

# Vanadium in South Africa (Metal Review Series no. 2)

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## SYNOPSIS

The paper deals briefly with the history of vanadium, and its uses, price movement, and world resources. It then describes the titanomagnetite ore of the Bushveld Complex, and the production of vanadium from this ore at Highveld Steel & Vanadium Corporation Limited, giving details of the various processes used, including the roast-leach, rotary-kiln, electric-smelting, shaking-ladle, and basic-oxygen-furnace operations. The paper concludes with a very brief account of the treatment of Highveld slags in Europe for the production of vanadium pentoxide and ferrovanadium.

## SAMEVATTING

Die referaat handel kortliks oor die geskiedenis van vanadium en die gebruike, prysveranderinge en wêreldbronne daarvan. Dit beskryf vervolgens die titanomagnetieterts van die Bosveldkompleks en die produksie van vanadium van hierdie erts by Highveld Steel & Vanadium Corporation Limited, en verstreke besonderhede van die verskillende prosesse wat gebruik word, insluitende die rooster-loog-, draaioond-, elektriese-uitsmelt-, skudgietspot- en basiese suurstofoondbewerkings. Die referaat sluit af met 'n kort verslag oor die behandeling van Highveldslakke in Europa vir die produksie van vanadiumpentoksied en ferrovanadium.

## History of Vanadium

In 1801 Del Rio expressed the opinion that a Mexican ore that he had analysed contained a new metal, which he called *erythronium*—from the Greek *erythros* meaning red—because it furnished red salts when treated with acids. Del Rio abandoned his opinion when four years later Collet-Descostilis claimed that the supposed new metal was impure chromium oxide. In 1830, Sefström realized that the wrought and cast iron produced from the ore supplied from the Taberg Mine in Sweden was of particularly high quality. He described a new mineral that he found in these Swedish iron ores, and suggested the name *vanadium*, after Freya Vandis, the Scandinavian goddess of love and beauty. One year later, Wöhler identified Sefström's vanadium and Del Rio's erythronium as the same material.

In 1831, Berzelius investigated vanadium, and was under the impression that vanadium oxide was the metal itself. At around 1850, Fritzsche produced some vanadium compounds from pig iron by dissolving the metal in sulphuric acid, and in 1867 H.E. Roscoe isolated the metal. In 1882, vanadium phosphate was produced by the Le Creuzot Steelworks from Bessemer slags that had a vanadium content of 1,1 per cent. The annual production, about 60 t, was consumed by aniline-black dye factories.

Vanadium entered the metallurgical industry only many decades later, when new and more efficient processes were developed for the production of the metal and its alloys. Initially, ferrovanadium was produced from vanadium oxides in an electric-arc furnace (Moissan, 1894). With the introduction of Goldschmidt's aluminothermic reduction process in 1897, technology became available for the efficient production of high-grade ferrovanadium. However, the problem was a short supply of vanadium, which was limited to small quantities of lead-vanadium concentrates supplied by various mines scattered over the world. The supply of vanadium improved substantially

when the vanadium-rich asphaltite deposit at Minas Ragra was discovered in the Peruvian Andes in 1905, and, shortly afterwards, the Colorado carnotite deposits were identified.

In 1896, the Firminy Steelworks in France produced three armour plates in which vanadium was used, and these plates were found to be far superior to those containing no vanadium<sup>1</sup>. But the large-scale commercial use of vanadium began only when Arnold, of Sheffield College, and Hirst, of Osborn's famous tool-steel manufacturers in Sheffield, produced tungsten tool steels at the beginning of this century. In 1905, high-speed chromium-vanadium tool steels were displayed at the Paris exhibition.

Between 1903 and 1905, the addition of vanadium to structural steels was developed by Sankey and Smith in Britain, and by Choubey in France. Henry Ford recognized the potential of the high strength and lightness of vanadium-alloyed steels for crankshafts and springs for motorcars, and by World War I vanadium-alloyed steels had become firmly established.

In the Republic of South Africa, vanadium was first produced in the late nineteenth century in the form of lead-vanadium concentrate by the Doornhoek Lead Mine, near Zeerust<sup>2</sup>. However, large-scale production started only in 1957, when the American-owned Minerals Engineering Company established a mine at Kennedy's Vale, some 20 km south-west of Steelpoort Station. The vanadium was extracted from the ore at the company's Witbank plant by the roast-leach process route.

## Consumption of Vanadium

Today, the following are the major consumers of vanadium<sup>3</sup>:

Steel industry	85%
Non-ferrous alloys	9%
Chemicals and ceramics	3%
Cast irons	1%
Other	2%

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The consumption of vanadium in different steel types by the major vanadium consumers in the Western World, the U.S.A., Japan, and West Germany is shown in Table I.

TABLE I  
CONSUMPTION OF VANADIUM BY U.S.A., JAPAN, AND W. GERMANY  
IN 1982<sup>3</sup>

Application	Vanadium, t	% of total
HSLA steels*	3141,5	34,5
Full alloy steels†	1040,7	20,2
Stainless steels‡	74,6	0,8
Other§	4052,0	44,5
Total	9108,8	100,0

\* High-strength low-alloy steels

† Including alloy tool steels, heat-resistant steels, etc.

‡ Stainless steels with a minimum chromium content of 11%, including heat-resistant steels

§ Estimated consumption

The most significant consumption of vanadium is initially in the manufacture of tool steels, since vanadium carbides impart increased hardness and strength at high temperatures, better wear resistance, and improved cutting-tool performance. Today the major consumption of vanadium is in high-strength low-alloy (HSLA) steels for the manufacture of high-strength pipelines for the transportation of gas and oil over long distances. Other applications for vanadium are in heavy-duty rails and high-strength cold-formed steels for the automotive industry.

#### Effect of Vanadium in Steel

The following are the main effects of the addition of vanadium to steel<sup>3</sup>.

- (1) Vanadium forms carbides, which impart improved hardness and wear resistance to tool steels at elevated temperatures.
- (2) The precipitation of vanadium carbide and nitride provides extra strength to structural and forging steels. The vanadium carbide and nitride precipitates limit the grain growth, and thus increase the strength and toughness of steels.
- (3) Vanadium delays the formation of bainite, i.e. it increases the hardenability, and is therefore added as an alloying element in fully heat-treated steel.
- (4) Vanadium is a ferrite stabilizer, and therefore does not delay the formation of ferrite, thereby suppressing the formation of bainite. These steels are suitable for use as welding steel under conditions of high heat input.
- (5) As vanadium is a strong nitride former, it is a suitable alloying element for case-hardened steels.
- (6) Vanadium delays the formation of pearlite, and is therefore used for steels with ferrite-martensite structures.

