present methods of sink-float concentration may be applied to the coarse (1/4 or 3/8 in.) fraction of any ore or mineral mixture provided only (1) that valuable and gangue minerals differ in specific gravity, and (2) that the dissemination is sufficiently coarse that an economically clean light fraction is freed in sufficient quantity by crushing to, say, 3/4-in. as a minimum. If finer crushing is required to free clean float, the easily treatable 1/4-in. fraction is likely to be too small in weight to justify the relatively elaborate installation for medium cleaning and reconditioning; if only heavy mineral is freed by coarse crushing, the medium density required is too high except in special cases of low-gravity minerals.

The heavy density method of concentration has never been used commercially for beneficiation of chromite ores, not because chromite cannot be treated by this process, but only because no opportunity has been given to use this method. The disadvantage of this method is that it can treat only very coarse size, the minimum size treatable being 1/4-in., and most of the chromite ores do not show an appreciable amount of

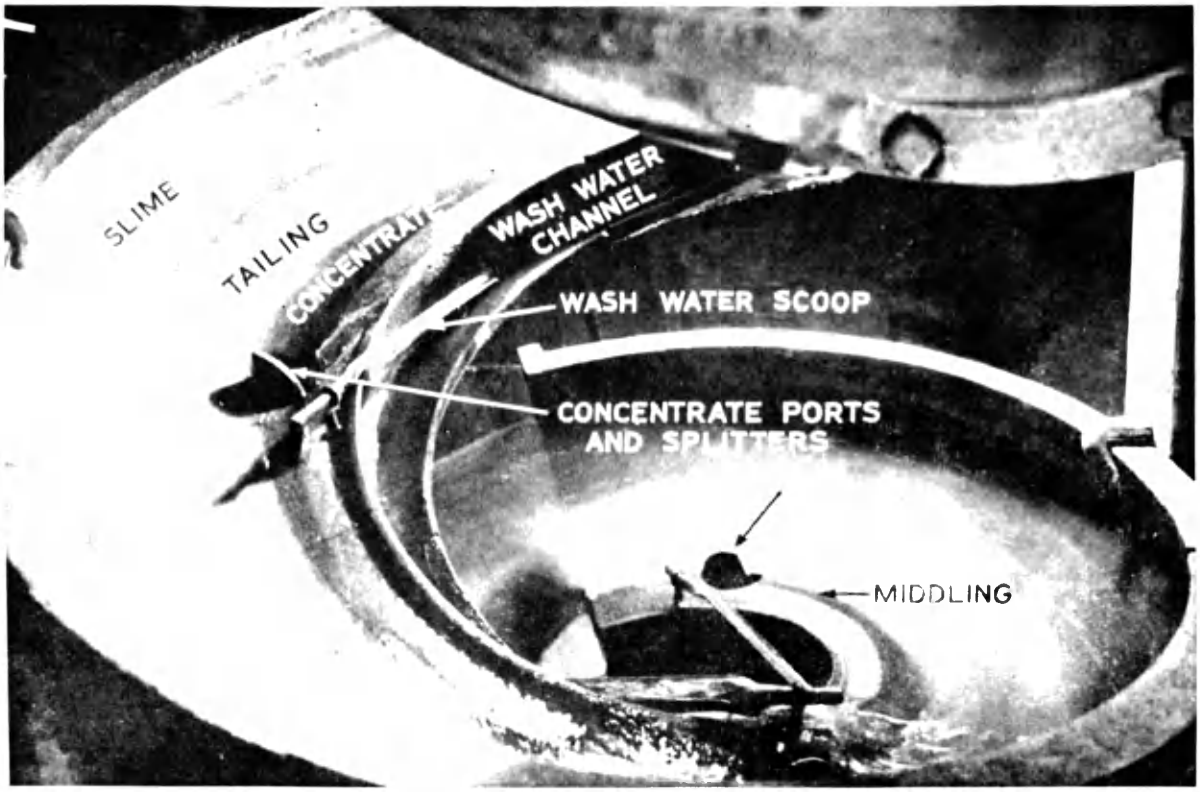

Fig. 3—Photograph Illustrating Concentrating Action and Position of Products in the Spiral

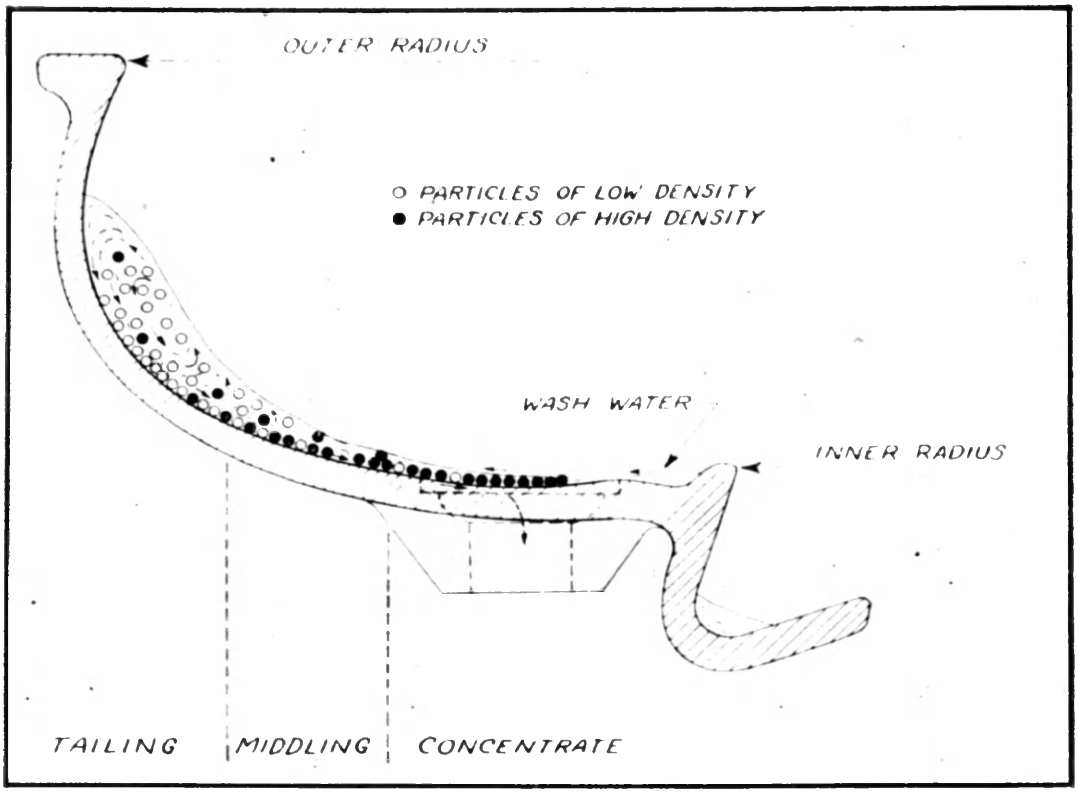

Fig. 4—Cross-section of Spiral Stream Showing Relative Position of Spiral Products.

liberation of the valuable mineral at that size. There are certain chromite ores, however, which show quite an appreciable amount of liberation at such coarse sizes, and in those cases heavy-density separation is attractive as a cheap and efficient method of making a close gravity separation of coarse and medium-sized material. The advantage of this process is that a large tonnage of the gangue in the preliminary steps of chromite concentration is eliminated.

In treating an ore like chromite, the function of sink-float separation is to discard tailing; hence the flowsheet in commercial practice comprises (a) crushing to a size that frees tailing (at present 3/4-in to 2-in.); (b) screening out undersize too fine for satisfactory sink-float treatment (1/2- to 3/8-in. at present); (c) washing oversize to remove slime and soluble salts; (d) floating tailing in a heavy medium; (e) crushing heavy-medium concentrate and joining it with undersize from raw feed for treatment by gravity concentration, flotation, etc.

The Weinig Concentrator: One of the latest developments in milling, for the treatment of marginal ores, is that of Weinig Concentrator, 17/ invent-

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17/ The Weinig Concentrator, Colorado Iron Works Company, Bulletin No. 50, 1950.

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ed by A. J. Weinig, the ex-director of the Experimental Plant, Colorado School of Mines. The Concentrator has been developed to bridge the gap between heavy density separations and flotation or other methods of treating extremely fine size of liberated mineral and gangue. The Concentrator is characterized by low power and water consumption, and a high unit capacity, with attending notable economics.

The concentrating action in the Weinig Concentrator is effected in a very unique manner. Raw ore feed passes into the center of the rotor and is expelled through peripheral ports, and the bottom third of the rotor comprises an air pocket in which air is rhythmically compressed and expanded by revolving action of the rotor. An impeller at the bottom of the rotor diffuses the water which rises in eddying currents to the top of the tank, carrying off the light constituents of the feed, thus effecting a very efficient separation of the lighter gangue from the heavier valuable material.

Some of the variable mechanical features of the Weinig Concentrator are: rotor speed, rotor distance above the tank bottom, hydraulic water setting and rate of feed.

The above Concentrator is capable of making efficient separations in a size range of 1/4-inch to between 28 and 35-mesh with a difference in specific gravity as low as 0.20. The Concentrator, however, is not recommended to replace sink and float processes, except under unusual conditions, but rather to supplement these processes in the fine size ranges. Its capacity is surprisingly large in relation to power and floor space requirements. Machine sizes are designated by the inside diameter of the concentrator tank in inches and a 14-inch Concentrator has a capacity of from 3 to 6 tons per hour of minus 1/4-inch feed, the variation depending upon the proportion of sink product in the crude material.

The capacity and metallurgical performance of the Weinig Concentrator depends entirely upon the characteristics of the material to be treated. It is not applicable to ores with finely disseminated minerals in which gangue and mineral are completely unlocked at the treatment size. Complete unlocking, however, is not essential if middlings can be tolerated

in the sink or float products.

The Weinig Concentrator is still in its infancy and still requires a considerable research and investigation. By taking into consideration the nature and character of the chromite ore under investigation, which appears to suit the requirements of the Concentrator, there are possibilities that the chromite ore will be amenable to concentration at coarse sizes up to 48-mesh.

PART III

LABORATORY INVESTIGATIONS OF CHROMITE ORE FROM BALUCHISTAN, PAKISTAN

The Problems Involved: A 65-pound sample of the chromite ore from the province of Baluchistan, Pakistan, arrived at the Colorado School of Mines at the beginning of June, 1950, and the investigation started soon thereafter. The sample was obtained through the courtesy of the Pakistan Industries Ltd., Karachi, Pakistan, which is in charge of chromite mining in Pakistan. An analysis of the typical ore analyzed by Messrs. Hughes and Davies of Bombay, India, was also received from the same source. The analysis was as follows:

		Percent	
Chrome Sesqui Oxide	Cr_2O_3	- 42.86 - Cr - 29.35 pct.	
Ferrous Oxide	FeO	- 14.05 - Iron - Fe - 10.92 pct.	
Alumina	Al_2O_3	- 17.58	
Silica	SiO_2	- 7.84	Cr:Fe ratio = 2.7:1
Lime	CaO	- Trace	
Magnesia	MgO	- 17.67	
		100.00	

The above analysis indicates that the chrome ore is a medium grade one and difficult to classify as of metallurgical, chemical, or refractory grade. But this is sure: that as it stands it will not bring any price if sold in the chromite-market, because it does not possess the required specification for any one of the above three grades. Since the alumina content is low, it is not of refractory grade. This fact leaves us to work with the remaining two grades, metallurgical and chemical. Both the above grades require a minimum of 45 to 48 percent Cr_2O_3, low iron and low silica, thus the possibilities of treating the ore to meet the required specifications for chemical and metallurgical grades seem very attractive.

Looking at the current prices (given by E. and M. J. Aug. 1950) for different grades of chromite ore, it is found that any ore containing 45 percent Cr_2O_3 is worth $17.00 per long ton. Thus if the above ore is treated to increase its Cr_2O_3 content to 45 percent, it will bring a reasonably good price, which may or may not pay for the mining and milling costs.

The first problem involved, then, is to increase the Cr_2O_3 content of the ore to at least 45 percent or over.

