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Vanadium

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In 2022, the United States did not produce any vanadium from primary ores and concentrates (table 1). The United States continued to be a major producer of vanadium products from secondary sources such as ash, petroleum residues, and spent catalysts. However, secondary producers continued to rely on supplies of imported feedstock for a large portion of their production. Unless otherwise specified, all statistics in this report are in metric tons (t) of vanadium content. In 2022, U.S. estimated production from ash, residues, and spent catalysts was 4,400 t, a 38% increase from that in 2021. Total imports for consumption increased by 31% from that in 2021. The United States imported 2,650 t of ferrovanadium (FeV), 1,980 t of vanadium pentoxide (V_2O_5), and 222 t of other oxides and hydroxides of vanadium, collectively valued at $238 million (table 3). The United States imported 104 t of aluminum-vanadium master alloy valued at $6.87 million (table 4). Imports of vanadium chemicals were 804 t valued at $12.4 million (table 6). The United States exported 172 t of FeV, 143 t of V_2O_5, and 309 t of other oxides and hydroxides of vanadium, collectively valued at $11.0 million (table 3). Exports of aluminum-vanadium master alloy were 50.4 t (gross weight) valued at $2.51 million, and exports of vanadium metal were 7.86 t valued at $362,000 (table 4). Exports of ash and residues were 2,010 t (gross weight) valued at $2.66 million (table 5). Estimated vanadium reported consumption in the United States was 7,510 t, a 6% decrease from that in 2021 (table 1). In 2022, estimated worldwide production of vanadium was 102,000 t, a 3% decrease from that in 2021 (tables 1, 7).

Vanadium's main use was as a hardening agent in steel because vanadium is critical for imparting toughness and wear resistance. These properties are especially important in high-strength low-alloy steels. Vanadium-containing steels can be subdivided into microalloy or low-alloy steels that generally contain less than 0.15% vanadium and high-alloy steels that contain as much as 5% vanadium. Catalysts are the leading nonmetallurgical use for vanadium.

Large-scale energy storage systems have been increasing in use owing to the increase in energy production by renewable energy sources. Vanadium redox flow batteries (VRFBs) have almost unlimited energy storage capacity, zero emissions, very long cycle lives, and can remain unused for long periods of time without negative effects. These advantages have made VRFBs a beneficial solution in different energy management strategy scenarios (U.S. Vanadium LLC, 2022a).

Government Actions and Legislation

On February 24, 2022, pursuant to section 7002 of the Energy Act of 2020 (Public Law 116–260) and using the definition of "critical mineral" and the criteria specified therein, the U.S. Geological Survey (USGS) published the "2022 Final List of Critical Minerals" in the Federal Register (87 FR 10381). The 2022 list of critical minerals, which revised the U.S. critical minerals list published in 2018 (83 FR 23295), included 50 mineral commodities, one of which was vanadium, instead of 35 mineral commodities or mineral groups that were in the 2018 list (U.S. Geological Survey, 2022a).

In July 2022, the USGS Earth Mapping Resources Initiative (Earth MRI), a collaborative project between the USGS and State geological surveys to collect and modernize the Nation's geologic mapping and data resources, released two reports. The first report was Open-File Report 2019–1023–D, which defined focus areas for future data collection for resources for the 13 critical minerals (antimony, barite, beryllium, chromium, fluorspar, hafnium, helium, magnesium, manganese, potash, uranium, vanadium, and zirconium) evaluated during phase 3 of the study in the conterminous United States and Puerto Rico. The second report, Open-File Report 2019–1023–E, similarly defined focus areas for further investigation into critical mineral resources in Alaska. Phases 1 and 2 of the Earth MRI addressed aluminum, cobalt, graphite, lithium, niobium, platinum-group elements (PGEs), rare-earth elements (REEs), tantalum, tin, titanium, and tungsten (Hammarstrom and others, 2022; Kreiner and others, 2022).

The Inflation Reduction Act of 2022 became Public Law 117–169 on August 16, 2022. This law included multiple funding and tax programs to stimulate domestic production, processing, manufacturing, and recycling of critical minerals, including vanadium. Key features of the law included consumer tax credits for electric vehicles with batteries containing critical minerals that meet domestic sourcing requirements, and loans and tax credits for the domestic production and sale of vehicle components that include critical minerals (White House, The, 2023, p. 10, 30, 46–50).

Production

Industry convention for describing the production of V_2O_5 usually applies the terms primary production, joint production, and secondary production depending on the raw source material for production. Primary production takes place from mined ore as mineral concentrates derived from vanadiferous titanomagnetite (VTM) and sandstone-hosted vanadium (with or without uranium). When a VTM iron ore is used to produce iron, vanadium is contained in the crude steel, which must be extracted whether the finished steel will contain vanadium or not. Joint production, therefore, refers to vanadium slags that are produced during steelmaking. Secondary vanadium production takes place from various industrial waste materials, such as vanadium-bearing fly ash, petroleum residues, and spent catalysts.

The major vanadium commodities are aluminum-vanadium master alloys; FeV; oxides and hydroxides of vanadium, such as vanadium trioxide (V_2O_3); vanadium-bearing ash, residues, and slag; vanadium chemicals; and V_2O_5. V_2O_5 is the most widely

produced oxide and most V_2O_5 and V_2O_3 are processed further into FeV.

Energy Fuels Inc.'s White Mesa Mill, near Blanding, UT, had the only vanadium-uranium coproduct recovery circuit in the United States. The company suspended operations in 2020 owing to low vanadium prices. Energy Fuels did not produce any vanadium in 2021 or 2022; however, in 2022, it sold 291 t of its existing V_2O_5 inventory (as finished product, FeV). The company did not expect to produce vanadium in 2023; however, it would continue to monitor its inventory and the vanadium market to make informed decisions on production or sales (Energy Fuels Inc., 2023).