As shown in Table I, substantial amounts of vanadium are consumed in the production of HSLA steels, which exhibit yield points higher than 276 MPa. The content of alloying elements, such as vanadium, niobium, titanium, and molybdenum, in HSLA steels is usually less than 0,1 per cent, and these steels achieve their strength in the hot-rolled or normalized condition. HSLA steels can have the strength and toughness of quenched and tempered grades, together with the formability and

weldability of low-carbon steels. Vanadium is often used in HSLA steels because of its strengthening effect by precipitation hardening of the ferrite and refining of the ferrite grain. A large proportion of HSLA steels is used in the construction of long-distance pipelines.

Some HSLA steels exhibit a dual-phase structure, and are suitable for use in automotive components because of their good formability. These steels are characterized by a microstructure consisting of islands of a hard martensitic phase in a matrix of softer ferrite, and their strength is substantially enhanced by work-hardening during the cold-forming process. These steels also find an application in pipelines.

#### Price Movement of Vanadium

The four expensive alloying elements in HSLA steels are vanadium, niobium, titanium, and molybdenum. The mechanical properties of such steels are specified, but their chemical composition allows many combinations of alloying elements. However, the substitution of one alloying element for another may require changes in the processing of the steel if the specified physical properties are to be obtained.

Vanadium, niobium, and molybdenum are added to steels to increase their strength, weldability, formability, and low-temperature toughness. These steels are employed mainly for the heavy plates used in the manufacture of welded pipes, hot- and cold-rolled strips, bars, and sections. The quantities of alloying elements added to steels can vary considerably, as shown in Table II for pipeline steel.

TABLE II  
ALLOYING ELEMENTS IN PIPELINE STEEL<sup>3</sup>

Element	Minimum %	Maximum %
Nb	0,03	0,06
V	0,04	0,08
Mo	0,15	0,30
Cr	0,15	0,25
Ni	—	0,35

The steelmaker has thus some degree of freedom as to the ratio of the alloying elements to be added provided that he has appropriate processing facilities. The price structures and availability of the different alloying elements therefore influence to some degree the ratio of the different elements used.

As Fig. 1 demonstrates, the slow rate of increase in the price of vanadium was similar to that of niobium, but remarkably more consistent and moderate than that of molybdenum. The price increases for vanadium are likely to continue at very modest levels because of the significant resources of the element and the existing, largely under-utilized production capacities.

#### World Resources

The major global source of vanadium has changed over the past fifteen years from uranium-vanadium ores to titanomagnetite ores. The extent of this change is apparent from the fact that during 1979 about 80 per cent of the vanadium produced was recovered from titanomagnetite ores. This change is not surprising in face of the realization that some 98 per cent of the world's known vanadium reserves are contained in titanomagnetites.

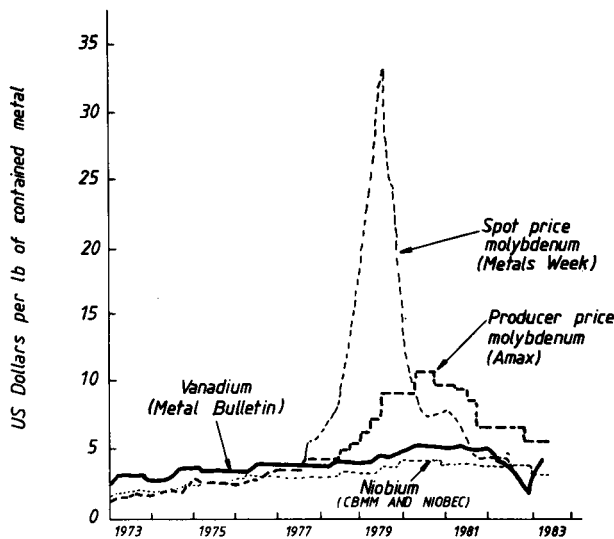


Fig. 1—The price movement of vanadium, niobium, and molybdenum (after IISI report<sup>3</sup>)

About 49 per cent of these reserves are located in the Republic of South Africa, with a further 45,5 per cent being situated in the U.S.S.R.<sup>4</sup>. Of the world's production of vanadium ore during 1979, about 35 per cent was mined in the Republic of South Africa and about 29 per cent in the U.S.S.R.<sup>4</sup>.

#### Vanadium in South Africa

The world's largest known reserves of vanadium ore are contained in the titanomagnetite seams and plugs of the Upper Zone of the Bushveld Complex. This extremely large, layered, mafic intrusive is situated within the Transvaal in the Republic of South Africa. The important vanadium-bearing titanomagnetites are confined to the Principal Group of magnetite seams at the base of the Upper Zone, the highest vanadium values in the Main magnetite seam occurring at the base of the group<sup>5</sup> (Fig. 2).

The Main magnetite seam has a remarkably consistent tenor of  $1,6 \pm 0,2$  per cent vanadium pentoxide. This seam can be traced for hundreds of kilometres round the elliptical rim of the Complex. The orebody outcrops at Roossenekal, Magnet Heights, Pretoria, Brits, Rustenburg, and north of the Pilanesberg.

The highly magnetic titanomagnetite from the Main seam consists of closely packed, almost equant grains, with interstitial minor accessory silicates. The titanium in the ore is present mainly as a solid solution in the titanium-rich magnetite phase (ulvospinel,  $Fe_2TiO_4$ ), and to a lesser degree as ilmenite. The ilmenite is present as individual grains, as elongated intergranular bodies, or as exsolution lamellae arranged parallel to the octahedral planes of the magnetite<sup>6</sup>.

The vanadium occurs in the ore as a solid solution within the magnetite-ulvospinel, where  $V^{3+}$  has replaced  $Fe^{3+}$ . Researchers have suggested that the vanadium is distributed uniformly throughout the magnetite grains excluding the ilmenite lamellae, and does not occur as a separate mineral phase<sup>7</sup>. Where exposed to weathering, the magnetite has been oxidized to vanadomahemite,  $(FeTi)_2O_3$ , and small concentrations of hematite, without any alteration in the texture of the ore.