Again looking at the price, it is noted that a chrome-ore or concentrate having a Cr_2O_3 content of 48 percent, with a chromium to iron ratio of 3:1, will bring $37.00 per long ton. This means that this grade of material is worth $20.00 more per long ton than the one with the Cr_2O_3 content of 45 percent. In short, an increase of 3 percent, with the chromium to iron ratio of 3:1, is worth more than twice as much. Of course it is the second requirement of chromium to iron ratio of 3:1 which is responsible for the two-fold increase in price. Thus, if the ore is so treated that the Cr_2O_3 content is raised to 48 percent, at the same time obtaining the chromium to iron ratio of 3:1, it will definitely bring the top price of $37 per long ton, which will not only pay for mining and milling cost, but also yield a good profit.

The second problem involved, then, is to obtain a chromium-to-iron ratio of 3:1, with an increase of Cr_2O_3 content to 48 percent or above.

The above two problems at first seem to be very easy to solve. The ore as it is mined already contains about 42 percent Cr_2O_3, while the critical content is 45-48 percent -- that is, an increase of only 5-6 percent is required. In usual ore dressing treatments an increase of 6 percent in the content of the valuable mineral is looked upon as

easily attainable. However, the above problem of beneficiation of chromite is not as simple as it appears. As stated in the previous pages, chromite seldom occurs in its purest form (in which Cr_2O_3 content is 68 percent) in nature, and the usual marketable deposits contain not more than 55 percent Cr_2O_3.

A test was made to determine the maximum percent of Cr_2O_3 in the purest concentrate of this ore, and the super-panner concentrates showed that the Cr_2O_3 content of the cleanest product runs about 54 percent.

The above test indicates that there is a limit to the percentage of Cr_2O_3 in the concentrates; so that in no case will it be possible to obtain a higher Cr_2O_3 content than 54 percent. But the test definitely points to the fact that the above ore is amenable to concentration. Amenability naturally depends upon the nature and the amount of the various gangue minerals present in the ore.

Having made sure that the ore can be treated to increase the Cr_2O_3 content, the next step is to investigate the chromium-to-iron ratio. The given analysis shows that the chromium to iron ratio in the ore is about 2.7:1, which is less than the specified ratio of 3:1. The usual concentration methods applied to chromite in general increases the iron content along with that of chromium, so that the final ratio is little improved. This fact shows that the second problem is more difficult to solve than the first one, or perhaps there is no solution to this problem at all.

Of course, there may be possibilities of having free-iron-bearing minerals like magnetite, hematite, etc. which can be removed by magnetic methods, and which will increase the ratio. Also there may be possibilities of removing some of the higher iron-bearing chromite particles by

the same magnetic means in order to increase the ratio to the required limit.

A determination was made to ascertain the amount of free iron (as magnetite) present in the ore, and it was found that about 0.6 percent of free iron was present. The above test indicates that the amount of free iron is so small that magnetic separation would hardly be of any benefit in increasing the chromium-to-iron ratio. However, there are possibilities that the ratio may be increased by passing the final concentrates over a magnetic separation unit to remove the higher iron-bearing material. In this case it may not be possible to increase the ratio to the required limit, but may approach closely to the limit, so that the penalty usually applicable may be reduced.

From the above discussion of the problems involved, it is found that the chromite ore from Baluchistan offers good possibilities of concentration and is worthy of investigation.

Plan of Investigation: For a systematic study and a successful solution of an ore-dressing problem, it is absolutely necessary to draw a plan of investigations. This plan should be based on the following:

(a) The nature and the amount of valuable and gangue minerals present in the ore, (b) the size of the various mineral grains (c) the problems and aims involved in beneficiation (d) the concentration methods used on a similar ore in the past (e) modern concentration methods and equipment which have shown promise on a similar ore, and (f) other methods of concentration to which no opportunity was given because of the difference in character between the tested and to-be-tested ores. In no case should anyone lose sight of the first three factors on which

the application and success or failure of an investigation depends.

Based on the above principles, the following plan of laboratory investigations for the treatment of chromite ore from Baluchistan was made.

(1) Chemical and Spectrochemical analyses for detection and determination of major and minor constituents of the ore.

(2) Mineralogical and Petrographical Examination of the ore to determine the ore structure, texture, dissemination, and mineralogical constitution. The above information is absolutely necessary in determining the nature, and the amount of gangue minerals, the purity of the valuable mineral, and the size range at which liberation of the minerals may be attained.

(3) Screen-Sizing Tests and Analyses to determine the extent of liberation at different size ranges and determination of the best working range by analyses and graph.

(4) Grinding Tests to determine the time required to grind up to the economic point of liberation.

(5) Sink-Float Tests to investigate the possibilities of making an economic separation at coarser size.

(6) Tabling Investigations to determine the best size ranges to be used in tabling so as to obtain the highest Cr_2O_3 content, and the possibilities of cleaning the concentrates from other methods to increase their Cr_2O_3 content.

(7) Flotation Tests to investigate the possibilities of treating the slime and finer sizes (minus 100-mesh material).

(8) Humphreys Spiral Investigation to determine the best size ranges for this method for treating of slimes and finer sizes and to

investigate the possibilities of utilizing the spiral as the major concentration method in combination with flotation and tabling.

(9) Weinig Concentrator Test to investigate the possibilities of making an efficient separation at coarse sizes.

(10) Magnetic Separation Tests for separating the free-iron-bearing material and higher-iron-bearing chromite mineral to increase the ratio of chromium to iron to meet the required specifications.

Analytical Procedure: In an ore-dressing problem like this one it is absolutely necessary to establish an accurate and a quick method for the quantitative determination of the principal constituents of the ore and the products of concentration.

Several technical methods have been introduced for the above determinations by various authors of textbooks on quantitative analysis, U. S. Geological Survey 18/, American Ceramic Society 19/, etc.

18/ Analytical Procedure for Chromite Ores, American Mineralogist, vol. 29, 1944, p. 5.

19/ Analysis of Chrome Ore and Chrome-ore Refractory Products, Jou. of American Ceramic Society, Jan. 1941.

Various methods from different sources were tried out in the laboratory to determine the best and the most efficient method. The best method found was a modification of the Low, Weinig, and Schoder 20/ method,

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20/ Low, Weinig, and Schoder, Technical Methods of Ore Analysis, John Wiley and Sons, 1945.

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the analytical procedure for which is as follows:

(a) Place 0.5 grams of finely ground sample in a silver or nickel

crucible and make a sodium peroxide fusion. Dissolve the melt in distilled water; boil and dilute well to reduce caustic.

(b) Filter through a caustic resistant paper and wash well. The filtrate contains chromium and aluminum as sodium chromate and sodium aluminate, whereas the residue contains R_2O_3 (where R stands for iron, titanium, zirconium, etc.), calcium, magnesium, and silver salt (from the crucible).

(c) Aluminum from the filtrate of (b) is precipitated as aluminum hydroxide by adding ammonium chloride and boiling. The precipitate is filtered, ignited, and weighed as Al_2O_3.

(d) To the aluminum-free filtrate of (c) 1:1 hydrochloric acid is added until the solution turns acid, then add about 30 ml. more of the same 1:1 acid. It is then diluted and allowed to cool. To the cool solution add about 10 ml. of a 50 percent solution of potassium iodide, a few milliliters of starch solution, and titrate at once with standard thiosulphate. The end-point is very sharp and without care is very easily passed. Multiply the number of milliliters of thiosulphate used by the percentage value for chromium of 1 ml. to obtain the chromium content of the sample.

(e) The residue from (b) is taken up in hydrochloric acid which dissolves every thing except silver chloride. The silver chloride is removed by filtration. The filtrate is treated with ammonium to precipitate out R_2O_3, leaving calcium and magnesium in solution. The precipitated R_2O_3 is redissolved in hydrochloric acid and about 6 grams of pure granulated zinc are added to reduce iron from ferric to the ferrous condition. After the reaction is complete, about 10 ml. of strong sulphuric acid are added and the mixture is filtered through a plug of absorbent

cotton. The filtrate is diluted with distilled water to about 700 ml. and the solution titrated with standard permanganate. The number of milliliters of permanganate used is multiplied by the percentage value of 1 ml. for iron to obtain the percentage of iron in the sample. (Note: In this case R_2O_3 is assumed to consist entirely of iron as the amount of titanium, zirconium, columbium, etc., is very small and can be neglected. These rarer elements can be determined by "Cupferron Titanium Procedure").

(f) The filtrate from (d) contains calcium and magnesium, and these are separated by the alcohol method, in which the filtrate is evaporated to dryness and taken up with 18 ml. of water and 2 ml. of strong sulphuric acid. Then 100 ml. of methyl alcohol is added. Calcium sulphate is precipitated and removed by filtration. The filter paper with its contents is ignited to calcium sulphate and weighed. Calcium oxide is 41.19 percent of calcium sulphate.

(g) To the filtrate from (f) which now contains only magnesium, 10 grams of ammonium chloride and 20 ml. of concentrated ammonium hydroxide are added, following which the solution is brought to a boil. Magnesium is precipitated as magnesium phosphate by adding ammonium phosphate. The phosphate is removed, ignited, and weighed. This weight is multiplied by 0.3621 to obtain the amount of magnesia present in the sample.

(h) For the determination of silica, a similar peroxide fusion is made in an iron crucible, and the melt dissolved in water. After boiling the melt, hydrochloric acid and a little nitric acid are added and the solution allowed to boil till brown fumes cease. 50 ml. of perchloric acid are next added and the solution allowed to boil until dense white fumes appear, after which boiling is continued for at least one half an

hour to dehydrate all the silica which is now a precipitate. The precipitate is collected by filtration, is ignited and is weighed as silica.

Chemical and Spectrochemical Analysis

Aim: To determine quantitatively the constituents of the chromite ore in the laboratory and to check it with the analysis made by Messrs. Hughes and Davies of Bombay, India, of a sample from the same deposit.

A spectrochemical analysis was run prior to the chemical analysis to determine the presence of minor elements (calcium and manganese) and rarer elements (titanium, zirconium and columbium). These minor and rarer elements usually interfere with the chemical analysis; or, if not separated, they tend to give higher results. This is especially true in the case of the iron determination, in which some chemists precipitate R_2O_3 (R stands for iron, titanium, zirconium, columbium, etc.) as iron, because the percentage of the rarer elements is usually very small and can be neglected. Naturally this gives a higher result for iron, thus decreasing the chromium-to-iron ratio, which is of commercial importance.

The results of the spectrochemical analysis were as follows:

Constituents Found		
Major	Minor	Traces
Chromium	Calcium	Titanium
Aluminum	Manganese	Zirconium
Magnesium		Columbium
Iron		Tantalum

Conclusions: From the above analysis it is found that the rarer elements, titanium, zirconium, columbium, and tantalum, are definitely present as trace elements; and it would be advisable to determine the percentage of these rarer elements as a reference so that it is possible to obtain

pure iron content instead of R_2O_3 when desired.

The above analysis also indicates the presence of calcium and manganese, and they too should be determined quantitatively.

The analytical procedure for the quantitative determination of the constituents of chromite as followed in the laboratory is given on the preceding pages.

The results of the chemical analysis obtained in the laboratory as compared to the analysis made by Messrs. Hughes and Davies, Bombay, India, are given in the following table:

Constituents of Chromite	Formula	Percent	
		Analysis at the Lab. of Colo. School of Mines	Analysis by Hughes and Davies Bombay, India
Chrome Sesqui Oxide	Cr_2O_3	40.06	42.86
Ferrous Oxide (All Fe as FeO)	FeO	17.69	14.05
Alumina	Al_2O_3	12.66	17.58
Silica	SiO_2	8.02	7.84
Lime	CaO	0.75	Trace
Magnesia	MgO	20.35	17.67
Oxides of Titanium, Zirconium, Columbium, etc.	R_2O_3	0.40	Trace
Total Percent		99.93	100.00

Conclusions: The marked difference in the analysis of the chromite ore, as obtained in the laboratory and as received from Bombay, indicates that the above two samples came from two different parts of the same deposit. Apparently the sample of ore sent for treatment was taken at random from the stock pile.