Silver Elephant Mining Corp.'s Gibellini vanadium project in Eureka County, NV, advanced through the permitting stages, with a final Bureau of Land Management (BLM) environmental impact statement expected to be completed in 2023, as the project area is located on Federal land managed by the BLM. The draft environmental impact statement was open for public comment and review from July through September 2022. The Gibellini vanadium project was designed to be an open pit mine with an annual production of approximately 4,600 metric tons per year (t/yr) of V_2O_5. The mine and heap-leach processing facility were expected to produce approximately 52,000 t of V_2O_5 during its 11-year mine life (Silver Elephant Mining Corp., 2021; Bureau of Land Management, 2022).

U.S. Vanadium LLC (USV) operated its facility in Hot Springs, AR, where vanadium ash, residues, and other waste materials were converted into high-purity vanadium oxides and vanadium chemicals used by the chemical, steel, and titanium industries. In addition to the production of high-purity vanadium oxides, USV completed a new electrolyte production facility, in Benton, AR, adjacent to the company's vanadium oxide production facility. The facility produced ultra-high-purity electrolyte and other high-purity vanadium products by recovering vanadium from a variety of post-industrial waste streams (U.S. Vanadium LLC, 2022a, undated).

USV completed a $5.8 million upgrade to its vanadium-processing operations at its Hot Springs, AR, facility. An industrial belt filter system was installed which was expected to improve the facility's vanadium recovery rates and reduce operating costs. The plant's new belt filter system would generate a nonliquid material referred to as 'dry cake,' which has only a 5% to 6% moisture content. The cake would then be recycled for use in other industrial applications, such as the cement industry, eliminating the need to store it in tailings ponds (U.S. Vanadium LLC, 2022b).

AMG Vanadium LLC, a wholly owned subsidiary of AMG Advanced Metallurgical Group N.V. (Netherlands), was a major producer of FeV and other ferroalloys from spent oil refinery catalysts and powerplant residues at its facility in Cambridge, OH (AMG Vanadium LLC, undated). AMG Vanadium completed construction of its new spent catalyst recycling facility in Zanesville, OH. Operations began on October 29, and full capacity was expected in the second quarter of 2023 (AMG Advanced Metallurgical Group N.V., 2023, p. 3).

Gladieux Metals Recycling LLC (GMR), a wholly owned subsidiary of Aleon Metals, operated a facility in Freeport, TX, that had an estimated production capacity of 5,000 t/yr of V_2O_5 and a recycling capacity of 55,000 t/yr of V_2O_5. GMR recycled spent hydroprocessing catalysts produced by petroleum refineries during diesel fuel, jet fuel, and gasoline production (Aleon Metals, 2022, undated).

Consumption

Reported consumption statistics were derived by the USGS from voluntary surveys of U.S. operations. Consumption data in 2007 and before only included statistics derived by one survey. For this survey, more than 50 companies with a broad range of metal consumption were canvassed on a monthly or annual basis. It is important to note that reported consumption data after 2007 included a second annual voluntary survey of domestic vanadium-processing companies. Combined reported consumption data and stocks from both surveys and estimates to account for nonrespondents are included in tables 1 and 2.

Reported consumption of vanadium in the United States was 7,510 t in 2022, a 6% decrease from reported consumption in 2021 (tables 1, 2). Most vanadium is used in the form of FeV, which is used to introduce vanadium into steel to provide additional strength and toughness. In 2022, 4,470 t of FeV was used, representing 60% of the total amount of the reported vanadium consumed (table 2). FeV is available as alloys containing either 45% to 50% vanadium or 80% vanadium. The 45%- to 50%-grade FeV is produced by silicothermic reduction of V_2O_5 in slag or other vanadium-containing materials. Most of the 80%-grade FeV is produced by aluminothermic reduction of V_2O_5 in the presence of steel scrap or by direct reduction in an electric arc furnace.

Metallurgical applications of vanadium, primarily its use as an alloying agent for iron and steel, continued to dominate U.S. vanadium use in 2022. Nonmetallurgical applications included batteries, catalysts, ceramics, pigments, and other miscellaneous vanadium chemical applications. Catalyst and pigment consumption data were withheld to avoid disclosing company proprietary data (table 2). A variety of vanadium chemicals were used in catalysts to manufacture a variety of industrial chemicals and to clean industrial process waste streams. V_2O_5 was used as a catalyst in the sulfuric acid industry and as a corrosion inhibitor for equipment in the petrochemical industry (Yang and others, 2020, p. 19).

VRFBs use a liquid vanadium electrolyte composed of vanadium dissolved in a stable, nonflammable, water-based solution to store energy in large, separate storage tanks. Lithium-ion batteries, however, store electrochemical energy in solid forms of lithium. One of the main advantages of VRFBs is that they provide design flexibility because their power generation and energy storage components are separate. This allows for any storage capacity to be matched with any power output capacity. By pairing variable renewable energy sources, such as wind turbines or solar arrays or panels, excess renewable energy can be captured and used later, giving VRFBs a strategic advantage in applications where balancing the electricity grid would be necessary. Trial VRFB projects have begun where VRFBs were used as electric vehicle charging stations. VRFBs can be added to existing charging infrastructure in urban areas. In remote areas, VRFBs can be paired with solar systems as stand-alone charging systems.