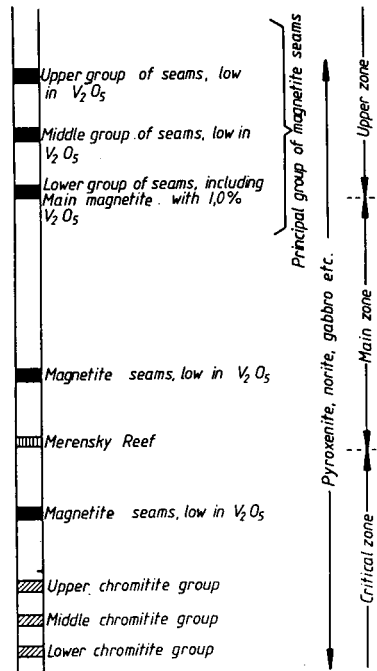


Fig. 2—A generalized section of the titaniferous-vanadiferous magnetite seams in the Bushveld Complex<sup>5</sup>

The mineralogical composition of the titanomagnetite ore explains the limitations that are encountered when the ore is upgraded with the aim of reducing the titania content. Even after the ore has been milled to minus 320 mesh, only 5 to 6 per cent of the ilmenite can be liberated by high-intensity magnetic separation. The high density of the magnetite ore is responsible for its poor reducibility in rotary pre-reduction kilns, and also for its high degree of decrepitation under reducing conditions, which are due to changes in the crystal lattice and to thermo-mechanical stresses.

The vanadium producers in South Africa include Union Carbide (operating at Brits), Transvaal Alloys (operating at Stoffberg), and Highveld Steel and Vanadium. As the author is most conversant with practices at Highveld, the description of vanadium operations in South Africa is confined to the activities of that organization.

#### Mapochs Mine

The opencast Mapochs Mine of Highveld Steel & Vanadium Corporation Limited was commissioned in 1967, and is situated to the north of the village of Roossenekal in the eastern Transvaal. In this region, the Main magnetite seam dips westwards at an angle of about 13 degrees, which nearly coincides with the topography in the vicinity of the Mine.

At the Mine, magnetite fragments and boulders, often referred to as rubble ore, occur to the east of the seam outcrop. Between the Main seam outcrop and the rubble ore lies weathered pavement ore, which is about 0,75 to 1 m thick. The pavement overburden is of negligible proportions. The Main seam follows the pavement on the dip side (Fig. 3).

The compositions of the rubble, pavement, and Main seam ores, which are very similar, are typically as follows:

Fe total	53% to 57%	Cr <sub>2</sub> O <sub>3</sub>	0,15% to 0,6%
TiO <sub>2</sub>	12% to 15%	SiO <sub>2</sub>	1,0% to 1,8%
V <sub>2</sub> O <sub>5</sub>	1,4% to 1,9%	Al <sub>2</sub> O <sub>3</sub>	2,5% to 3,5%

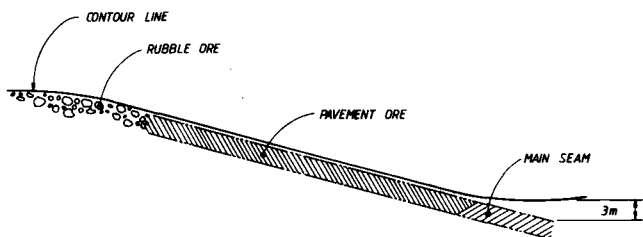


Fig. 3—Schematic illustration of the magnetite ore at Mapochs Mine

The rubble ore is collected by bulldozing the ore into field stockpiles. The pavement ore is broken up either by blasting or mechanically by the use of a hydraulic rock-breaker. This ore is also dozed into the field stockpiles. The overburden covering the seam ore is removed by bulldozers to a vertical overburden depth of 3 m. The exposed, cleaned, solid seam is then drilled, blasted, and pushed into stockpiles.

From the field stockpiles, the ore is loaded by front-end loaders into 35 t capacity Haulpack trucks and transported to the ore-treatment plant, which is illustrated schematically in Fig. 4.

The products from the ore-treatment plant are lumpy ore 4,5 to 25 mm in size, and magnetically up-graded ore fines of minus 4,5 mm sizing. The lumpy ore is railed to the Iron and Steel Works, and the ore fines to the Vantra Roast-Leach Plant.

The ore-treatment plant is rated to handle 3,5 Mt of run-of-mine ore annually. The proven ore reserves to open-cast limit at the mine are in excess of 130 Mt.

The Company is legally bound to rehabilitate the mined-out area. Stripped soil and slimes are therefore brought back, and grass, aloes, succulents, and indigenous trees are planted to encourage the re-establishment of the original flora.

### Extraction of Vanadium by the Roast-Leach Technique

The first industrial plant in the Republic of South

Africa for the recovery of vanadium was built in Witbank and commissioned in 1957 by an American company, Minerals Engineering of South Africa, an associate of Minerals Engineering of Colorado, controlled by Rockefeller interests.

The roast-leach process route was adopted for the production of ammonium metavanadate (AMV) and vanadium pentoxide. Anglo American Corporation of South Africa took over the management of this plant in 1959, and one year later purchased the plant and changed its name to Transvaal Vanadium Company, abbreviated to Vantra.

The process route employed at Vantra for the recovery of vanadium pentoxide from titanomagnetite ore is presented schematically in Fig. 5. The illustrated AMV precipitation route was used exclusively until 1972. During the ensuing year, the ammonium polyvanadate (PV) precipitation route was gradually introduced, and the production of AMV was stopped in 1974. The main motivations for this change were economic and product-quality considerations. Up to 1972 the titanomagnetite ores were supplied by various mines situated around the Bushveld Complex, the Kennedy's Vale Mine being the main supplier. From 1972 onwards, only ore fines from Mapochs Mine were processed.

At Vantra the ore is received by rail. Some of the silica and alumina-rich gangue is liberated from the ore during wet milling, and is separated from the ore pulp by high-intensity magnetic separators before the dewatering stage. The (dry) filter cake has the following typical composition:

V <sub>2</sub> O <sub>5</sub>	1,65%	SiO <sub>2</sub>	1,2%
Fe	56,4%	Al <sub>2</sub> O <sub>3</sub>	3,1%
TiO <sub>2</sub>	14,1%	Cr <sub>2</sub> O <sub>3</sub>	0,4%

On the feed tables, sodium carbonate, sodium sulphate, or a mixture of the two is added to the milled ore before it is charged to the roasting units. These consist of four identical 10-hearth Skinner roasters with a shell diameter of 6,1 m, three small rotary kilns with a shell diameter of 1,52 m and a length of 18,3 m, and one larger rotary kiln with a shell diameter of 2,6 m and a length of 36,5 m.