The analysis from Bombay does not give the assays for the oxides of rarer elements, while the analysis made in the laboratory shows that 0.4 percent of R_2O_3 is present in the ore.

Mineragraphic Examination

Aim: To determine the mineralogical constitution, ore structure, texture, and dissemination of the chromite ore, so as to obtain the necessary information regarding the type, nature, and amount of gangue mineral and its association with the valuable mineral. The above information is essential in determining the amenability of the ore to any mechanical or mineral dressing methods of treatment.

The above examination was made under the supervision of Professor Reichert, at the Mineralography Laboratory of the Geology Department of the Colorado School of Mines. In this examination, polished sections of hand specimens and specimens mounted in briquettes were examined with reflected light under the metallurgical microscope. No thin sections of the ore were prepared, but the petrographic microscope was used to a limited extent in confirming the presence of certain minerals. The polished section of the hand specimen was also compared to the polished section of a high grade chromite specimen to determine the relative purity of the chromite mineral in the ore.

Results: The mineragraphic examination revealed the following:

Valuable Mineral: (1) Chromite ..... $Cr_2O_3 \cdot FeO$ (Impure)

Gangue Minerals: (1) Serpentine ..... $Mg_3Si_2O_5(OH)_4$

(2) Olivine ..... $(Mg,Fe)_2SiO_4$

(3) Calcite ..... $CaCO_3$

Remarks: During the above examination it was noticed that the individual crystals of chromite were fairly pure and could be easily distinguished from the gangue minerals by their color and isotropic characteristics,

Fig. 5. Binocular Microscope and Illuminator Used in Mineragraphic Examination.

which is typical of all chromite minerals. The gangue minerals seemed to occur as separate units and sometimes had intruded in the chromite crystals. Serpentine was the most predominant gangue mineral, followed by olivine and calcite. The chromite crystals of this ore compared favorably with the crystals of the high-grade, known specimen of chromite. The only difference was in the purity of the crystals, the crystals of the high-grade specimen appearing cleaner than the crystals of the low-grade specimen. There is no way of determining mineralogically the purity of the chromite crystals, that is, how much alumina, magnesia and iron oxide is present in the chromite crystals, by simply examining the chromite crystals. The only methods for determining this are (a) to analyze the purest crystals of chromite and, (b) to analyze the gangue minerals microscopically and figure out the amounts of different constituents present in the gangue and the valuable mineral by calculation. This last method is an approximate method and is subject to errors.

An attempt was made to determine the amounts of the different constituents present in the valuable chromite mineral by the latter method. The procedure followed in performing the above test was to determine, with the help of a microscope, the amount of gangue present in the ore and the amounts of different minerals present in the gangue. Having obtained the above amounts the next step was to figure out theoretically the percentages of magnesia, alumina, calcium oxide, and iron oxide present in the gangue minerals. The difference between the percentages of each constituent as obtained by the above method and the percentage of the same constituent present in the head sample of the ore (as determined by chemical analysis) gave the amount of that constituent present in the valuable mineral. The results obtained were confirmed and checked

by the chemical analysis of the purest chromite mineral obtained by the superpanner.

Results: The results of the above test were as follows:

Amount of gangue present in the ore ..... 20 percent.

Gangue Mineral	Formula	Pct. Present in Gangue	Pct. Present in Total Gangue	Pct. Present in Mineral			
				MgO	SiO_2	FeO	CaO
Serpentine	$Mg_3Si_2O_5(OH)_4$	80	16	43	44	-	-
Olivine	$(MgFe)_2SiO_4$	13	2.6	41	39	20	-
Calcite	$CaCO_3$	7	1.4	-	-	-	56
	Total	100	20				

Percent Constituents in the Total Gangue

Gangue Mineral	Pct. in Total Gangue x Pct. in Mineral			
	MgO	SiO_2	FeO	CaO
Serpentine	6.88	7.04	-	-
Olivine	1.07	1.00	0.56	-
Calcite	-	-	-	0.78
Total Gangue	7.95	8.04	0.56	0.78

Type of Assay	Percent					
	Cr_2O_3	Al_2O_3	MgO	SiO_2	FeO	CaO
Heads	39.46	12.56	20.35	8.02	18.09	0.75
Gangue (in original ore, theoretical)	-	-	7.95	8.04	0.56	0.78
Valuable Mineral (from Calculations)	-	-	12.40	-	17.53	-
Check (nearly pure chromite)	53.57	16.45	12.14	0.5	17.04	Trace

Metallurgical Balance

Conclusions: The Mineragraphic examination shows that the principal gangue minerals in the ore are serpentine, olivine and calcite. The first two of these minerals are magnesium silicates and the last one is a calcium carbonate. An examination of the chemical analysis reveals that the ore contains about 8 percent silica, which can be accounted for by the silica in the gangue minerals. Calcium, too, can be accounted for by the calcite in the gangue. Since serpentine and olivine both contain magnesia, it can also be accounted for up to a certain extent. Alumina is the only constituent which cannot be accounted for in the gangue minerals. Thus alumina has to occur along with most of the iron oxide in the chromite mineral.

Therefore it is concluded that the chromite mineral in this ore is not pure, but is composed of chromic oxide, ferrous oxide, alumina and some magnesia.

This conclusion is confirmed by the microscopic examination of the gangue minerals and calculations, the results of which show that the valuable mineral chromite contains 16.45 (all) percent alumina, 12.40 percent magnesia, and 17.53 percent iron oxide, besides chromic oxide (53.62 percent).

The above result is confirmed by the analysis of the nearly pure chromite mineral obtained by the superpanner.

Since the gangue minerals occur as separate units and since the chromite mineral is fairly pure, a reasonably good separation between the two at a certain size is definitely possible. Thus the possibilities of concentrating the chromite ore from Baluchistan seem quite attractive.

Screen-Sizing Test and Assay-Size Analyses

The effectiveness of practically all ore-dressing operations is a function of the size of the particles treated, and for this reason a thorough knowledge of the size characteristics of the material handled is of the greatest importance.

There are several methods for sizing mineral particles, the most important of which is screening. Classification (elutriation) and microscope sizing are next in importance. For particle sizes down to about 0.05 (200-mesh) millimeters, sizing is accomplished satisfactorily by screening. Under about 0.10 millimeters, however, screening is rather limited, the finest screen manufactured and used in the laboratory having an aperture of 0.037 millimeter (400-mesh). Elutriation and sedimentation methods are usually used for sizing under 200- or 400-mesh down to a colloidal fineness (1 to 2-microns).

In establishing a procedure for standardization of sieve analyses one must consider -- (1) the size or weight of sample to be tested, (2) length of sieving time, (3) required accuracy of test, and (4) type of test -- wet or dry.

In ore-testing studies it is a common practice to use a binocular microscope in close cooperation with the screen-sizing test. The binocular microscope is useful for examination of unmounted grains of each sized product, the aim being to determine the size-range at which partial or complete liberation occurs. Determinations of liberation of minerals from each other at different sizes, with specific information as to the types and amounts of locked particles present, are of great value in establishing the most efficient treatment methods for any ore.

There are many advantages in the graphic method of showing the data

obtained in a screen analyses. Graphs of sizing tests afford quick and easy comparison of different materials and bring out significant relations not always readily recognized in the table of results. Several methods of plotting are used, depending on the use to be made of the data. The cumulative direct plot and cumulative logarithmic plot are the two most valuable and generally used. The former plot has the disadvantage of spreading the curve for large particle sizes and crowding the finer sizes, whereas the latter plot gives equal intervals between successive screen sizes and thus affords probably the best method for general comparative work.

Results and Experimental Data:

The results of the Screen-Sizing Test and the microscopic examination of the sized product, are given in the following data:

Material: Chromite Ore from Baluchistan

Weight Taken: 1000 grams

Feed Sample: The material passed through a 6-mesh screen and slimes removed by washing through a 200-mesh screen.

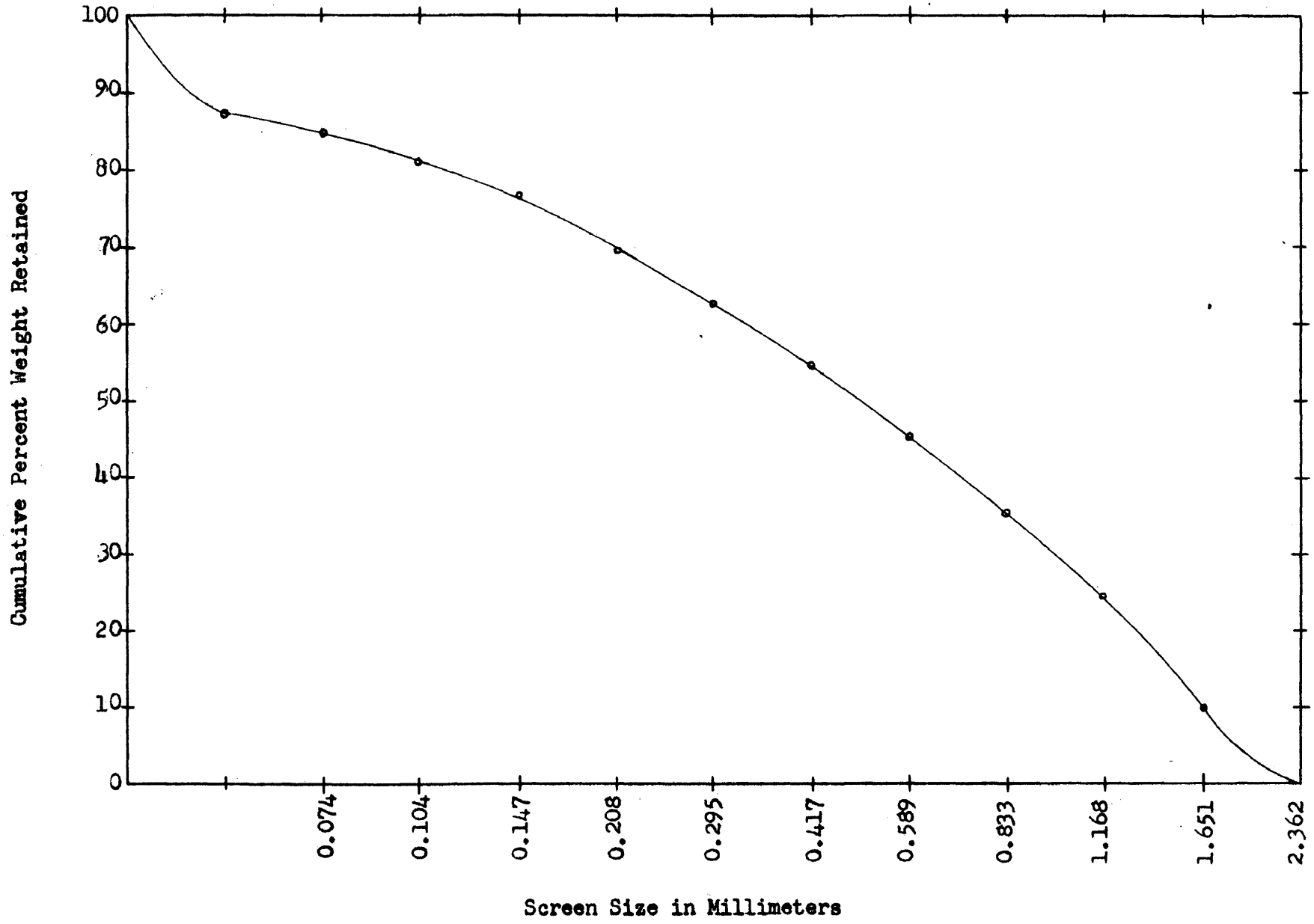
Machine Used: Ro-Tap Time of Sieving: 15 minutes.