Cost, equipment, and raw material availability, however, continued to be barriers for entry of VRFBs into the battery

market in 2022. The vanadium used in VRFBs accounts for approximately 30% to 50% of the cost of the battery, requiring between 3 and 6 kilograms of vanadium per kilowatthour of energy storage. VRFBs require large electrolyte tanks and pumping systems and are therefore primarily suited for stationary applications. Lithium-ion batteries have been proven to be versatile in not only stationary applications but also in electric vehicles and consumer electronics. This versatility and their capital cost have continued to make lithium-ion batteries the current dominant technology compared to VRFBs (Bushveld Minerals Ltd., 2018, p. 25; Gunjan and others, 2022, p. 5, 8–9; Invinity Energy Systems, undated).

According to leading researchers, VRFBs are one of the most recyclable types of batteries. VRFBs are composed mainly of alloys and plastics that can be recycled easily. The actual vanadium electrolyte accounts for approximately one-third of the total VRFB system and never degrades. A study by USV on a decommissioned VRFB showed that approximately 97% of the vanadium from the vanadium electrolyte was successfully recovered. This high level of recyclability and reusability of VRFBs make it a viable option in many stationary energy storage applications (U.S. Vanadium LLC, 2021).

As of December 2022, U.S.-based manufacturers, all at different levels of establishing VRFB production lines, included Ashlawn Energy, LLC (Binghamton, NY); ESS Inc. (Wilsonville, OR); Perennial Power Holdings, Inc. (New York, NY); Primus Power Corp. (Hayward, CA); StorEn Technologies Inc. (Greenville, SC); and ViZn Energy Systems Inc. (Columbia Falls, MT).

Prices

In 2022, the U.S. average monthly price for domestic FeV (80% vanadium content), as published by CRU Group, ranged from $16.335 per pound to $33.325 per pound of vanadium content, compared with $12.532 per pound to $17.300 per pound in 2021. The 2022 average annual price for U.S. FeV (80% vanadium content) was $23.780 per pound. In 2022, the European average monthly price for FeV (80% vanadium content) ranged from $34.000 per kilogram to $56.650 per kilogram, compared with $26.732 per kilogram to $38.900 per kilogram in 2021. The 2022 average annual price for European FeV (80% vanadium content) was $40.341 per kilogram. The average monthly price for Chinese V_2O_5, published by CRU Group, was $9.250 per pound in 2022, compared with $6.578 per pound to $9.250 per pound in 2021.

Foreign Trade

Vanadium enters international trade in the form of FeV; V_2O_5; vanadium-bearing ash, residues and slag; and vanadium metal including aluminum-vanadium master alloys, waste, and scrap. It is important to note that it is difficult to calculate the total quantity of vanadium entering international trade owing to multiple factors. The first factor is that not all countries publish data for all forms of vanadium. The second factor is that when countries do publish trade data, some data are not distinguished correctly between different vanadium forms. Data can be quoted in terms of either gross weight, V_2O_5 content, or vanadium content. It is also important to note that the U.S. Census Bureau has suppressed some of the data from individual countries in some of their trade reports. When data were suppressed by the U.S. Census Bureau, it has been noted in the footnotes of each table. In table 1, USGS estimates have been included for data that were suppressed by the U.S. Census Bureau.

World Review

Most of the world's supply of vanadium was derived from either coproduct steel slag production or from primary ore production. Production from these two sources is shown in table 7. The leading vanadium-producing nations from these two sources in 2022 remained China (66%), Russia (20%), South Africa (9%), and Brazil (6%).

World vanadium reserves, estimated at 26 million metric tons, are likely sufficient to meet vanadium needs into the next century at the present rate of consumption. Increased recovery of vanadium from fly ash, petroleum residues, slag, and spent catalysts was not included in the reserve estimate and would significantly extend the life of the reserves if included. World reserves for 2022 can be found in the "World Mine Production and Reserves" section of the vanadium chapter of the USGS Mineral Commodity Summaries 2023.

According to Project Blue Group Ltd., global vanadium consumption was estimated to be 111,000 t (vanadium content) in 2022, a 5% decrease from that in 2021 (Project Blue Group Ltd., 2022).

Australia.—Australian Vanadium Ltd. (AVL) completed its bankable feasibility study for its vanadium project in the State of Western Australia, and according to the company, development of the project was subject to raising finance. The project was based on a proposed open pit mine, a crushing-milling and beneficiation plant, and a vanadium-processing plant for final conversion and sale of V_2O_5. Average annual vanadium production was expected to be 11,200 t of V_2O_5 in the form of a 99.5% V_2O_5 high-purity flake with an anticipated mine life of 25 years. AVL was awarded grant money by the Government of Australia to help build the high-purity V_2O_5-processing circuit and a commercial vanadium electrolyte plant. AVL signed a Memorandum of Understanding (MOU) for offtake agreements with USV for the supply of vanadium oxides for vanadium electrolyte production in Australia. The MOU included a license for USV's vanadium electrolyte manufacturing technology to convert the vanadium oxides to the vanadium electrolyte for use in VRFBs in Australia (Australian Vanadium Ltd., 2022, p. 4, 6–9, 13).

Neometals Ltd. completed a prefeasibility study for its Barrambie vanadium-titanium project located approximately 80 kilometers (km) northwest of Sandstone, Western Australia. According to the company, the results of the study would allow Neometals to enter into a formal offtake agreement for the supply of ilmenite and iron-vanadium concentrates with Jiuxing Titanium Materials Co. Ltd. for a period of 5 years (Neometals Ltd., 2022a, p. 1, 4, 13, 21).

TNG Ltd. completed a review of METS Engineering Group Pty Ltd.'s technology and process design study for the development of a production facility to produce a high-purity vanadium electrolyte for the VRFB market. The study confirmed that V_2O_5 would be the preferred form of feedstock

for the facility. The feedstock would be from TNG's Mount Peake vanadium-titanium-iron project in the Northern Territory. TNG also announced that it would collaborate with Ultra Power Systems Pty Ltd., an energy technology company based in Perth, for the supply of vanadium electrolyte and for the installation of VRFBs for the Australian market (TNG Ltd., 2022, p. 2, 8).