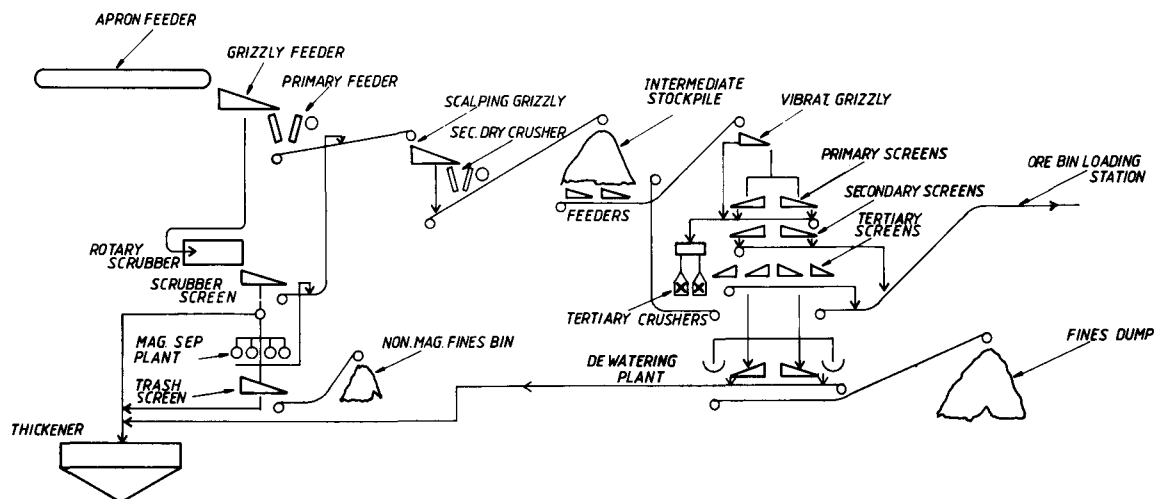


Fig. 4—Flowsheet of the ore-treatment plant at Mapochs Mine

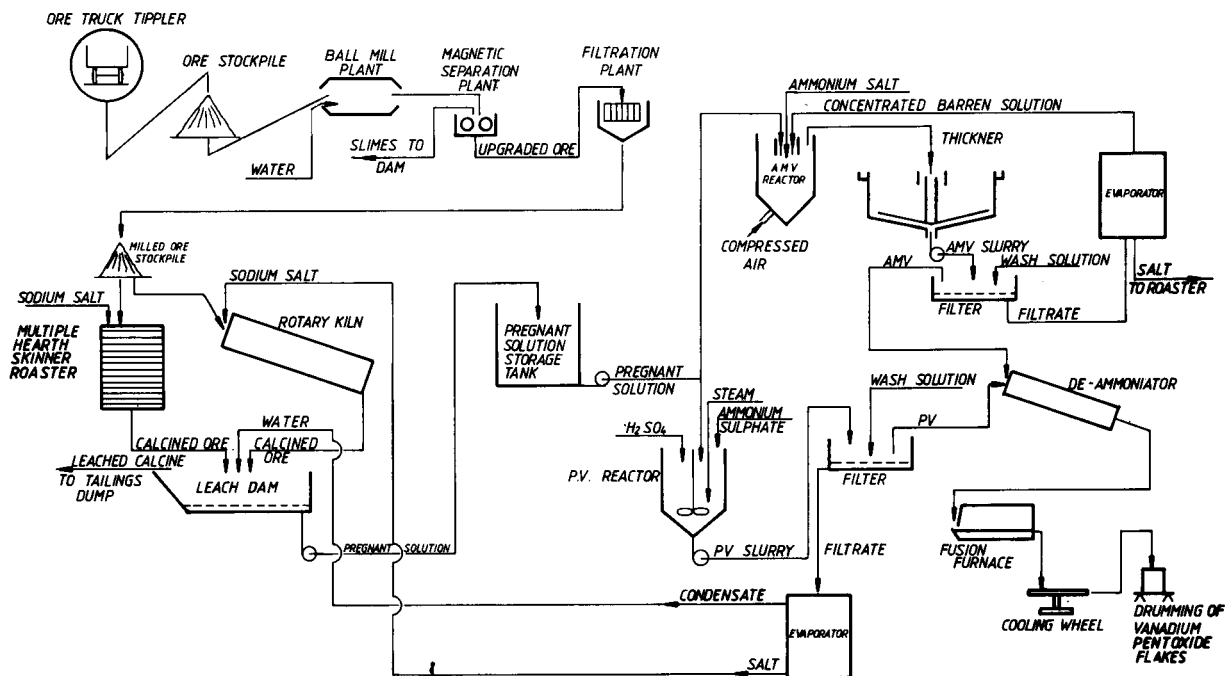
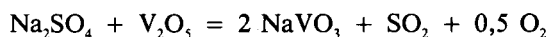
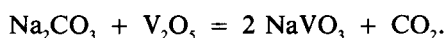


Fig. 5—Flowsheet of the roast-leach process at Vantra

All the roasting units are fired with pulverized coal. The maintenance of an oxidizing atmosphere during roasting is essential for maximum efficiency in the conversion of vanadium pentoxide in the ore to sodium vanadate according to



and/or

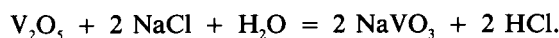


Accurate temperature control in the roasting units is important to avoid excessive ringing in the kilns and hearth build-up in the Skinner roasters. The optimum calcine temperature is largely determined by the purity of the ore and the type of flux being used. For 'dirty' ore or sodium carbonate flux, the sintering temperature of the ore is lower than for an upgraded ore or sodium sulphate flux. High flux levels also lower the ore-sintering temperature. Sintering of the ore must be avoided to ensure that the access of free oxygen from the furnace atmosphere to the ore particles is not impaired, thus optimizing the conversion of vanadium to sodium vanadate. Volkert *et al.*<sup>8</sup> confirmed the experience gained at Vantra in that ore roasted with a flux of sodium sulphate produces a purer pregnant solution than with a flux of sodium carbonate. With the latter flux, the formation of water-soluble sodium aluminate, chromate, and silicate is substantially higher.