Tyler Mesh	Aperture Millimeters	Sample Weights	Percent Weight	Percent Cum. Weight	Microscopic Examination
on 8	2.362	108	10.8	10.8	No liberation, all middlings
-8+10	1.651	140	14.0	24.8	" "
-10+14	1.168	106	10.6	35.4	" "
-14+20	0.833	100	10.0	45.4	" "
-20+28	0.589	90	9.0	54.4	" "
-28+35	0.417	85	8.5	62.9	Slight liberation, some free minerals
-35+48	0.295	68	6.8	69.7	little more liberation
-48+65	0.208	68	6.8	76.5	More liberation
-65+100	0.147	49	4.9	81.4	fair liberation
-100+150	0.104	34	3.4	84.8	good liberation
-150+200	0.074	27	2.7	87.5	better liberation
pass 200	0.074	125	12.5	100.0	complete liberation
		1000			

Graph for general comparative work a Cumulative Logarithmic plot was made, as shown in Graph No. 1

Conclusions: The above experimental data indicates that (a) up to 35-mesh there is no liberation and that more than half the weight of the material taken remains above 35-mesh. There are, however, possibilities of removing the coarsely occurring gangue and middlings by a coarse concentration method to reduce the tonnage. (b) The size range minus 35 plus 100, shows little to fair liberation and so extensive tests must be carried out in this range to investigate the possibilities of concentrating finer sizes up to 100-mesh. This size range appears to be the best range for usual gravity separation methods and in actual practice most of the tonnage may have to be treated at this size range. (c) Best

GRAPH NO. 1. CUMULATIVE LOGARITHMIC PLOT



liberation occurs below 100-mesh, complete liberation taking place below 200-mesh, accordingly it will be necessary to investigate the possibilities of treating the finest or slime product by the usual gravity and flotation methods. The treatment of slime in this case should not be overlooked as it constitutes quite an appreciable amount of original tonnage.

Proposal: To carry out an Assay-Size Analyses.

Assay-Size Analysis:

If each size fraction from the above screen analysis is assayed, the assay data and the sizing data may be used to calculate the size distribution of each ore constituent assayed for. Frequently this information is of somewhat more practical interest than the composite size distribution of the ore as a whole. Having found out the extent of liberation taking place at different size ranges, the next step in the investigation was to find out the best "working range" for this chromite ore. The best working range being the one in which the Cr_2O_3 content is the highest and the SiO_2 (gangue) content the least.

The usual procedure followed for making an assay-size analysis is to break up the above twelve size ranges into four convenient size ranges and assay each size fraction for the main constituent (Cr_2O_3) of the chromite mineral and the main constituent (SiO_2) of the gangue minerals. (The only condition laid down in this test is that the main constituent of the gangue mineral should not be present in the valuable mineral.) The assay percentages of the Cr_2O_3 and SiO_2 obtained are then plotted against their corresponding size ranges to obtain the Cr_2O_3 and SiO_2 distribution curves, which clearly shows the best working range.

Results of the Assay-Size Analyses:

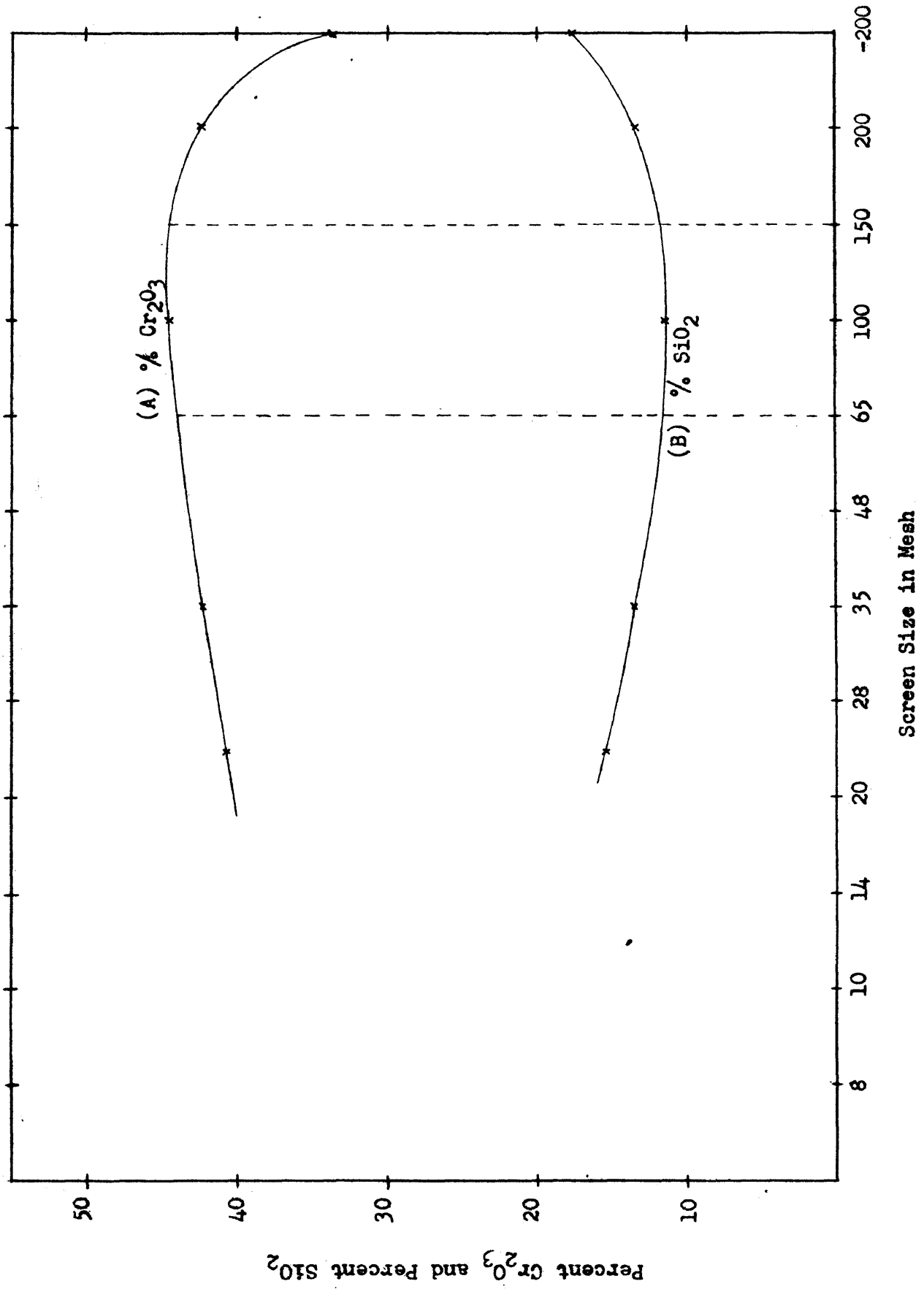
Size Range	Percent Cumulative Weight	Percent	
		Cr_2O_3	SiO_2
-8+35	62.9	42.29	13.56
-35+100	81.4	44.44	11.40
-100+200	87.5	42.33	13.14
-200	100.0	33.64	17.76

Graph: The percentages of Cr_2O_3 and SiO_2 obtained were plotted against their corresponding size ranges and distribution curves for Cr_2O_3 and SiO_2 obtained, as shown in Graph No. 2.

Conclusions: The results of the assay-size analysis as given in the above table and corresponding Graph No. 2 clearly indicate that the gangue minerals are more readily comminuted than the valuable chromite mineral, and that the minus 65 plus 150-mesh size range is the best working range, because in that range the valuable mineral content is the highest and the gangue content the least. The above results confirm the results obtained in the previous screen-sizing and microscopic analysis tests.

GRAPH NO. 2. ASSAY-SIZE ANALYSES PLOT FOR THE DETERMINATION OF THE BEST WORKING RANGE

Ref: (A) Cr_2O_3 Curve (B) SiO_2 Curve



Grinding Test

Aim: The main objective behind the grinding test was to find out the time it would take to grind the above chromite ore in a ball mill, to obtain complete liberation, which occurs at about minus 150-mesh.

The time of grinding the above ore, in the laboratory ball mill was determined graphically (Graph No. 2) by plotting time against percentage of the minus 150 mesh portions. To keep all the conditions of the ball mill constant three 1000-grams samples were wet ground in the same ball mill with 750 ml. water, for 5, 10, and 15 minutes respectively. After filtering and drying the usual screen analyses of the ground ore and the unground ore were made.

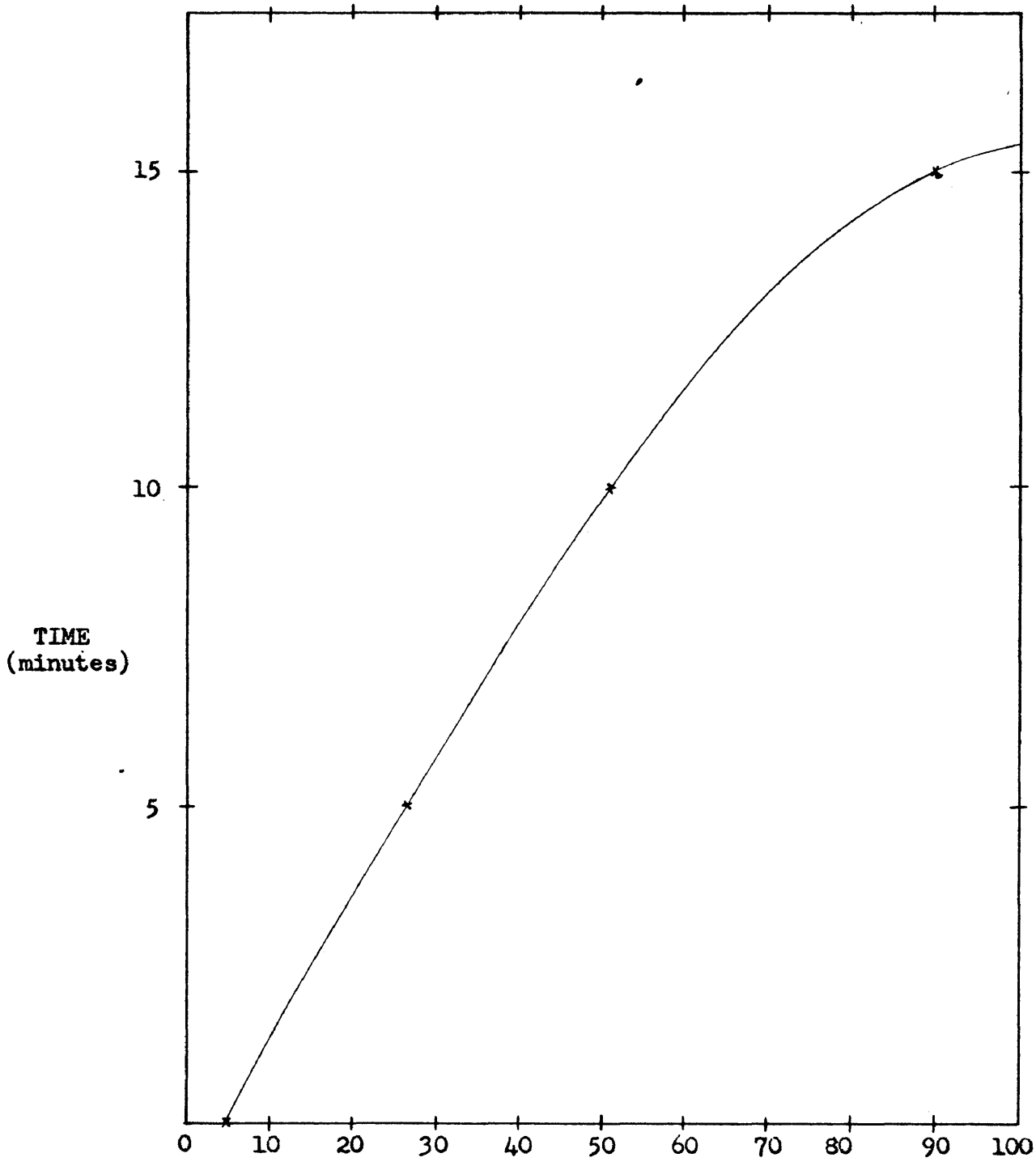
Note: It is a known fact that a ball-mill produces too much slimes and since the slimes are not desired for this particular ore, the necessary grinding should be done in a rod-mill. Unfortunately, a small scale rod mill was not available in the laboratory and so a ball mill was substituted for grinding the ore.