Brazil.—Largo Inc.'s (Toronto, Ontario, Canada) Maracás Menchen Mine, located 813 km northeast of Brasilia, produced 10,436 t of V_2O_5 in 2022, essentially unchanged compared with 10,319 t of V_2O_5 produced in 2021 (Largo Inc., 2023, p. 2; undated). In February 2022, Largo announced the creation of Largo Physical Vanadium Corp. that would purchase and hold physical vanadium for use in the company's VCHARGE batteries. In 2021, Largo Clean Energy, a subsidiary of Largo, signed a 10-year offtake agreement with GMR for the purchase of all standard and high-purity grade vanadium products from GMR's Freeport, TX, recycling facility (Largo Inc., 2022a, p. 1–3; 2022b, p. 2).

China.—In June 2022, China's National Energy Administration banned the use of ternary lithium batteries and sodium-sulfur batteries for energy storage owing to safety issues. The ban encouraged major Chinese vanadium producers to consider producing a safer alternative, such as VRFBs. Panzhihua Iron and Steel Group was expected to supply 4,000 t of V_2O_5 for its joint venture with Dalian Rongke Power Group to build a 2,000-cubic-meter-per-year vanadium electrolyte factory in Sichuan Province. In July 2022, Hebei Iron & Steel Group completed construction of a production line with a capacity of 1,000 t/yr of vanadium electrolyte. China's vanadium consumption from the VRFB industry was expected to reach 9,100 t of V_2O_5 equivalent in 2022, an 88% increase from 4,846 t of V_2O_5 equivalent in 2021. However, even with the current expansion, VRFBs would continue to represent a much smaller proportion of energy storage than lithium batteries. Data from the China Energy Storage Alliance showed that lithium batteries accounted for 89.6% of total installed energy storage capacity in 2021 compared with 0.9% for VRFB batteries (Argus Metals International, 2022; Long and Lun, 2022).

Some of the China-based VRFB companies included Big Pawer Electrical Technology Xiangyang Inc. Co. Ltd., Dalian Rongke Power Co. Ltd., LE System Co., Ltd., Shanghai Shenli Technology Co., Ltd., and Shanxi Jinneng Century Technology Co., Ltd. According to the company, Shanghai Shenli Technology is a private entity with funding from the Ministry of Science and Technology of China and the Shanghai municipal government (Shanghai Shenli Technology Co., Ltd., undated).

Czechia.—EVRAZ NIKOM, a.s. (which changed its name to Czech Vanadium, a.s. in 2023) had one processing facility, which was used to process vanadium oxides from China and Russia and from Bushveld Minerals Ltd.'s Vametco Mine (South Africa) into FeV. The processing facility was located in Mnisek pod Brdy, 30 km southwest of Prague (Czech Vanadium, a.s., undated).

Finland.—In December 2022, Neometals agreed to a short-term extension of its agreement with Critical Metals Ltd. (Sweden) to finalize evaluation studies of its proposed vanadium recovery operation in Finland. The facility would include a 300,000-t/yr slag-processing plant in Pori and the company had a 10-year slag supply agreement with Swedish steel producer, SSAB AB. The final decision to form a 50–50 joint venture was expected in the first quarter of 2023, and the project investment decision was expected by June 2023 (Neometals Ltd., 2022b).

Germany.—AMG Advanced Metallurgical Group received approval to build a vanadium electrolyte plant at its subsidiary, AMG Titanium, in Nuremberg. The facility was expected to have 6,000 cubic meters per year of vanadium electrolyte capacity, and production was expected to commence at the end of 2023 (AMG Advanced Metallurgical Group N.V., 2022).

Kazakhstan.—Ferro-Alloy Resources Ltd. (United Kingdom) (FAR) reported that, during the fourth quarter of 2022, the company experienced delays in the delivery of concentrates to its processing plant, which was expected to reduce vanadium production for 2022. FAR signed a new regular concentrate delivery contract with an additional supplier to help avoid future delays, with deliveries expected in March 2023. FAR also modified the design of its new dissociation oven to convert ammonium metavanadate to V_2O_5 to allow for future production of various oxides of vanadium as part of its vanadium electrolyte project. In the fourth quarter of 2023, FAR expected to complete the feasibility study for the development of the Balasausqandiq vanadium project in Qyzylorda Province in southern Kazakhstan (Ferro-Alloy Resources Ltd., 2023, undated).

Russia.—EVRAZ Nizhny Tagil Metallurgical plant (NTMK), an integrated metallurgical complex located in Nizhny Tagil in Sverdlovsk Province, continued to be one of the world's leading processors of VTM. The Vanady Tula facility, located 180 km south of Moscow, used a low-cost, highly efficient technology to process the vanadium slag produced by NTMK into FeV and V_2O_5. EVRAZ Vanady Tula's Research and Development (R&D) Centre continued to focus on decreasing vanadium losses in byproducts. One of the R&D Centre's goals for 2022 was to implement a vanadium recycling facility project. Another goal was to continue to focus on producing battery-grade vanadium oxides for the VRFB market (EVRAZ plc, 2022a, p. 4, 48–49, 82).