The hot calcine is discharged from the roasting units onto drag conveyors, and is transported to quench tanks positioned above the water-filled leaching dams. During the filling of these dams, the sodium vanadate, which is soluble in water, is leached from the ore. The leach liquor, normally referred to as pregnant solution, is pumped to storage tanks once a concentration of 50 to 60 g of vanadium pentoxide per litre is reached. After several

displacement washes, the leached calcine is removed from the leaching dams and is discarded on the tailings dump.

Up to 1974 the ore was roasted with sodium chloride in the Skinner roasters. The disadvantage of this roasting process was the generation of large amounts of hydrochloric acid in the presence of the moisture contained in the ore:



Most of the hydrochloric acid was captured and converted in an ammonia solution to ammonium chloride, which was then used for the precipitation of AMV. However, this process was inefficient, and the production of ammonium chloride and hydrochloric acid vapour presented major atmospheric-pollution and plant-corrosion problems. Furthermore, the conversion of vanadium to sodium vanadate during roasting with sodium chloride was lower than with sodium carbonate or sulphate fluxing.

For the AMV-precipitation process, an excess of ammonium chloride was added to a continuous flow of pregnant solution inside an air-agitated reactor. The overflow from this precipitation reactor passed into a second reactor and finally into a thickener, where the settled AMV precipitate was raked towards the centre discharge port and pumped into filter boxes. The thickener overflow or barren solution was pumped to coal-fired flash evaporators, from where the concentrated ammonium chloride solution was returned to the precipitation plant for re-use.

After filtration and washing, the AMV was discharged from the box filters and fed to externally heated tube spiral-conveyor type deammoniators. During this process, the white AMV powder turned a dark-grey colour owing to the loss of crystal water and ammonia. The vanadium pentoxide powder was melted in Glowbar

heated furnaces at about 850°C, and was then tapped on-to cooling wheels, from where a metal blade scraped the flakes into a bucket elevator for drumming.

For the polyvanadate (PV) batch process used at present, about 20 t of pregnant solution is pumped into a cylindrical reactor, which is equipped with a mechanical agitator, an outlet valve at the bottom of the inverted cone, and a steam supply pipe.

Sulphuric acid is added to the stirred alkaline pregnant solution until a pH value of 5,5 is reached. The required quantity of ammonium sulphate is then added, followed by further additions of sulphuric acid to give a final pH value of 2. This solution is steam-heated and maintained at temperature until the vanadium tenor of the mother liquor has dropped to a value of about 0,5 g of vanadium pentoxide per litre. Once this value has been reached, the coarse, bright-orange precipitate is pumped into box filters, filtered, and washed. The further processing of the polyvanadate is via deammoniators and fusion furnaces as employed earlier for the AMV route. Recently, a rotary dryer-deammoniator was provided to improve the efficiency of the deammoniation operation.

The typical analysis of fused vanadium pentoxide is as follows (in percentages): 95,5 V<sub>2</sub>O<sub>5</sub>, 3,5 V<sub>2</sub>O<sub>4</sub>, 0,25 Na<sub>2</sub>O, 0,15 Fe, 0,006 S, and 0,002 P.

The barren solution from the polyvanadate plant is evaporated in a modern two-stage vacuum evaporator, where the recovered condensate is made available for re-use in the leach dams, and the return salt, after flashdrying, is fed back to the roasting units.

#### **Pyrometallurgical Recovery of Vanadium**

Only vanadium is recovered from the ore by the Vantra roast-leach process. The leached tailings with their high contents of iron, titania, and sodium are dumped.

The Bushveld magnetite ore with its high titania content is not suited to smelting in a blast furnace since titanium carbo-nitrides form and clog up the hearth of the blast furnace. By 1949 Dr W. Bleloch had successfully tested the suitability of submerged-arc furnaces for the smelting of Bushveld magnetite. In these furnaces, additions of carbon can be 'tailored' to the charge so that the iron and vanadium are reduced preferentially to yield a sufficiently carburized, low-titanium pig iron while the bulk of the titania is absorbed in the slag<sup>9</sup>. Dr Bleloch had also demonstrated that the vanadium could be recovered from this pig iron as a slag rich in vanadium pentoxide by the use of a side-blown air converter.

In 1960 the Anglo American Corporation of South Africa established the Highveld Development Company Limited with the tasks of developing a route for the recovery of iron and vanadium from the Bushveld titanomagnetite ore, of evaluating the availability and magnitude of suitable ore reserves, and, finally, of conducting a market survey of the global demand for vanadium.

During 1961 the Highveld Development Company Limited began testwork at Witbank in their new pilot plant, which was designed to produce up to 10 t of pig iron per day. The main features of this pilot plant were a pre-reduction rotary kiln and a submerged-arc furnace for the production of pig iron, an oxygen top-blown shaking ladle for the recovery of vanadium from the pig iron,

a basic oxygen converter (BOF) for the processing of the pre-blown iron to steel, and ingot-casting facilities. By March 1963 this pilot plant had produced about 5 kt of vanadium-bearing pig iron and 1,5 kt of steel.

By that time also, the geological exploration programme had proved the presence of at least 200 Mt of magnetite ore to opencast limits in the Roossenekal district.

In March 1963, after the completion of the pilot-plant tests, Davy and United Engineering Company of Sheffield was commissioned to undertake an engineering study for a full-scale integrated iron, steel, and vanadium plant based on the pilot-plant concept.

#### **The Iron-making Division of Highveld**

##### *The Rotary-kiln Plant*

Early in 1968 the full-scale production plant was commissioned. The Iron Plant consisted of four Lurgi rotary kilns and four 27 MVA closed-top submerged-arc Elkem furnaces (Fig. 6).

Because of the poor kiln availability, a fifth kiln was commissioned in 1972 to provide sufficient mix for the smelters. Together with a fifth smelter (45 MVA), a sixth kiln was provided in 1974, and in 1976 a seventh kiln was commissioned, together with a sixth (45 MVA) smelter. During 1976, the first four Elkem furnaces were uprated and equipped with higher-rated transformers: 33 MVA for No. 1 and No. 2, and 45 MVA for No. 3 and No. 4 furnaces respectively. Three more kilns were commissioned, one each during 1977, 1980, and 1981, and, with this configuration of 10 pre-reduction kilns and 6 submerged-arc smelters, the development of No. 1 Iron Plant was completed.

Additional iron-making capacity is provided by No. 2 Iron Plant, which consists of three Lurgi rotary kilns, identical in size to the kilns installed in No. 1 Iron Plant, and one 63 MVA Demag submerged-arc furnace. This plant will be commissioned only after the present recession in the steelmaking industry.