Results and Experimental Data:

The results obtained in the grinding test are shown in the following table.

Mesh	Weight Percent			
	0. min.	5 min.	10 min.	15 min.
-14+35	53.0	1.5	1.0	-
-35+65	24.0	10.0	8.0	-
-65+100	10.0	29.0	15.0	-
-100+150	8.0	30.0	21.0	10.0
-150	5.0	29.5	55.0	90.0

GRAPH NO. 3. TIME DETERMINATION FOR MINUS 150 MESH GRINDING
(Grinding Time Vs. Percent -150 Mesh)



From the Graph No. 3; the time of grinding of the above chromite ore to all minus 150-mesh is about 16 minutes.

Conclusions: The results of the above grinding test indicate that the ore is relatively a soft one and that grinding in one pass produces too much slimes. To eliminate the problem of slimes it would be necessary to use a rod mill or rolls.

Sink-Float Separation Test

Aim: The main purpose of the sink-float separation test was to investigate the possibilities of separating the valuable mineral from the gangue at coarser sizes, since sink-float separation is the simplest and most accurate method of gravitational separation available in the laboratory.

In usual laboratory testing work, when testing is directed towards investigations of mineralogical characteristics, heavy liquids are used. Since in the above test, the separation was desired between the valuable mineral chromite (sp. gr. 4.6) and the gangue minerals (average sp. gr. 2.7), acetylene tetrabromide (tetrabromethane) having a specific gravity of 2.96 was used. Carbon tetrachloride was used in the above test work to recover tetrabromethane which is comparatively a costly liquid. The size range used in the above test was from plus 10 to +200-mesh, and was divided into four convenient groups. The sink products of all the size ranges were assayed for their Cr_2O_3 content.

Results and Experimental Data:

The results of the sink-float test were as follows:

Test No.	Size Range	Weight Taken	Pct. Weight		Pct. Cr_2O_3 in Sink	Remarks
			Sink	Float		
1	+10	25 gms	84.0	16.0	45.24	middlings in sink product
2	-10+35	"	83.5	16.5	46.52	middlings in float product
3	-35+100	"	84.0	16.0	50.58	very little gangue in sink product
4	-100+200	"	79.2	20.8	49.63	valuable fines in float

Conclusions: (a) The above results show that at coarser sizes up to 35 mesh, there is an appreciable amount of separation, but the sink product obtained is not very clean as it assays only about 46 percent Cr_2O_3, yet this size

range definitely indicates some possibilities of a reasonably good separation with the help of a sink-float process in practice.

(b) The best results are obtained at the size range minus 35 plus 100-mesh, at which the sink is the cleanest. Unfortunately, this size range is too fine for a commercial application of sink-float (heavy density) separation.

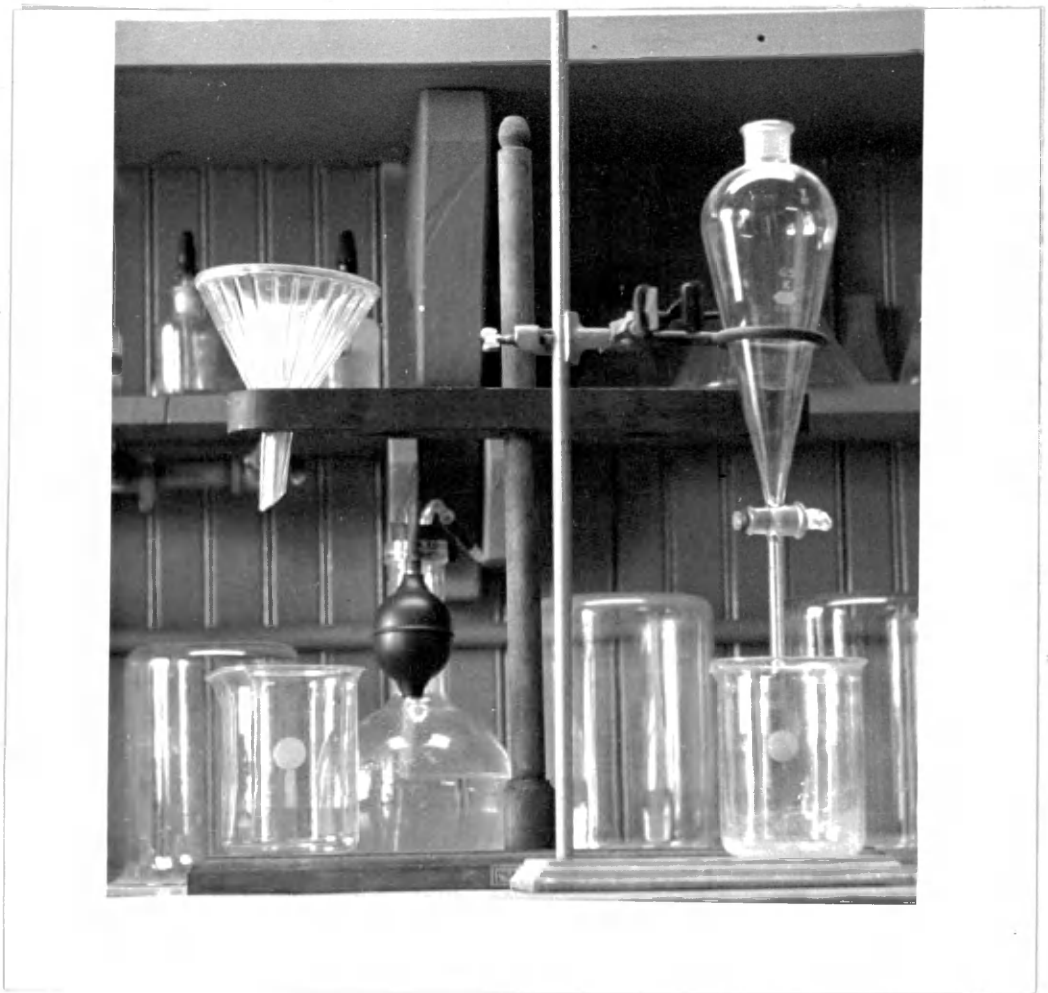


Fig. 6. Sink-Float Unit Used in Laboratory

Tabling Test

Aim: Table concentration has been used to a considerable extent in treatment of chromite ores in the past, and from its past performance tabling is considered as the best method of concentrating chromite ores. It is the purpose of this test to investigate the possibilities of tabling on all size ranges and to determine the best size range for tabling. Possibilities of using tabling in combination with other concentrating methods were also investigated.

The table used in the laboratory was of the Wilfley type, with interchangeable decks for coarse and fine feeds. It was necessary to prepare the feed for tabling and a screen-sized product was used in the tests. (It is a usual practice to hydroclassify the feeds for tabling rather than screen-classify them.) During the tests, adjustments for the amount of wash water, the cross tilt, the speed, and the length of the stroke, were varied as required.

Note: 1. In ore-testing tests like tabling, flotation, spiral concentration, etc., where the success or failure of the test depends on the results obtained, it is a good practice to make a metallurgical balance with the products of concentration to check the results.

2. Content as used in the following experimental data is the product obtained by multiplying the percent weight by percent assay of Cr_2O_3.

Fig. 7. General View of Wilfley Table Used in Tabling Tests

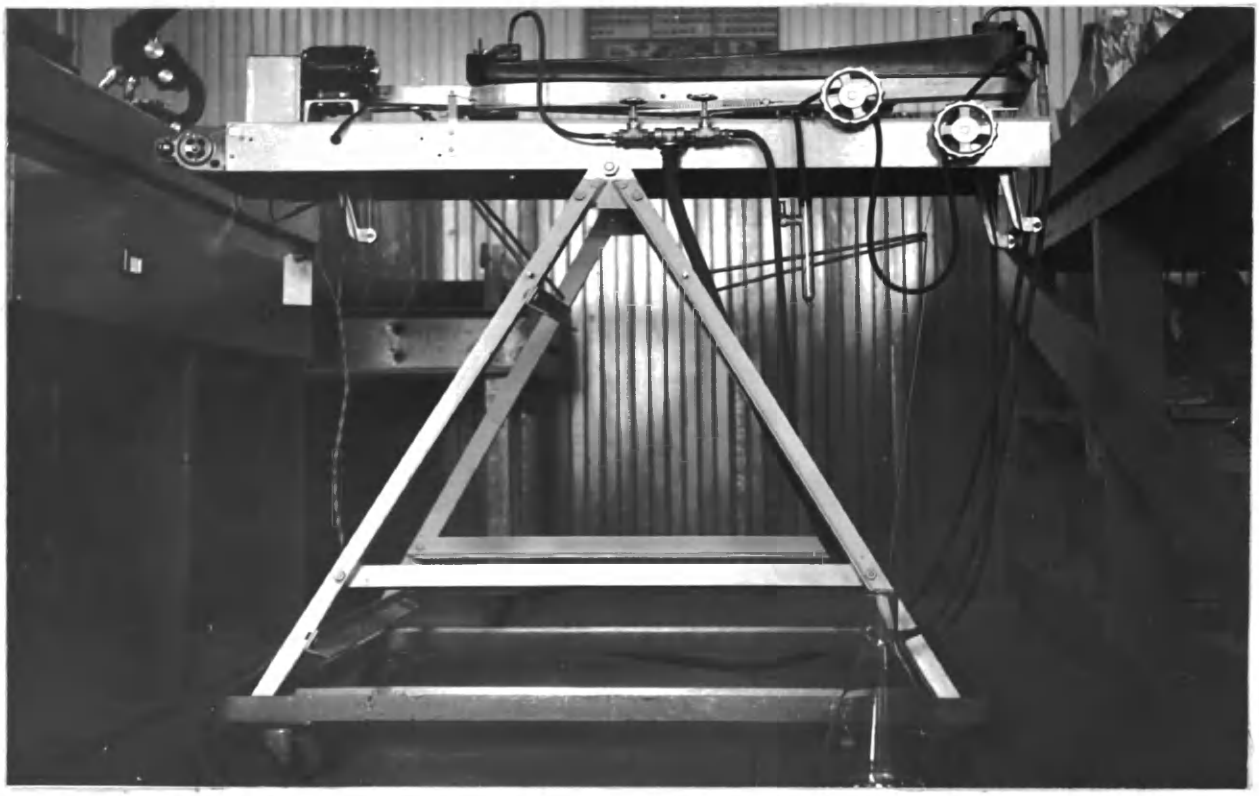


Fig. 8. Haultain Superpanner

Results and Experimental Data:

The results of the tabling tests were as follows:

Test. No.	Feed Size	Percent Weight		Percent Cr_2O_3	
		Concentrates	Tails	Concentrates	Tails
1	-28+65	80	20	51.42	18.73
2	-48+65	82	18	52.50	15.30
3	-65+100	80	20	51.86	13.35
4	-100+150	65	35	53.57	26.10

Metallurgical Balance

Test No.	Feed Size	Cr_2O_3 Content		Total Content	Head Assay	Percent Recovery
		Conc.	Tails			
1	-28+65	41.13	3.74	44.87	44.40	92
2	-48+65	42.00	2.86	44.86	44.44	94
3	-65+100	41.48	2.67	44.15	44.44	93
4	-100+150	34.85	9.13	43.98	43.50	79

Conclusions: Following conclusions are drawn from the above results of the tabling test.

(a) All the four size ranges show very encouraging results. The Cr_2O_3 percentage in each concentrate is higher than the critical percentage (48 percent) and the tailings run below 20 percent of the valuable material except in the last test.

(b) The percentage recovery in all four tests is fairly high, the highest being 94 percent and the lowest being 79 percent. The above two conclusions confirm the statement that tabling is found to be one of the best methods of concentration of this chromite ore, and also proves the fact that tabling will

work efficiently on all sizes of this ore including slimes.

(c) The above results also indicate the possibilities of using the table concentration method for cleaning of the concentrates obtained from other concentration methods, because the table concentrates show a tendency to possess the highest Cr_2O_3 content.

