= halide ; L =
other ligand) .
Many vanadium oxyhalides (formula VOmXn) are known . The oxytrichloride and oxytrifluoride (VOCl3 and VOF3) are the most widely studied . Akin to POCl3 , they are volatile , adopt tetrahedral structures in the gas phase , and are Lewis acidic .

= = = Coordination compounds = = =

Complexes of vanadium (II) and (III) are relatively exchange inert and reducing . Those of V (IV) and V (V) are oxidants . Vanadium ion is rather large and some complexes achieve coordination numbers greater than 6 , as is the case in [V (CN) 7] 4 ? . Oxovanadium (V) also forms 7 coordinate coordination complexes with tetradentate ligands and peroxides and these complexes are used for oxidative brominations and thioether oxidations . The coordination chemistry of V4 + is dominated by the vanadyl center , VO2 + , which binds four other ligands strongly and one weakly (the one trans to the vanadyl center) . An example is vanadyl acetylacetonate (V (O) (O2C5H7) 2) . In this complex , the vanadium is 5 @-@ coordinate , square pyramidal , meaning that a sixth ligand , such as pyridine , may be attached , though the association constant of this process is small . Many 5 @-@ coordinate vanadyl complexes have a trigonal bypyramidal geometry , such as VOCl2 (NMe3) 2 . The coordination chemistry of V5 + is dominated by the relatively stable dioxovanadium coordination complexes which are often formed by aerial oxidation of the vanadium (IV) precursors indicating the stability of the + 5 oxidation state and ease of interconversion between the + 4 and + 5 states .

= = = Organometallic compounds = = =

Organometallic chemistry of vanadium is well developed , although they are mainly only academic significance . Vanadocene dichloride is a versatile starting reagent and even finds some applications in organic chemistry . Vanadium carbonyl , V (CO) 6 , is a rare example of a paramagnetic metal carbonyl . Reduction yields V (CO) ?
6 (isoelectronic with Cr (CO) 6) , which may be further reduced with sodium in liquid ammonia to yield V (CO) 3 ?
5 (isoelectronic with Fe (CO) 5) .

= = Occurrence = =

= = = Universe = = =

The cosmic abundance of vanadium in the universe is 0 @.@ 0001 % , making the element nearly as common as copper or zinc . Vanadium is detected spectroscopically in light from the Sun and sometimes in the light from other stars .

= = = Earth 's crust = = =

Vanadium is the 22nd most abundant element in the earth 's crust ; metallic vanadium is rare in nature (known as the mineral vanadium , native vanadium) , but vanadium compounds occur naturally in about 65 different minerals . Economically significant examples include patronite (VS4) , vanadinite (Pb5 (VO4) 3Cl) , and carnotite (K2 (UO2) 2 (VO4) 2 · 3H2O) . Much of the world 's vanadium production is sourced from vanadium @-@ bearing magnetite found in ultramafic gabbro bodies . Vanadium is mined mostly in South Africa , north @-@ western China , and eastern Russia . In 2013 these three countries mined more than 97 % of the 79 @,@ 000 tonnes of produced vanadium .
Vanadium is also present in bauxite and in deposits of crude oil , coal , oil shale and tar sands . In

crude oil , concentrations up to 1200 ppm have been reported . When such oil products are burned , traces of vanadium may cause corrosion in engines and boilers . An estimated 110 @,@ 000 tonnes of vanadium per year are released into the atmosphere by burning fossil fuels .

= = = Water = = =

The vanadyl ion is abundant in seawater , having an average concentration is 30 nM . Some mineral water springs also contain the ion in high concentrations . For example , springs near Mount Fuji contain as much as 54 ?g per liter .

= = Production = =

Most vanadium is used as a steel alloy called ferrovanadium . Ferrovanadium is produced directly by reducing a mixture of vanadium oxide , iron oxides and iron in an electric furnace . The vanadium ends up in pig iron produced from vanadium @-@ bearing magnetite . Depending on the ore used , the slag contains up to 25 % of vanadium .