Ore and metallurgical coal are delivered by train and stored in covered stockpiles, and dolomite is received by rail and stored in the weighfeeder bunkers of the kilns. Quartz and duff coal are delivered by road trucks. The duff coal is stored in a covered stockpile prior to being milled and used as pulverized coal for kiln firing. The quartz is fed direct to the kiln weighfeeder bunkers.

The dimensions of all the kilns at Highveld are identical, having a length of 60 m and a shell diameter of 4 m.

The firing of the kilns is co-current and by means of pulverized coal, which is supplied pneumatically from a common ball-mill plant. Combustion air is introduced into each kiln at the feed end from air pipes arranged along the kilns (Fig. 7), and air-injector rings situated at the inlet end of the kilns. The air pipes and air-injector rings are connected to air fans mounted on the outside of the kiln shell. The supplies of air and pulverized coal are regulated to maintain a temperature profile throughout the kiln length close to the maximum of 1140 °C.

The first air-injector rings were installed into No. 9 kiln. Previously, the kilns had been equipped with air pipes only. The reasons for the installation of air injectors were as follows:

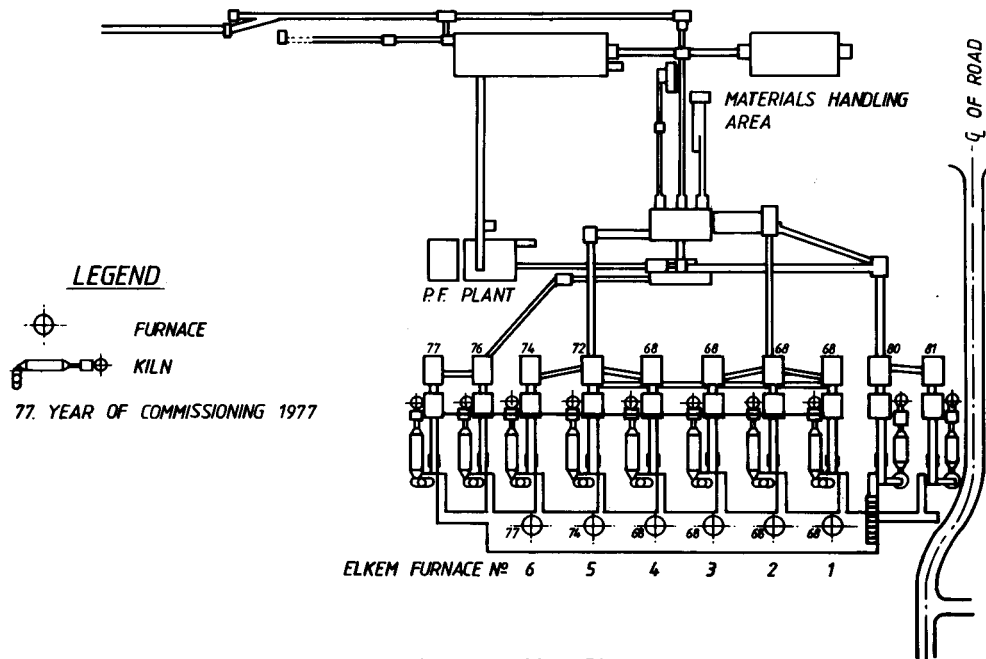


Fig. 6—Development of Iron Plant No. 1

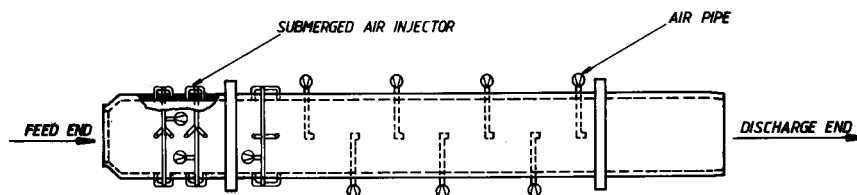


Fig. 7—Schematic diagram of a rotary kiln with air pipes and submerged air injection

- (a) to establish an alternative to the air pipe system because of the short life of air pipes in the inlet zone of the kiln;
- (b) to provide a means of increasing the heating rate of the kiln burden: if the volatile content of the metallurgical coal is burnt inside the charge bed, the heat transfer from the combustion gas to the charge is improved and a higher degree of ore pre-reduction is achieved.

The air injectors are confined to the inlet zone of the kiln, where the burden can absorb the heat without the ore particles fusing together. Plant trials are on-going to establish the most effective configuration of air pipes and submerged air injectors.

The hot kiln discharge collects in the kiln hoppers, from where it is transferred batch-wise into hot-charge skips; these are transported by means of rail-mounted hot-charge cars to the feed hoppers of the smelting furnaces.

The following raw materials are charged to the kilns:

1. Magnetite ore  
Sizing: 4,8 to 32 mm  
Analysis: 54% Fe, 14% TiO<sub>2</sub>, 1,6% V<sub>2</sub>O<sub>5</sub>
2. Greenside No. 5 Seam metallurgical coal at 430 kg of coal per ton of ore  
Sizing: 6 to 60 mm

Analysis: 16% ash, 30% volatile matter, swelling index 1 to 1,5, ash fusion temperature 1450 °C

3. Dolomite at 220 kg per ton of ore  
Sizing: 6 to 32 mm  
Analysis: 30% CaO, 20% MgO, 1% SiO<sub>2</sub>
4. Quartz at 40 kg per ton of ore  
Sizing: 6 to 32 mm  
Analysis: 98% SiO<sub>2</sub>.

Dolomite and quartz are added to flux the titania into a fluid smelter slag.

The object of the kiln operation is to pre-reduce the ore to the extent of 50 to 70 per cent pre-reduction, to calcine the coal and dolomite, and to provide a hot charge for the smelting furnaces. The advantages of a hot, pre-reduced charge are either a decrease in the consumption of electric power to less than 50 per cent of that required for a cold feed, and a proportional increase in the smelting rate.

The combustion of pulverized coal at the inlet end of the kiln supplies sufficient thermal energy to dry and heat up the mix and to initiate the devolatilization of the metallurgical coal. Towards the middle and discharge end of the kiln, heat is provided by the combustion of the remaining volatile matter and some fixed carbon from the metallurgical coal.

The feed rates of the kiln vary from 30 to 40 t/h, depending largely on the availabilities of the rotary-kiln plant and the smelters, as well as on the smelting performance of the furnaces.