Flotation Test

Aim: In all milling operations in which the ore to be treated is crushed and ground to liberate the valuable mineral from the gangue, a certain amount of slimes is bound to be produced, and an efficient mill always possesses one or more methods of concentration for taking care of these slimes. It is the object of these tests to investigate the possibilities of treating slimes by flotation.

The above investigation was investigated from two different viewpoints:

(1) Flotation of the valuable mineral chromite, which has been successfully used with other similar ores.

(2) Flotation of gangue mineral and collecting the discharge from the flotation cell as a concentrate. Since the amount of gangue minerals is comparatively small (about 20 percent by weight) it is logical to remove the gangue than the valuable mineral.

Note: (1) The reagents used in the following flotation tests were selected from the point of view of both efficiency and availability (in Pakistan). For example, in the flotation of gangue, a long chain amine is required as a promoter and Soy Amine was used in this case because soybean is available in large quantities in Pakistan and the above reagent can be prepared more cheaply than importing a long chain synthetic amine from United States. The same is true for many other reagents used in the above tests.

(2) All the reagents used, both for the flotation of chromite and gangue minerals, are the reagents recommended by the American Cyanimid

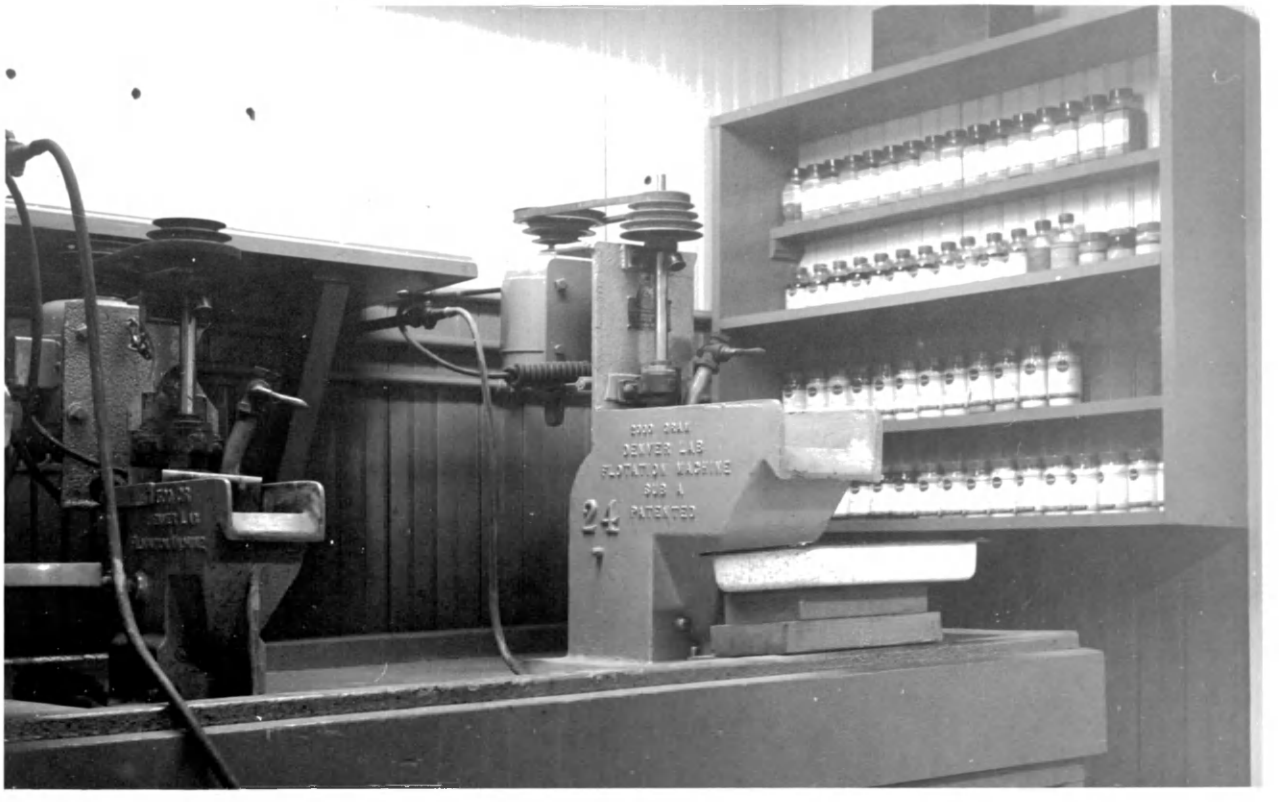


Fig. 9. Denver Sub. A Flotation Machine Used in Flotation Investigations.

Company 21/.

21/ "Flotation Reagents," Mineral Dressing Division, American Cyanamid Company; Mineral Dressing Notes No. 15, Jan., 1947.

Test Number 1

Plan: Flotation of Chromite

Sample: 1000 grams

Grind: 15 minutes in the ball mill with 750 ml. water to minus 150-mesh

Reagents: Added to the flotation cell.

Regulator - sulphuric acid

Activator - molybdic acid ..... 0.2 lb. per ton

Promoter - R.708 ..... 0.3 lb. per ton

Frother - Pine Oil ..... 4 drops

pH Value: 7 (neutral circuit)

Conditioning Time: 4 minutes

Machine Used: Denver Sub A Laboratory Type Flotation Machine

Results: The results and the metallurgical balance sheet for the above test are as follows:

Product	Weight		Assay		Pct. Distribution of Cr_2O_3
	grams	pct.	pct. Cr_2O_3	Wt. Pct. Cr_2O_3	
Concentrates	500	50	49.85	24.92	65.0
Tails	500	50	40.79	20.49	35.0
Heads	1000	100	44.03	45.41	100.0

Conclusions: The above results indicates that although the percent Cr_2O_3 in the concentrate is acceptable, the tails are considerably higher

in Cr_2O_3 content. Of course, the concentrates and the tails can be cleaned to obtain a better grade and higher recovery, but here again the question of tonnage to be treated comes in.

The test definitely points out the disadvantage of floating the valuable mineral chromite.

Test Number 2

Plan:	Flotation of the gangue minerals
Sample:	1000 grams
Grind:	15 minutes in the ball mill with 750 ml. water to minus 150-mesh
Reagents:	Added to the flotation cell:
	Regulator - Sulphuric acid
	Activator - Copper sulphate ..... 0.4 lb. per ton
	Promoter - Long chain amine
	Soy-Amine ..... 0.3 lb. per ton
	Frother - Pine oil ..... 4 drops
pH Value:	7 (neutral circuit)
Conditioning Time:	4 minutes
Machine Used:	Denver Sub A Laboratory Type Flotation Machine
Results:	The following table gives the results and the metallurgical balance obtained from the above test.

Products	Weight		Assay		Pct. Distribution of Cr_2O_3
	grams	pct.	pct. Cr_2O_3	Wt. pct. Cr_2O_3	
Concentrates	900	90	44.91	40.42	93.5
Tails	100	10	28.49	2.84	6.5
Heads	1000	100	44.03	43.26	100.0

Remarks: During the performance of the above test it was noticed that up to 3 grams (0.3 lb. per ton) the Soy Amine is a promoter for the gangue minerals only and gives a well loaded froth, but on the addition of the fourth gram (0.4 lb. per ton), the Soy Amine imparts promoting action to the valuable mineral chromite and brings it up also. Therefore a close control on the addition of this reagent is absolutely necessary.

Conclusions: (1) The above test clearly shows the advantage of floating the gangue minerals instead of the valuable mineral. The percent recovery obtained is as high as 93.5 percent, but the grade of the concentrate is less than the 48 percent Cr_2O_3 required. The percentage of Cr_2O_3 in the tails is not as high as it was in the previous test, and there are possibilities of cleaning the tails or running it through another concentration method to recover the remaining value.

(2) There are two ways of dealing with the above products of concentration. The first one is to mix up these low-grade concentrates with the higher grade concentrates from other methods to make the mixture up to the acceptable grade and retreat the tails to obtain the remaining value. The second way is to clean the above concentrates by reflotation or by treating it on the table, spiral, etc.

Of course there is always a possibility of sacrificing the high percentage recovery to a certain extent, while obtaining an acceptable grade product.

Spiral Concentration Test

Aim: The first application of the Humphreys Spiral in commercial practice was the treatment of chromite ores. This application was a great success and since that time, spirals have been very extensively used in treatment of chromite ores throughout the world. The objects of the above test were to investigate the possibilities of treating this particular chromite ore by spiral concentration, to determine the best size-range for the spiral concentration and lastly to investigate the possibilities of applying the spiral as the principal concentration method in the treatment of the above chromite ore.

The above tests were carried out on the Humphreys spiral concentrator closed circuit test unit at the Experimental Ore Dressing and Metallurgical Plant of the Colorado School of Mines. Usually in a spiral test the amount of feed required runs into several hundred pounds, but due to the shortage of the ore only 25 pounds of feed material were used. Since the unit is close circuited it was possible to run the same material over and over again, collecting only small samples at various adjustments, for examination and analysis.

Plans: Various size ranges and slimed as well as deslimed feeds were run through the spiral to find out the best size range and the best condition of the feed. Since one of the main advantages of spiral concentration is that it does not require a classified feed, a test was run on an unclassified product to find out how far the above statement was true. Treatment of slimes is always a big problem in practice, accordingly a test was run on slimes to find out their amenability to treatment by spiral.

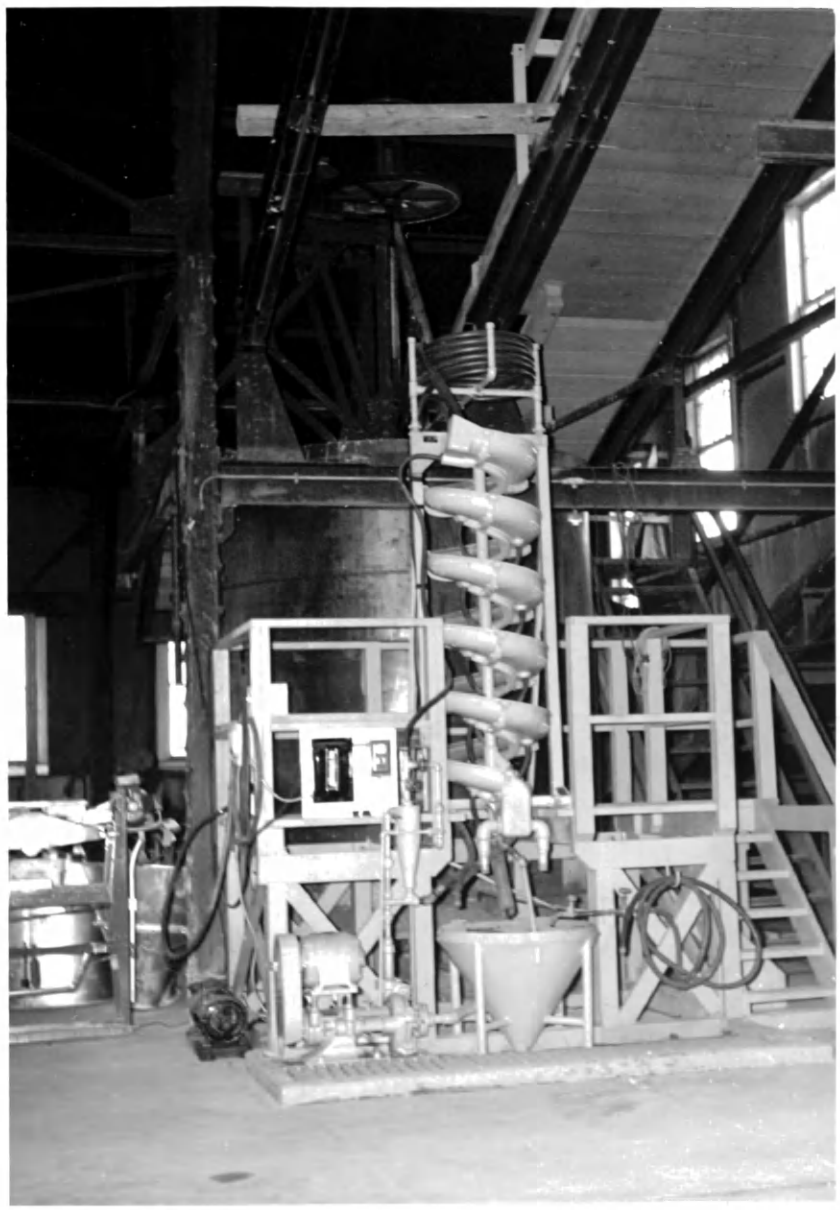


Fig. 10. Humphreys Spiral Unit at the Experimental Plant, Colo. School of Mines

Test Number 1

Purpose: Treatment of unclassified and unslimed feed

Sample: 25 pounds

Size of feed: All passed through 48-mesh screen

Water: 12 gallons

Pulp feed to spiral: ± 24 percent solids

Number of Outlets: 13 out of 14 ports

Remarks: The tests showed (a) that the slimes present in the feed were carried along with the wash water with the result that they contaminated the concentrates, (b) the tail product was loaded with valuable slime material, and (c) the middlings were high in coarser gangue. Due to the failure of the test no metallurgical balance was made.