Vanadium metal is obtained by a multistep process that begins with the roasting of crushed ore with NaCl or Na2CO3 at about 850 ° C to give sodium metavanadate (NaVO3) . An aqueous extract of this solid is acidified to give " red cake " , a polyvanadate salt , which is reduced with calcium metal . As an alternative for small @-@ scale production , vanadium pentoxide is reduced with hydrogen or magnesium . Many other methods are also in use , in all of which vanadium is produced as a byproduct of other processes . Purification of vanadium is possible by the crystal bar process developed by Anton Eduard van Arkel and Jan Hendrik de Boer in 1925 . It involves the formation of the metal iodide , in this example vanadium (III) iodide , and the subsequent decomposition to yield pure metal .

2 V + 3 I2 ? 2 VI3

= = Applications = =

= = = Alloys = = =

Approximately 85 % of vanadium produced is used as ferrovanadium or as a steel additive . The considerable increase of strength in steel containing small amounts of vanadium was discovered in the early 20th century . Vanadium forms stable nitrides and carbides , resulting in a significant increase in the strength of steel . From that time on , vanadium steel was used for applications in axles , bicycle frames , crankshafts , gears , and other critical components . There are two groups of vanadium steel alloys . Vanadium high @-@ carbon steel alloys contain 0 @.@ 15 % to 0 @.@ 25 % vanadium , and high @-@ speed tool steels (HSS) have a vanadium content of 1 % to 5 % . For high @-@ speed tool steels , a hardness above HRC 60 can be achieved . HSS steel is used in surgical instruments and tools . Powder @-@ metallurgic alloys contain up to 18 % percent vanadium . The high content of vanadium carbides in those alloys increases wear resistance significantly . One application for those alloys is tools and knives .

Vanadium stabilizes the beta form of titanium and increases the strength and temperature stability of titanium . Mixed with aluminium in titanium alloys , it is used in jet engines , high @-@ speed airframes and dental implants . One of the common alloys is Titanium 6AL @-@ 4V , a titanium alloy with 6 % aluminium and 4 % vanadium .

Several vanadium alloys show superconducting behavior . The first A15 phase superconductor was a vanadium compound , V3Si , which was discovered in 1952 . Vanadium @-@ gallium tape is used in superconducting magnets (17 @.@ 5 teslas or 175 @,@ 000 gauss) . The structure of the superconducting A15 phase of V3Ga is similar to that of the more common Nb3Sn and Nb3Ti .

It has been proposed that a small amount , 40 to 270 ppm , of vanadium in Wootz steel and Damascus steel significantly improved the strength of the product , though the source of the

vanadium is unclear .

= = = Other uses = = =

Vanadium foil is used in cladding titanium to steel because it is compatible with both iron and titanium . The moderate thermal neutron @-@ capture cross @-@ section and the short half @-@ life of the isotopes produced by neutron capture makes vanadium a suitable material for the inner structure of a fusion reactor .

The most common oxide of vanadium , vanadium pentoxide V2O5 , is used as a catalyst in manufacturing sulfuric acid by the contact process and as an oxidizer in maleic anhydride production . Vanadium pentoxide is used in ceramics . Vanadium is an important component of mixed metal oxide catalysts used in the oxidation of propane and propylene to acrolein , acrylic acid or the ammoxidation of propylene to acrylonitrile . In service , the oxidation state of vanadium changes dynamically and reversibly with the oxygen and the steam content of the reacting feed mixture . Another oxide of vanadium , vanadium dioxide VO2 , is used in the production of glass coatings , which blocks infrared radiation (and not visible light) at a specific temperature . Vanadium oxide can be used to induce color centers in corundum to create simulated alexandrite jewelry , although alexandrite in nature is a chrysoberyl .

The Vanadium redox battery , a type of flow battery , is an electrochemical cell consisting of aqueous vanadium ions in different oxidation states . Batteries of the type were first proposed in the 1930s and developed commercially from the 1980s onwards . Cells use + 5 and + 2 formal oxidization state ions , and (as of 2016) are used commercially for small scale (c . 0 @.@ 1 - 10 MW , 0 @.@ 1 - 100 GJ) grid energy storage .

Vanadate can be used for protecting steel against rust and corrosion by conversion coating .