### Electric-smelting Plant

The six smelters of No. 1 Iron Plant are accommodated in one line in the smelter building. The furnaces are of closed-top design, with a shell 14 m in diameter, and are equipped with three Söderberg electrodes with diameters of 1,6 m. The furnace bunkers can be charged with hot mix from any of the kilns on line. The burden moves by gravity from the furnace bunkers through charging shafts into the furnaces. The furnace off-gas is cleaned in venturi washers, and is then pumped to a gas holder for distribution to the Steel Plant and to the re-heat furnaces of the Structural Mill.

Each furnace is equipped with two tapholes positioned just to the left and right of No. 1 electrode. The two tapholes are used alternately. Pig iron and slag are separated by a weir placed in the tapping launder; the hot metal flows into railroad-transfer ladles, and the slag into slag pots, which are transported to the slag dump by road carriers.

The furnaces are tapped after a power input of 80 to 100 MW. Under normal operating conditions, the power input rate varies from 20 to 24 MW for furnaces 1 and 2, and 22 to 28 MW for furnaces 3 to 6.

The daily smelting capacity of this plant is 2250 t of pig iron, 1750 t of titania-rich slag, and about  $0,7 \times 10^6 \text{ m}^3$  of gas ( $3,8 \times 10^6 \text{ MJ}$ ). Typically, the pig iron contains the following:

3,5% C	0,3% Cr
1,22% V	0,25% Mn
0,2% Ti	0,07% S
0,2% Si	0,08% P.

The smelter slag has the following composition:

32% $\text{TiO}_2$	14% $\text{Al}_2\text{O}_3$
22% $\text{SiO}_2$	0,9% $\text{V}_2\text{O}_5$
17% CaO	0,17% S.
15% MgO	

Elkem slags have good fluidity at temperatures higher than 1350 °C, and ferrous oxide contents of 1 per cent or more. To maintain the ferrous oxide level between 1 and 1,5 per cent, the carbon input to the smelting furnace must be accurately controlled.

### Steel-making Division

The steel-making division comprises the shaking ladle bay, the BOF bay, the casting-ladle bay, and the continuous-casting bay (Fig. 8). Adjacent to the Steel Plant are the plant for the treatment of vanadium slag, the raw-materials storage silos, and the pollution-control equipment. The shaking-ladle bay features 4 shaking-ladle emplacements, 16 shaking ladles, and three 180 t overhead cranes.

A shaking-ladle emplacement consists of a triangular frame into which the shaking ladle is lowered until the three trunnion pins of the ladle are firmly supported in

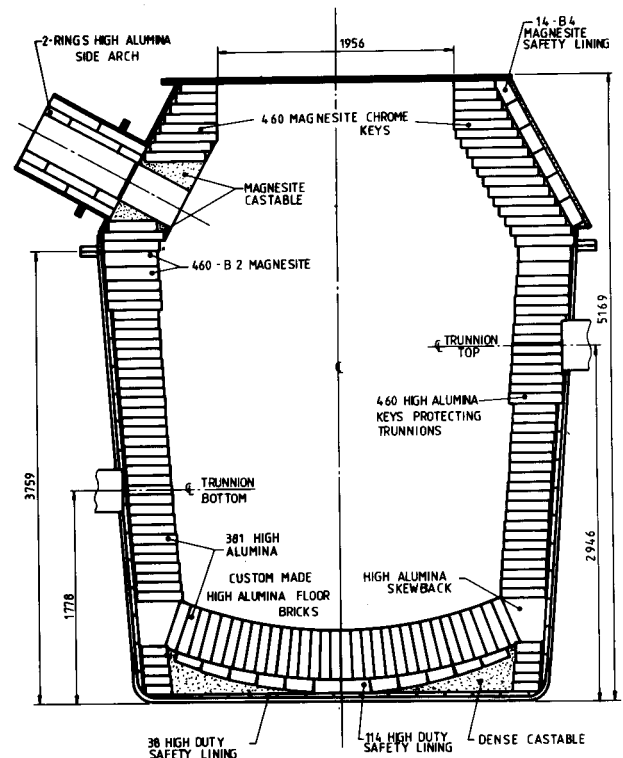


Fig. 8—Schematic diagram of the lining of a shaking ladle

the V-shaped notches provided on the shaking frame. The frame itself is mounted on three crank bearings. Two of these crank bearings are connected to d.c. electric motors to provide speed control. The eccentricity of the shaking frame in motion is 200 mm.

A water-cooled hood is swung over the shaking ladle before the pig iron is oxygen-blown to convey the evolved fume, via refractory-lined gas off-takes, to the disintegrators. The water-cooled hood provides support for the additions chute, the liquid-metal sampling device, and the oxygen lance. The oxygen lance is water-cooled and has a straight copper nozzle 75 mm in diameter. The oxygen lance can be lowered by up to 3,6 m into the shaking ladle.

Overhead bunkers and weighfeeders allow additions of anthracite, ore, and mill scale to be made to the shaking ladle during the blowing cycle.

The shaking ladles serve both as hot-metal storage and reaction vessels, and consist of a slightly tapered barrel and a flanged-on inverted cone equipped with a tapping spout. The ladle height is 5,1 m, and the maximum internal diameter at the top of the barrel is 3,1 m. The working lining inside the ladle barrel consists of high-fired bricks with an alumina content of 60 per cent. The cone is lined with chemically bonded tar-impregnated high-fired magnesite-chromium bricks (Fig. 8).

The nominal shaking-ladle capacity is about 80 t of metal. The mass of a newly lined shaking ladle is about 115 t, of which the lining weighs about 35 t. The cone refractory wear is reduced by regular gunning with a protective phosphate-bonding magnesite material. Shaking-ladle refractory lives of around 300 heats are thus obtained.