Results: The results of the above test were as follows:

Feed Size	Percent Cr_2O_3		
	Concentrates	Middlings	Tails
-48 mesh	48.62	33.68	43.85

Conclusions: The results of the above test show that it is not advisable to use an unclassified or unslimed feed. In an unslimed and unsized feed the slimes tend to run along with the wash water as well as follow the path of the tails in the spiral. The percentage of Cr_2O_3 in the tails are very high although the concentrate contains the acceptable grade. It appears that for a successful operation the product must be at least deslimed if not classified.

Test Number 2

Purpose: Treatment after desliming

Sample: 6000 grams

Size of Feed: All passed through 48-mesh screen

Water: 12 gallons

Number of Outlets: 13 out of 14

Remarks: In this test only 6000 grams of feed was used, without encountering any trouble. Thus smaller samples can be used successfully on spiral.

Results: The results and the metallurgical balance of the above test are given in the following table:

Products	Weight		Assay		Pct. Distribution of Cr_2O_3
	grams	pct.	Pct. Cr_2O_3	Wt. Pct. Cr_2O_3	
Concentrates	4200	70	52.42	36.69	80.0
Middlings	300	5	35.36	1.76	3.8
Tails	1500	25	30.37	7.56	16.2
Heads	6000	100	45.50	46.04	100.0

Conclusions: The advantage of desliming the spiral feed is clearly shown by the results of the above test. The recovery obtained in the above test was 80 percent and the Cr_2O_3 percent in the concentrate is considerably above the critical grade. The results on the whole are very encouraging, except for the percentage of valuable mineral in the tails, which is quite high. This is due to the fact that the very fine valuable mineral travels along with the tailings, thereby increasing its Cr_2O_3 content. To eliminate the above defect, it is absolutely necessary to classify the feed into two or more size ranges so that the fines are kept apart from

the coarser material.

Proposal: The best plan for classification of the above product is to break it up into two ranges as follows:- (a) minus 35 plus 100-mesh, and (b) minus 100-mesh. In this case the first range will be devoid of any fine material while in the second range all fines can be included, including the slimes (minus 200-mesh product).

Test Number 3

Purpose: Treatment of deslimed as well as classified product

Sample: 6000 grams

Size of feed: Minus 35 plus 100-mesh

Water: 12 gallons

Number of Outlets: 14

Results: The following table and metallurgical balance show the results obtained in the above test.

Product	Weight		Assay		Pct. Distribution of Cr_2O_3
	grams	pct.	Pct. Cr_2O_3	Wt. Pct. Cr_2O_3	
Concentrates	4200	70.0	51.94	36.35	83.80
Middlings	200	3.3	28.10	0.92	2.10
Tails	1000	26.7	23.24	6.20	14.10
Heads	6000	100.0	44.80	43.47	100.00

Conclusions: From the results of the above test, it is found that this test was a big success, with an overall recovery of 84 percent. Looking at the Cr_2O_3 percent of the products it is noted that although there is no improvement in the grade of concentrate (as compared to results of the previous tests) there is definite improvement in the content of the

valuable mineral in the tail, which has been reduced to 23.24 percent.

The above test definitely indicates the advantage of desliming and classifying the feed to the spiral.

Test Number 4

Purpose: Treatment of Slimes

Sample: 6000 grams

Size of Feed: All through -100 mesh including slimes

Water: 12 gallons

Number of Outlets: 14

Remarks: In this test all the product through 100 mesh screen is considered as slime. In running this test all the outlet lids had to be rearranged and set to allow only the best concentrates to pass through them.

Results: The results obtained in the above test are as follows:

Product	Weight		Assay		Pct. Distribution of Cr_2O_3
	grams	pct.	Pct. Cr_2O_3	Wt. pct. Cr_2O_3	
Concentrates	4620	77.0	51.42	39.59	84.5
Middlings	60	1.0	42.97	0.43	0.9
Tails	1320	22.0	32.08	7.05	14.6
Heads	6000	100.0	46.42	47.07	100.0

Conclusions: Though the results of the above tests are not as good as the results of the last test, they are quite good. The tailings run higher in Cr_2O_3 content, as expected, because of the presence of slimes. The middlings too are high in Cr_2O_3 content, but it is only one percent by

weight and can be neglected in actual practice, as it would be rerun.

In spite of the difficulties imparted to concentration, due to the presence of slimes, the above test clearly indicates attractive possibilities of treating the chromite slimes by spiral concentration.

Weinig Concentrator Test

Aim: The main idea behind this test is to investigate the possibilities of treating the chromite ore at coarse sizes up to 48-mesh with Weinig Concentrator, which is suited for concentration at coarse sizes.

Note: The Weinig Concentrator has been successfully applied to the treatment of taconite ores at Mesabi Range since the beginning of this year, and since the problem involved in the treatment of chromite ore is somewhat similar to that of taconite, there are possibilities that the Weinig Concentrator can be applied successfully to the treatment of chromite ores.

The above test was carried out at the Laboratory of the Colorado Iron Works Company, the Experimental Plant of the Colorado School of Mines, under the supervision of Mr. Storm, who is in charge of the laboratory. The usual test with the Weinig Concentrator requires a large quantity of ore and it requires a lot of test work to obtain the best conditions and adjustment for a successful operation and high recovery. Since both the ore and time were short it was proposed by Mr. Storm to run only one test, without disturbing the adjustments.

Test Number 1

Sample: 5000 grams

Size of Feed: Minus 14 plus 48-mesh product

Water: 6 gallons per minute

Remarks: (1) The two conditions essential for running a test on the above Concentrator are: Constant rate of feed and constant flow of water.

(2) According to Mr. Storm, the Company had never

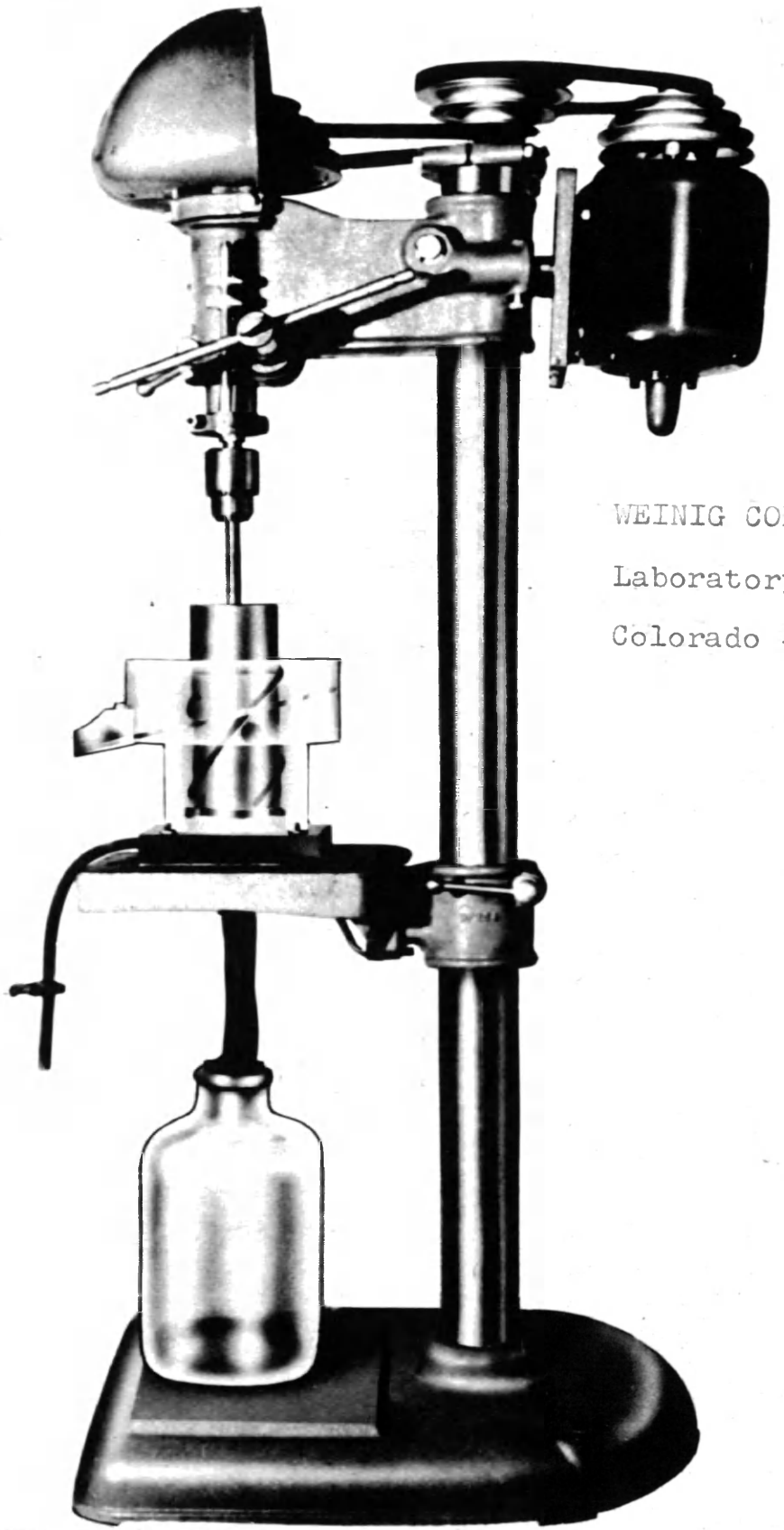


Fig. 11. Weinig Concentrator, Laboratory Model.

before made any test work on chromite ores, nor had it made any test on any ore at the finer size range up to 48-mesh.

(3) Out of above 5000 grams of sample used in the test, 1340 grams were utilized as a bed in the concentrator tank, and the results, therefore, were figured out on the basis of 3660 grams instead of 5000 grams.

Results: The results and the metallurgical balance obtained from the above test were as follows:

Product	Weight		Assay		Pct. Distribution of Cr_2O_3
	grams	pct.	Pct. Cr_2O_3	Wt. pct. Cr_2O_3	
Concentrates	2050	56.0	50.82	28.46	65.0
Tails	1520	41.5	35.72	14.82	33.8
Slimes	90	2.5	21.96	0.55	1.2
Heads	3660	100.0	42.86	43.83	100.0

Conclusions: The above test with the Weinig Concentrator shows definite possibilities of treating the chromite ore at coarse sizes. The results seem very encouraging, if we take into consideration the facts that this was the first time that chromite ore was treated by the Concentrator, that only one pass (test) was made, and that no variation in the numerous adjustments available were made. With extensive investigation and test-work on this particular ore, it should be possible to obtain a better and a cleaner concentrate and higher recovery.

Magnetic Separation Test

Aim: In order to obtain the highest price for chromite in the market it is necessary that the concentrate should have a chromium to iron ratio of 3:1. On the analysis of the various concentrates it was found that the ratio of chromium to iron usually ran about 2.5:1 which is considerably less than the required ratio. Thus the main object of this magnetic separation was to investigate the possibilities of increasing the ratio to the required specification by removing the free-iron-bearing (not associated with chromite) or higher-iron-bearing chromite particles from the final concentrates.