In 2022, EVRAZ proceeded with its $228 million vanadium-processing facility at EVRAZ Uzlovaya, in Tula Province, with a design capacity of 8.6 t/yr of vanadium slag. The new vanadium-processing facility would allow vanadium slag to be processed within EVRAZ, instead of having to send vanadium slag to other tolling parties. The company expected the plant to be commissioned in 2025. EVRAZ also confirmed that it maintained all its vanadium supply and conversion chains despite the geopolitical environment in Russia. EVRAZ also increased its share of vanadium products sold under long-term contracts in the first half of 2022 (EVRAZ plc, 2022a, p. 27, 40; 2022b, p. 9–10).

South Africa.—Bushveld Minerals Ltd.'s operations consisted of three mineral assets—the Brits Mine, the Mokopane Mine, and the Vametco Mine—and two processing facilities—Vametco and Vanchem. The Vametco Mine and processing facility were located in Brits, North West Province. The Vametco processing facility produced Bushveld nitro-vanadium (formerly called Nitrovan), a proprietary steel-alloying vanadium carbon nitride product. The Vanchem processing facility consisted of three roasting kilns, a vanadium chemical facility, two FeV-processing facilities, and a V_2O_5-processing plant. Vanchem produced FeV,

V_2O_5, a variety of vanadium chemicals, and had the ability to produce V_2O_3. The Mokopane project was expected to be the primary source of feedstock for Bushveld's Vanchem facility. Bushveld produced 2,705 t of nitro-vanadium at its Vametco facility and 1,137 t of vanadium (657 t of FeV, 288 t of V_2O_5 flake, and 193 t of vanadium chemicals) at its Vanchem facility, for a total of 3,842 t of vanadium at both facilities (Bushveld Minerals Ltd., 2023, undated).

Bushveld expected production in 2023 to be higher than in 2022; however, it acknowledged that production was highly reliant on the consistency of its power supply. In November 2022, Vanchem and the Emalahleni local municipality agreed on a plan to prevent the facility to experience total power loss during scheduled outages. Bushveld was developing alternative energy solutions, including renewable energy solutions, to supplement the requirements of Vanchem (Bushveld Minerals Ltd., 2023).

Bushveld also reported that the Bushveld Electrolyte Company (BELCO) electrolyte manufacturing plant was under construction as planned with a targeted capacity of 8 million liters per year of vanadium electrolyte. Each liter of vanadium electrolyte was expected to contain between 82 and 92 grams of vanadium, with the plant using approximately 1,100 t/yr of vanadium oxide equivalent during full production. BELCO was owned by Bushveld Energy Ltd. (55%) and the Industrial Development Corporation of South Africa (45%) (Bushveld Minerals Ltd., 2023).

Glencore plc's (Switzerland) Rhovan vanadium facility, 30 km northwest of Brits, produced approximately 8,980 t of V_2O_5 in 2022, compared with approximately 9,300 t of V_2O_5 in 2021 (Glencore plc, 2022, p. 6; undated).

Outlook

Since almost all vanadium is consumed in the production of steel, vanadium consumption trends are greatly influenced by trends in steel production. The use of vanadium in a wider range of steels than is currently used is expected to gradually increase. The outlook for consumption in nonferrous alloys is largely dependent on trends in consumption for titanium alloys in business, commercial, and military aircraft.

VRFB batteries have lower environmental effects in terms of battery disposal and have higher energy capacity limits owing to the ability of the system to have very large tanks for the electrolyte solution storage. The battery is also in a nonflammable liquid form. However, VRFB implementations continued to have some major disadvantages including the high cost of the electrolyte used in the battery and the system complexity of the batteries. These factors made it difficult for VRFBs to compete with lithium-ion batteries. According to many analysts, the market leader in flow battery chemistry was vanadium, but researchers continued to work on other chemistries that could potentially be less expensive, and companies were expected to continue to improve VRFBs to make them more competitive in the battery market. Project Blue projected VRFB consumption growth of more than 35% per year until 2027, with China leading the growth (Project Blue Group Ltd., 2022).

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TABLE 1
SALIENT VANADIUM STATISTICS[1]

(Metric tons, vanadium content, unless otherwise specified)

	HTS and Schedule B codes[2]	2018	2019	2020	2021	2022
United States:						
Production from primary ores and concentrates		--	460	17	--	--
Production from ash, residues, and spent catalysts[e]		2,600	3,000	2,900	3,200	4,400
Consumption, reported		9,280	9,900	7,920	8,030	7,510
Imports for consumption:						
Aluminum-vanadium master alloy	8112.99.2000	281	222	101	35	104
Ash and residues[3, 4, 5]	2620.40.0030, 2620.99.1000	2,810	2,120	1,550	1,680	2,240
Chloride oxides and hydroxides of vanadium	2827.49.1000	477	532	176 r	207 r	175
Ferrovanadium[6]	7202.92.0000	2,970	2,280	1,360	2,170	2,650
Hydrides and nitrides, of vanadium	2850.00.2000	72	54	57	200	352
Oxides and hydroxides, other	2825.30.0050	98	105	67	69	222
Sulfates	2833.29.3000	9	74	34	408	117
Vanadates	2841.90.1000	389	73	104	15	92
Vanadium chlorides	2827.39.1000	45	1	11	16	68
Vanadium metal	8112.92.7000	28	45	(7)	(7)	18
Vanadium ores and concentrates[5]	2615.90.6090	331	108	2	4	492
Vanadium pentoxide (anhydride)	2825.30.0010	4,600	3,620	1,670	1,710 r	1,980
Total imports		12,100	9,230	5,130 r	6,520 r	8,510
Exports:						
Aluminum-vanadium master alloy[5]	8112.99.2000	90 r	29 r	14 r	72 r	28
Ash and residues[3, 5]	2620.50.0000, 2620.99.1000	1,430 r	1,280 r	503 r	930 r	1,130
Ferrovanadium	7202.92.0000	575	295	210	173	172
Oxides and hydroxides, other	2825.30.0050	53	750	51	235	309
Vanadium metal	8112.92.7000	39	27	1	4	8
Vanadium ores and concentrates[5]	2615.90.6090	48 r	95 r	92 r	81 r	185
Vanadium pentoxide (anhydride)	2825.30.0010	563	423	50	17	143
Total exports		2,800	2,900	920	1,510	1,970
Stocks, yearend:						
Ferrovanadium		188	197	206	209	184
Other[8]		62	60	63	62	64
World, production from ore, concentrate, slag[9]		89,800	92,800	105,000	105,000	102,000

[e]Estimated. [r]Revised. -- Zero.