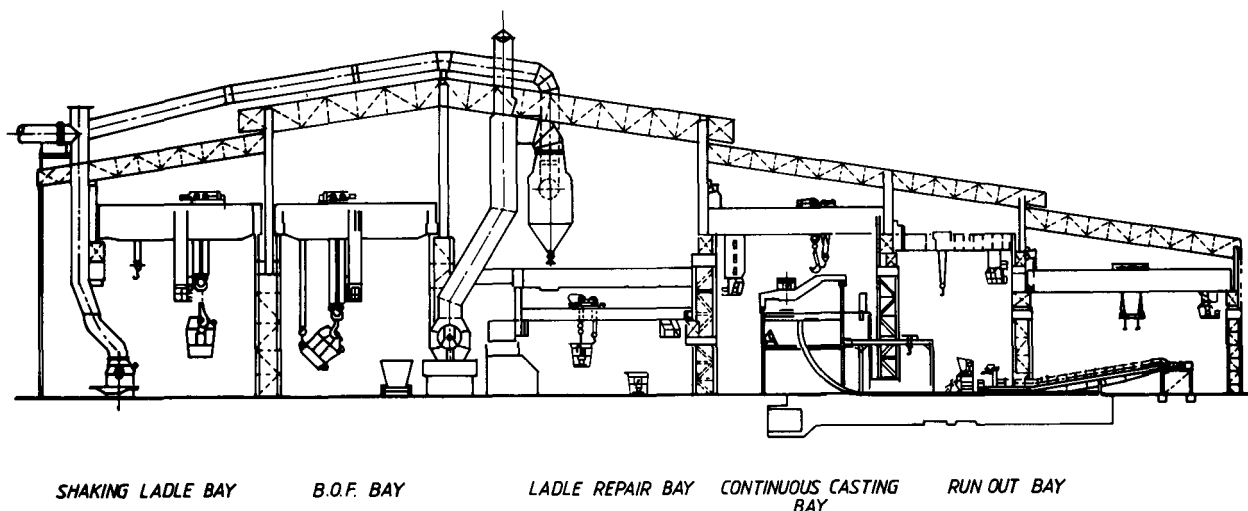


Fig. 9—Cross-section through the Steel Plant at Highveld

### The Shaking-ladle Operation

The objectives of the shaking ladle operation are as follows:

- (1) the production of a dry spinel-type slag containing more than 23 per cent vanadium pentoxide,
- (2) the maximum recovery of the vanadium contained in the pig-iron charge,
- (3) the maximum yield of iron from the steel scrap and pig iron charged,
- (4) the production of blown metal having a sufficiently high temperature and carbon content for subsequent conversion to steel in the BOF,
- (5) the melting of a high ratio of steel scrap to pig iron for increasing the output of liquid steel from the plant, and
- (6) the attainment of high shaking-ladle lives for maintaining adequate storage capacity for pig iron and pre-blown metal.

A typical shaking-ladle charge consists of about 63 t of pig iron and 14 t of scrap. Mill scale and anthracite are added during the oxygen blow to control the temperature of the pig iron and the carbon content of the bath respectively.

The bath temperature must be controlled at less than 1400 °C if a high rate of vanadium and a low rate of carbon oxidation are to be achieved. To dissipate the heat from the oxygen impact area, the metal is agitated by the shaking motion. Only light scrap can be melted at bath temperatures below 1400 °C since the scrap melting takes place mainly by diffusion. Anthracite is added to make up for the carbon losses in the bath. The standard addition of about 3000 kg of anthracite compensates for these losses, which amount to about 2 per cent of the carbon in the metal.

The shaking-ladle slag produced is of a dry consistency at 1400 °C if the following conditions are met.

- (a) The vanadium pentoxide must be greater than 23 per cent.
- (b) The ferrous oxide content must be lower than 30 per cent.
- (c) The silica content must be lower than 20 per cent.

- (d) The amount of smelter slag added with the pig iron must be low.

After the oxygen blow, the shaking ladle is railed by transfer car into the BOF Bay. The pre-blown pig iron is decanted by overhead crane from the ladle via the tapping spout into the tilted BOF, and the slag is retained in the shaking ladle. The shaking-ladle slag is then removed by the up-ending of the ladle above a slag pot.

The typical composition of the slag tipped from the shaking ladle is as follows:

24,5% V <sub>2</sub> O <sub>5</sub>	4,5% TiO <sub>2</sub>
26% FeO	4% Al <sub>2</sub> O <sub>3</sub>
17% SiO <sub>2</sub>	4% MnO
10% Magnetics (Fe)	3% MgO
5% Cr <sub>2</sub> O <sub>3</sub>	2% CaO.

The shaking-ladle slag is transported to the slag-processing plant, where the cooled slag is crushed and lumps of iron are removed by means of an overhead magnet. A screen separates the slag fines for milling from the coarse slag of 6 to 32 mm, which is stored in large concrete silos. The milled slag is drummed, and the coarse slag is shipped in bulk. All the shaking-ladle slag produced is exported.

### Production of Steel

Charges of pre-blown metal and scrap are converted to steel in the BOFs and cast by means of billet, bloom, or slab casters. Blocks and blooms are rolled in the universal combination mill to structural section, rails, round, flats, angles, channels, etc., and the slabs to hot-rolled plate or strip.

A schematic diagram of the Steel Plant is given in Fig. 9.

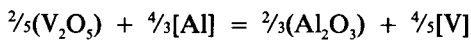
### Recovery of Vanadium from Shaking-ladle Slags

At present, all Highveld slag is exported to slag converters in Europe who employ the roast-leach process. The ground slag is diluted with roasted and leached slag tailings to give a vanadium concentration in the roaster

feed of about 7 to 8 per cent, which prevents the slag from sintering at the required roasting temperature of about 800 °C. Sodium carbonate and/or sodium sulphate are mixed into the roaster feed. During roasting in an oxidizing atmosphere, sodium vanadate is formed, which is removed from the roasted slag by leaching in water. The vanadium is recovered as vanadium pentoxide from the pregnant solution by the same method as employed at the Vantra Plant.

### Production of Ferrovandium

All the European converters of Highveld slag also produce ferrovandium, usually employing the aluminothermic production process. For this, a mixture of vanadium pentoxide flakes, steel punchings, aluminium granules, and lime is placed in a refractory-lined reaction crucible and an ignition mix, e.g. barium dioxide and magnesium, is added. The highly exothermic reaction of the ignition mix is triggered off electrically, and this heat in turn initiates the exothermic reduction of vanadium pentoxide with aluminium according to



$$\therefore G_T^0 = -11\,2350 - 2,65 T \cdot \lg T + 21,21 T.$$

The recovery of vanadium from the vanadium pentoxide to the ferrovandium alloy is about 85 to 93 per cent. Higher recoveries of vanadium are achieved if, immediately after the completion of the aluminothermic

reaction, the slag is kept fluid by means of electrical heating and if the vanadium oxide from the slag is reduced with additions of ferrosilicon, carbonaceous reductant, aluminium, etc.

Special processes have been developed for the production of vanadium alloys rich in carbon, nitrogen, and aluminium for special applications.

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