The equipment used in the laboratory for the above magnetic separation test consisted of an Isodynamic Separator, an old Wethrill magnetic separator and a small horse-shoe hand magnet.

From the previous analysis made for the determination of free-iron (in form of iron-bearing minerals) it was found that the concentrates contain about 0.6 percent free-iron, which can be easily removed. But the above amount is so small that it did not make an appreciable difference in the chromium to iron ratio. For this reason it was necessary to remove higher-iron-bearing chromite particles.

Test Number 1

Purpose: Separation by a hand magnet

Sample: (1) Table Concentrate from Tabling Test No. 4

(2) Sink fraction from Sink-Float Test No. 4

Remarks: The amount of highly magnetic material removed was comparatively very small.

Results: The above test gave the following results:

Fig. 12. Franz Isodynamic Separator Used in Magnetic Separation Test.

Sample	Size	Pct. Assay of Concentrated Product After removal of hi-magnetic material			New Cr:Fe Ratio	Original Cr:Fe Ratio
		Cr_2O_3	Cr	Fe		
1	-100+150	54.00	36.85	12.95	2.80	2.5
2	-100+200	49.63	33.96	11.95	2.80	2.5

Test Number 2

Purpose: Separation by an Isodynamic Separator at 1 amp.

Sample: (1) Table Concentrates from Tabling Test No. 4

(2) Sink fraction from Sink-Float Test No. 4

Remarks: The amount of high magnetic material removed was about 5 percent of the total amount

Results: Following results were obtained from the above test.

Sample	Size	Pct. Assay of Concentrated Product After removal of hi-magnetic material			New Cr:Fe Ratio	Original Cr:Fe Ratio
		Cr_2O_3	Cr	Fe		
1	-100+150	54.30	36.95	12.75	2.85	2.5
2	-100+200	50.21	33.99	11.85	2.85	2.5

Test Number 3

Purpose: Separation by Wetherill magnetic separator at 1 amp.

Samples: (1) Table Concentrate from Tabling Test No. 1, 2, and 3

(2) Spiral Concentrate from Spiral Test No. 3

Remarks: The amount of high-magnetic material removed, amounted to 4 percent of the total amount

Results: The results obtained in the above test were as follows:

Sample	Size	Pct. Assay of Concentrated Product After removal of high-magnetic material			New Cr:Fe Ratio	Original Cr:Fe Ratio
		Cr_2O_3	Cr	Fe		
1	-28+100	51.62	35.32	13.15	2.7	2.5
2	-35+100	52.42	35.87	12.95	2.8	2.5

Test Number 4

Purpose: Separation by Wetherill magnetic separator at 2 amps.

Samples: (1) Table Concentrates from Tabling Test No. 1, 2, and 3

(2) Spiral Concentrates from Spiral Test No. 3

Remarks: The amount of high-magnetic material removed was about 20 percent of the total amount. This percentage would be considered as very high in actual practice.

Results: Following results were obtained from the above test.

Sample	Size	Pct. Assay of Concentrated Product After Removal of high-magnetic material			New Cr:Fe Ratio	Original Cr:Fe Ratio
		Cr_2O_3	Cr	Fe		
1	-28+100	51.90	35.51	12.5	2.8	2.5
2	-35+100	52.10	35.65	13.15	2.7	2.5

Conclusions: The following conclusions were drawn from the results of the above four magnetic separation tests.

1. In all cases, with all the magnetic separators it is possible to increase the chromium to iron ratio of the concentrates from 2.5:1 to about 2.8:1.
2. It seems that on the removal of free-iron bearing and higher-iron-bearing material there is a corresponding increase in chromium content and decrease in the iron content, so that the overall

chromium to iron ratio is increased up to 2.8:1. This seems to be true up to a certain limit only, after which there is a decrease in both the chromium and iron content so that there is no appreciable change in the ratio.

3. The validity of the above assumption is confirmed by the results of the tests 3 and 4 in which the same new ratios were obtained although the current applied in one case was twice that of the other.

Note: As stated previously, in all the above tests, iron was determined analytically as R_2O_3 because the amount of titania, zirconia, columbia, etc. in the ore was very small. However from the previous determination it was known that the above rarer elements amounted to about 0.4 percent.in the ore and about 0.5 percent in the concentrates. Thus the actual percentages of iron in the above tests are lower than as indicated. Taking the above fact into consideration the chromium to iron ratio in the final concentrates is increased from 2.8:1 to about 2.9:1 which is the ultimate limit.

SUMMARY AND CONCLUSIONS

Summary: The chromite ore under investigation came from the province of Baluchistan in the country of Pakistan, and was obtained through the courtesy of Pakistan Industries Ltd., Karachi, the miners for chromite in Pakistan. The above chromite ore is of great economic importance to the country, as it is one of the chief exports badly needed to obtain dollars and sterling exchange.

The problem involved in this investigation was to investigate the possibilities of treating the above low-grade chromite ore by the usually feasible concentration methods in order to obtain the required commercial grades ore, a minimum of 45 percent Cr_2O_3 for a second grade product (worth $17.00 per long ton) and a minimum of 48 percent Cr_2O_3 with a chromium to iron ratio of 3:1, for a first grade product (worth $37.00 per long ton).

The mineragraphic examination in combination with chemical analysis revealed that the chromite mineral was not very pure and that it consisted of about 54 percent Cr_2O_3, 17 percent iron oxide, 16.5 percent alumina, and 12.5 percent magnesia. The gangue minerals which amounted to 20 percent of the total weight, occurred as separate entities, and consisted of serpentine, olivine and calcite, with serpentine predominating.

The screen-sizing and size-assay tests showed that no liberation occurred up to 35-mesh while complete liberation occurred below 150-mesh. The best size range for commercial treatment was found to be between minus 65-mesh and plus 150-mesh, because between these two sizes the content of the valuable chromite mineral was the highest and the gangue content was the least.

Preliminary investigations showed, that the above chromite mineral contained about 54 percent Cr_2O_3, that the best working range was between

65 and 150-mesh, and that the difference in the specific gravity between the valuable chromite mineral (sp. gr. 4.6) and the gangue minerals (average sp. gr. 2.7) was considerable. After these facts were ascertained the usual gravity methods of concentration including the latest ones were attempted. Flotation was applied to investigate the possibilities of treating slimes and magnetic separation to increase the chromium to iron ratio in the final concentrates.

In the laboratory, various concentration methods were tried to investigate the possibilities of treating the chromite ore and to determine the best size range and conditions for each method. The concentration methods included in the investigation were sink-float, tabling, flotation, Humphreys spiral, the Weinig Concentrator, and magnetic separation.

In all the above tests it was always possible to obtain a better than the critical grade (48 percent Cr_2O_3) in the concentrates. The highest grade of Cr_2O_3 obtained was 53.57 percent, in the table concentrates on a feed size of minus 100 plus 150-mesh. The least Cr_2O_3 content in any concentrates was 44.91 percent, which was obtained by flotation of gangue minerals away from the chromite. The Cr_2O_3 content in the tailings ran from as low as 13.35 percent in tabling tests, to as high as 40.49 percent in case of flotation of the valuable mineral chromite. The percent distribution or recovery in all the tests always exceeded 80 percent, except for a few cases where the recovery was only 65 percent. The highest recovery obtained was 93.5 percent in the case of flotation test in which gangue was removed by flotation. The least recovery obtained was 65 percent in the case of Weinig Concentrator test and also in the flotation test in which the valuable mineral chromite was floated.

A brief summary of the results of the tests is given in the Table No. 6.

Table No. 6. Showing the Summary of the Results Obtained by Different Tests

Test	Best Size Range in mesh	Pct. Cr_2O_3 for Best Range		Pct. Recovery for Best Range	Pct. Recovery in the test		Pct. Cr_2O_3 in concentrates		Remarks
		Conc.	Tails		Highest	Least	Highest	Least	
Tabling 1	-48+65	52.50	15.30	94	94	79	53.57	51.42	Tabling was still the best method for chromite concentration.
2	-65+100	51.76	13.35	93					
Sink-Float	-35+100	50.58	-	84	84	79.2	50.58	45.24	Best size range was too fine for sink-float process in practice.
Flotation	-100 (slimes)	44.91	28.49	93.5	93.5	65	50.82	44.91	Flotation of gangue was better than flotation of valuable mineral chromite.
Spiral Concentration	-35+100	51.94	23.24	84	84.5	80	52.42	51.42	Best method found. Worked very well with classified feed in all ranges, including slimes.
Weinig Concentrator	-14+48	50.82	35.72	65	65	-	50.82	-	Showed very good promise.

From an inspection of the table it is revealed that all the above mentioned methods except sink-float showed good promise. The older method tabling and the modern spiral showed the best performance, and they could be applied to all size-ranges of the material except slimes, which could be efficiently treated by flotation.

Tabling with all its disadvantages was still found to be the best method for treatment of the chromite ore, especially where grade of concentrates and low chromite loss in tailings were concerned. The table results were better when a closely sized feed was used, and a great "kick" was applied to the table. It was possible to treat successfully all the sizes (from -28 to plus 150-mesh) except slimes.

Sink-float tests gave good results on finer sizes than the coarser ones for which it is suitable. This was expected as there was no liberation occurring in sizes coarser than 35-mesh. However, there are possibilities that this method can be successfully applied in the primary stages of concentration to remove some percentage of freely occurring gangue mineral (from 1/4 inch to 10-mesh) and thus reduce the tonnage to be treated in subsequent concentration steps.

Flotation treatment was found to be ideal for treatment of slimes when the gangue minerals instead of the valuable chromite were floated. In this case there was a recovery of 93 percent but the grade of concentrates obtained was only 44.91 percent. In actual practice, however, it is possible to mix this low grade concentrate with high grade concentrates from other stages and methods to obtain the critical grade. The main aim was the recovery of the valuable slimy material and this was accomplished by the above treatment.

The modern method of spiral concentration suited the chromite ore

under investigation perfectly. It was possible to treat all sizes (from -28 to - 150 mesh) including the slimes. The test indicated that better recovery and more efficient operation resulted when coarse (-28+65 mesh), fines (-65+150-mesh), and slimes (-150 mesh) products were treated separately. Slimes had to be kept away from coarser material as the slimy gangue material traveled along with the wash water and contaminated the concentrates, at the same time the slimy valuable material traveled with the coarser tailings (lighter material) and thus increase the Cr_2O_3 content in the tails. The above disadvantage was eliminated when the feed was classified into the above-mentioned main sizes.

The latest concentration method by the Weinig Concentrator showed surprisingly good promise and indicated definite possibilities of treating coarse chromite material up to plus 48-mesh, which is very essential in a successful milling operation as it eliminates a large tonnage of the gangue material in preliminary stages of concentration.

Magnetic separation tests were very helpful in treating the final concentrates from all the above concentration methods in increasing the chromium to iron ratio from 2.5:1 to 2.9:1. It was found that the latter ratio of 2.9:1 was the ultimate limit attainable.

Conclusions: From the above investigation of the chromite ore from Baluchistan, Pakistan, the following conclusions were drawn:

(1) The chromite ore from Baluchistan is amenable to treatment by gravity separation methods. These methods include, (a) Sink-float and Weinig Concentrator for coarser sizes ranging from 1/4 inch to 48-mesh; (b) tabling and spiral for the most workable (highest grade and recovery) size range from minus 65 to plus 150 mesh, and (c) flotation and spiral

for the treatment of slimes and finest sizes (-150 mesh).

(2) By the application of the above methods alone or in combination with each other, it is possible to obtain a product which contains 48 percent or more of Cr_2O_3.

(3) The final concentrates from different methods contain a chromium to iron ratio of 2.5:1 and this ratio can be increased up to 2.9:1 by magnetic separation methods. It is not possible to increase the ratio higher than 2.9:1 by ore-dressing methods.

(4) To obtain the best results and the required specifications in commercial practice, it will be necessary to use some combination of spiral concentration, tabling and flotation.

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