[1]Table includes data available through August 30, 2023. Data are rounded to no more than three significant digits; may not add to totals shown. Includes U.S. Geological Survey estimates.

[2]Harmonized Tariff Schedule of the United States (HTS) codes are imports and Schedule B codes of the United States are exports.

[3]Includes both HTS codes 2620.04.0030 and 2620.99.1000.

[4]Includes U.S. Geological Survey estimates for data suppressed by U.S. Census Bureau.

[5]Reported by the U.S. Census Bureau as metric tons of vanadium pentoxide. Data were converted to vanadium content by multiplying reported data by 0.56.

[6]Some data suppressed by the U.S. Census Bureau; not included in ferrovanadium total.

[7]Less than ½ unit.

[8]Includes chlorides, vanadates, vanadium-aluminum alloy, other vanadium alloys, vanadium metal, vanadium pentoxide, and other specialty chemicals.

[9]May include estimated data.

TABLE 2
U.S. REPORTED CONSUMPTION OF VANADIUM, BY END USE AND FORM[1]

(Kilograms, vanadium content)

	2021	2022
End use:		
Steel:		
Carbon	1,460,000	1,210,000
Full alloy	1,770,000	1,770,000
High-strength low-alloy	W	W
Stainless and heat-resisting	88,000	86,000
Tool	W	W
Total	3,320,000	3,060,000
Cast irons	W	W
Alloys (including steels and superalloys)	2,640,000	2,620,000
Chemical and ceramic:		
Catalysts	W	W
Pigments	W	W
Miscellaneous and unspecified[2]	2,070,000	1,830,000
Grand total	8,030,000	7,510,000
Form:		
Ferrovanadium	5,320,000	4,470,000
Other[3]	2,710,000	3,040,000
Total	8,030,000	7,510,000

W Withheld to avoid disclosing company proprietary data; included with "Miscellaneous and unspecified."
[1]Table includes data available through August 30, 2023. Data are rounded to no more than three significant digits; may not add to totals shown. Includes U.S. Geological Survey estimates.
[2]Includes electrical steel and unspecified steel.
[3]Includes vanadium-aluminum alloy, other vanadium alloys, vanadium metal, vanadium pentoxide, vanadates, chlorides, and other specialty chemicals.

TABLE 3
U.S. IMPORTS AND EXPORTS OF FERROVANADIUM, VANADIUM PENTOXIDE (ANHYDRIDE), AND OTHER OXIDES AND HYDROXIDES OF VANADIUM[1]

(Kilograms)

	Ferrovanadium[2]			Vanadium pentoxide (anhydride)[3]			Other oxides and hydroxides of vanadium[4]		
Country or locality	Gross weight (kilograms)	Vanadium content (kilograms)	Value	Gross weight (kilograms)	Vanadium content (kilograms)	Value	Gross weight (kilograms)	Vanadium content (kilograms)	Value
Imports for consumption:									
2021	2,900,000	2,170,000	$92,700,000 r	2,180,000 r	1,710,000 r	$42,000,000 r	102,000	68,700	$2,100,000
2022:									
Austria	1,430,000	1,150,000	54,800,000	--	--	--	--	--	--
Brazil	--	--	--	1,010,000	859,000	25,200,000	136,000	88,400	3,280,000
Canada	1,540,000	1,220,000	53,900,000	--	--	--	--	--	--
China	--	--	--	18,900	10,900	181,000	13	8	2,340
Czechia	(5)	(5)	45,300,000	--	--	--	--	--	--
Germany	5,000	3,970	187,000	72,100	49,900	1,600,000	1	1	3,750
Iceland	--	--	--	--	--	--	490	318	2,800
India	30,000	23,900	1,010,000	--	--	--	1,040	673	11,400
Japan	150,000	79,800	2,540,000	--	--	--	--	--	--
Latvia	152,000	87,300	3,590,000	--	--	--	--	--	--
Russia	40,000	31,900	1,110,000	167,000	152,000	1,590,000	--	--	--
South Africa	2,300	1,630	82,200	1,560,000	912,000	35,800,000	200,000	133,000	5,800,000
Sweden	14,800	6,050	89,400	--	--	--	--	--	--
Ukraine	95,500	47,300	2,310,000	--	--	--	--	--	--
Total	3,460,000	2,650,000	165,000,000	2,830,000	1,980,000	64,400,000	337,000	222,000	9,100,000
Exports:									
2021	240,000 r	173,000	6,500,000 r	XX	17,200	238,000	XX	235,000	2,170,000
2022:									
Australia	--	--	--	NA	407	10,900	--	--	--
Austria	--	--	--	--	--	--	NA	43,700	389,000
Belgium	--	--	--	NA	39,100	1,090,000	--	--	--
Canada	34,000	21,900	962,000	--	--	--	NA	54,800	578,000
Colombia	1,540	1,150	30,900	--	--	--	--	--	--
Dominican Republic	--	--	--	--	--	--	NA	6,970	44,000
Egypt	--	--	--	NA	6,000	45,000	--	--	--
France	--	--	--	--	--	--	NA	828	7,370
Germany	--	--	--	NA	433	4,120	NA	10,700	95,500
India	7,680	5,760	233,000	NA	57,500	226,000	--	--	--
Korea, Republic of	--	--	--	--	--	--	NA	90,400	805,000
Mexico	51,200	33,300	1,320,000	--	--	--	NA	1,010	9,000
Netherlands	149,000	107,000	3,200,000	NA	12,400	290,000	NA	62,500	557,000
Peru	5,750	3,030	145,000	--	--	--	--	--	--
Trinidad and Tobago	--	--	--	NA	24,200	419,000	NA	37,600	445,000
United Kingdom	109	82	2,740	--	--	--	--	--	--
Venezuela	--	--	--	NA	2,940	140,000	--	--	--
Total	249,000	172,000	5,890,000	XX	143,000	2,220,000	XX	309,000	2,930,000