= = = = Proposed = = = =

Lithium vanadium oxide has been proposed for use as a high energy density anode for lithium ion batteries , at 745 Wh / L when paired with a lithium cobalt oxide cathode . Vanadium phosphates have been proposed as the cathode in the Lithium Vanadium Phosphate Battery , another type of lithium ion battery .

= = Biological role = =

Vanadium plays a limited role in human biology . It is more important in marine environments than terrestrial .

= = = Vanadoenzymes = = =

A number of species of marine algae produce vanadium bromoperoxidase as well as the closely related chloroperoxidase (which may use a heme or vanadium cofactor) and iodoperoxidases . The bromoperoxidase produces an estimated 1 ? 2 million tons of bromoform and 56 @,@ 000 tons of bromomethane annually . Most naturally occurring organobromine compounds are produced by this enzyme , catalyzing the following reaction (R @-@ H is hydrocarbon substrate) :

R @-@ H + Br ? + H2O2 ? R @-@ Br + H2O + OH ?

A vanadium nitrogenase is used by some nitrogen @-@ fixing micro @-@ organisms , such as Azotobacter . In this role , vanadium replaces more common molybdenum or iron , and gives the nitrogenase slightly different properties .

= = = Vanadium accumulation in tunicates and ascidians = = =

Vanadium is essential to ascidians and tunicates , where it is stored in the highly acidified vacuoles of certain blood cell types , designated " vanadocytes " . Vanabins (vanadium binding proteins)

have been identified in the cytoplasm of such cells . The concentration of vanadium in the blood of ascidians is as much as ten million times higher than the surrounding seawater , which normally contains 1 to 2 µg / l . The function of this vanadium concentration system and these vanadium @-@ bearing proteins is still unknown , but the vanadocytes are later deposited just under the outer surface of the tunic where they may deter predation .

= = = Fungi = = =

Amanita muscaria and related species of macrofungi accumulate vanadium (up to 500 mg / kg in dry weight) . Vanadium is present in the coordination complex amavadin in fungal fruit @-@ bodies . The biological importance of the accumulation is unknown . Toxic or peroxidase enzyme functions have been suggested .

= = = Mammals and birds = = =

Deficiencies in vanadium result in reduced growth and impaired reproduction in rats and chickens . Vanadium is a relatively controversial dietary supplement , used primarily for increasing insulin sensitivity and body @-@ building . Whether it works for the latter purpose has not been proven ; some evidence suggests that athletes who take it are merely experiencing a placebo effect . Vanadyl sulfate may improve glucose control in people with type 2 diabetes . Decavanadate and oxovanadates appear to play a role in a variety of biochemical processes , such as those relating to oxidative stress .

= = Safety = =

All vanadium compounds should be considered toxic . Tetravalent VOSO4 has been reported to be more than 5 times as toxic than trivalent V2O3 . The Occupational Safety and Health Administration (OSHA) has set an exposure limit of 0 @.@ 05 mg / m3 for vanadium pentoxide dust and 0 @.@ 1 mg / m3 for vanadium pentoxide fumes in workplace air for an 8 @-@ hour workday , 40 @-@ hour work week . The National Institute for Occupational Safety and Health (NIOSH) has recommended that 35 mg / m3 of vanadium be considered immediately dangerous to life and health , that is , likely to cause permanent health problems or death .

Vanadium compounds are poorly absorbed through the gastrointestinal system . Inhalation of vanadium and vanadium compounds results primarily in adverse effects on the respiratory system . Quantitative data are , however , insufficient to derive a subchronic or chronic inhalation reference dose . Other effects have been reported after oral or inhalation exposures on blood parameters , liver , neurological development , and other organs in rats .

There is little evidence that vanadium or vanadium compounds are reproductive toxins or teratogens . Vanadium pentoxide was reported to be carcinogenic in male rats and in male and female mice by inhalation in an NTP study , although the interpretation of the results has recently been disputed . The carcinogenicity of vanadium has not been determined by the United States Environmental Protection Agency .

Vanadium traces in diesel fuels are the main fuel component in high temperature corrosion . During combustion , vanadium oxidizes and reacts with sodium and sulfur , yielding vanadate compounds with melting points as low as 530 ° C , which attack the passivation layer on steel and render it susceptible to corrosion . The solid vanadium compounds also abrade engine components .