rRevised. NA Not available. XX Not applicable. -- Zero.

[1]Table includes data available through August 30, 2023. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Includes Harmonized Tariff Schedule of the United States (HTS) code and Schedule B number 7202.92.0000.

[3]May include catalysts that contain vanadium pentoxide. Includes HTS code and Schedule B number 2825.30.0010.

[4]Includes HTS code and Schedule B number 2825.30.0050.

[5]Data suppressed by U.S. Census Bureau; not included in "Total."

Source: U.S. Census Bureau.

TABLE 4
U.S. IMPORTS AND EXPORTS OF ALUMINUM-VANADIUM MASTER ALLOYS
AND VANADIUM METAL, INCLUDING WASTE AND SCRAP[1]

	Aluminum-vanadium master alloy[2]			Vanadium metal, including waste and scrap[3]			Vanadium ores and concentrates[4]		
Country or locality	Gross weight (kilograms)	Vanadium content (kilograms)	Value	Gross weight (kilograms)	Vanadium content (kilograms)	Value	Gross weight (kilograms)	Vanadium content[5] (kilograms)	Value
Imports for consumption:									
2021	50,400	35,200	$2,870,000	979	523	$249,000	14,000	4,380 r	$964,000
2022:									
Belgium	5,500	3,850	330,000	--	--	--	--	--	--
Canada	--	--	--	858	858	3,780	1,680,000	490,000	6,840,000
China	118,000	82,200	4,800,000	4	1	4,160	8	2	6,800
Germany	92	89	94,400	17,500	16,900	1,010,000	--	--	--
Latvia	--	--	--	230	225	43,300	--	--	--
Mexico	3,370	3,370	201,000	--	--	--	4,190	1,410	333,000
Poland	--	--	--	250	250	220,000	--	--	--
Russia	21,400	14,800	1,400,000	--	--	--	--	--	--
Turkey	--	--	--	--	--	--	1,600	717	2,470
United Kingdom	10	9	40,300	--	--	--	--	--	--
Total	149,000	104,000	6,870,000	18,900	18,300	1,280,000	1,690,000	492,000	7,190,000
Exports:									
2021	129,000	XX	4,310,000	XX	3,660	154,000	XX	81,400 r	1,890,000
2022:									
Belgium	--	--	--	NA	681	26,300	--	--	--
Cambodia	--	--	--	--	--	--	NA	2,090	48,600
Canada	--	--	--	--	--	--	NA	7,330	111,000
Cayman Islands	245	NA	9,450	--	--	--	--	--	--
China	553	NA	84,900	NA	729	119,000	--	--	--
Ecuador	--	--	--	NA	74	2,850	--	--	--
France	6,590	NA	280,000	--	--	--	--	--	--
Germany	350	NA	18,900	NA	6,370	209,000	--	--	--
Italy	293	NA	7,420	--	--	--	NA	1,030	28,900
Japan	789	NA	95,900	--	--	--	--	--	--
Kazakhstan	37,500	NA	1,880,000	--	--	--	--	--	--
Latvia	--	--	--	--	--	--	NA	1,090	25,200
Mexico	--	--	--	--	--	--	NA	159,000	656,000
Norway	3	NA	2,710	NA	5	5,980	--	--	--
Poland	617	NA	27,900	--	--	--	--	--	--
Romania	1,240	NA	68,100	--	--	--	--	--	--
United Kingdom	2,230	NA	39,100	--	--	--	--	--	--
Vietnam	--	--	--	--	--	--	NA	15,300	354,000
Total	50,400	XX	2,510,000	XX	7,860	362,000	XX	185,000	1,220,000

rRevised. NA Not available. XX Not applicable. -- Zero.

[1]Table includes data available through August 30, 2023. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Aluminum-vanadium master alloy consisting of 35% aluminum and 64.5% vanadium. Includes Harmonized Tariff Schedule of the United States (HTS) code and Schedule B code 8112.99.2000.

[3]Includes HTS code and Schedule B code 8112.92.7000.

[4]Includes HTS code and Schedule B code 2615.90.6090.

[5]Reported by the U.S. Census Bureau as metric tons of vanadium pentoxide. Data were converted to vanadium content by multiplying reported data by 0.56.

Source: U.S. Census Bureau; data adjusted by the U.S. Geological Survey.

TABLE 5
U.S. IMPORTS AND EXPORTS OF VANADIUM-BEARING ASH AND RESIDUES[1]

Material and country or locality	HTS and Schedule B codes[2]	2021 Gross weight (kilograms)	2021 Vanadium content[3] (kilograms)	2021 Value	2022 Gross weight (kilograms)	2022 Vanadium content[3] (kilograms)	2022 Value
Imports for consumption:	2620.40.0030, 2620.99.1000						
Canada		(4)	(4)	$5,550,000	(4)	(4)	$6,730,000
Curacao		--	--	--	169,000	74,700	622,000
Kuwait		--	--	--	(4)	(4)	587,000
Netherlands		98,100	29,900	240,000	--	--	--
Oman		120,000	33,200	267,000	--	--	--
Russia		194,000	26,200	308,000	774,000	126,000	1,290,000
Saudi Arabia		70,300	4,490	36,100	--	--	--
Switzerland		43,400	5,170	41,600	--	--	--
Trinidad and Tobago		93,000	28,500	229,000	--	--	--
Vietnam		--	--	--	(4)	(4)	2,050,000
Total		619,000 r	127,000 r	6,670,000 r	944,000	200,000	11,300,000
Exports:	2620.50.0000, 2620.99.1000						
Australia		--	--	--	4,990	NA	$3,000
Belgium		1,010,000	NA	1,940,000	345,000	NA	312,000
Brazil		--	--	--	38,500	NA	4,200
France		--	--	--	147,000	NA	357,000
Germany		284,000	NA	117,000	85,400	NA	28,100
Guadeloupe		40,800	NA	14,400	19,100	NA	6,720
Hong Kong		63,200	NA	36,000	--	--	--
India		20,000	NA	25,000	--	--	--
Italy		19,900	NA	55,700	--	--	--
Japan		--	--	--	410,000	NA	184,000
Korea, Republic of		--	--	--	126,000	NA	110,000
Mexico		98,200	NA	1,140,000	69,700	NA	888,000
Netherlands		107,000	NA	106,000	760,000	NA	698,000
United Arab Emirates		19,900	NA	10,000	5,770	NA	74,200
Total		1,660,000	XX	3,450,000	2,010,000	XX	2,660,000

rRevised. NA Not available. XX Not applicable. -- Zero.
[1]Table includes data available through August 30, 2023. Data are rounded to no more than three significant digits; may not add to totals shown. Does not include U.S. Geological Survey estimates for data suppressed by U.S. Census Bureau.
[2]Harmonized Tariff Schedule of the United States (HTS) codes are imports and Schedule B of the United States codes are exports.
[3]Data are in kilograms of vanadium pentoxide.
[4]Data suppressed by the U.S. Census Bureau; not included in "Total."

Source: U.S. Census Bureau.

TABLE 6
U.S. IMPORTS FOR CONSUMPTION OF MISCELLANEOUS VANADIUM CHEMICALS[1]

Material and country or locality	HTS[2] code	2021 Gross weight (kilograms)	2021 Vanadium content (kilograms)	2021 Value	2022 Gross weight (kilograms)	2022 Vanadium content (kilograms)	2022 Value
Chloride oxides and chloride hydroxide of vanadium:	2827.49.1000						
Colombia		--	--	--	132,000	82,400	$109,000
Japan		221,000	207,000	$3,290,000	92,300	92,300	1,500,000
Total		221,000	207,000	3,290,000	224,000	175,000	1,610,000
Hydrides and nitrides:	2850.00.2000						
China		--	--	--	18,800	15,000	64,500
Denmark		--	--	--	40	40	4,080
France		1	1	2,190	3	3	2,780
Germany		176,000	143,000	1,220,000	334,000	271,000	2,830,000
India		--	--	--	17,900	14,200	70,200
Ireland		7,100	5,610	51,400	17	14	20,400
Japan		991	783	30,200	--	--	--
Korea, Republic of		7	5	23,500	--	--	--
Poland		19,500	19,500	36,800	--	--	--
South Africa		35,400	28,000	448,000	60,700	48,000	459,000
Sweden		4,550	3,870	160,000	4,400	3,960	172,000
United Kingdom		--	--	--	7	7	4,200
Total		244,000	200,000	1,970,000	436,000	352,000	3,630,000
Sulfates:	2833.29.3000						
Canada		--	--	--	1,870	1,170	4,270
China		2,300	1,510	31,200	2,650	1,760	25,500
Finland		431,000	406,000	6,440,000	122,000	114,000	1,740,000
Total		433,000	408,000	6,480,000	127,000	117,000	1,770,000
Vanadates:	2841.90.1000						
Austria		50	22	2,500	152,000	76,800	3,360,000
China		13,400	10,600	255,000	5,600	4,470	141,000
Germany		7,480	4,560	124,000	--	--	--
India		7	3	6,140	--	--	--
Japan		372	207	17,800	2,540	1,650	16,900
Russia		7	5	3,560	--	--	--
United Kingdom		--	--	--	14,100	9,390	306,000
Total		21,300	15,400	408,000	174,000	92,400	3,820,000
Vanadium chlorides:	2827.39.1000						
China		8,000	7,620	76,800	2,160	2,060	164,000
France		8,430	8,030	242,000	9,210	8,770	290,000
Germany		400	381	15,800	225	214	8,290
India		--	--	--	500	476	32,300
Japan		--	--	--	55,400	55,400	966,000
Singapore		--	--	--	1,000	952	80,100
Total		16,800	16,000	335,000	68,500	67,800	1,540,000

-- Zero.
[1]Table includes data available through August 30, 2023. Data are rounded to no more than three significant digits; may not add to totals shown.
[2]Harmonized Tariff Schedule of the United States.

Source: U.S. Census Bureau.

TABLE 7
VANADIUM: WORLD PRODUCTION, BY COUNTRY OR LOCALITY[1, 2]

(Metric tons, vanadium content)

Country or locality	2018	2019	2020	2021	2022
Brazil	5,500	5,923	6,622	5,779	5,844
China	59,500	60,000	70,200	70,300	66,900
Russia[3]	17,052	18,380	19,533	20,058	20,000 [e]
South Africa	7,700	8,030	8,584	8,799	8,871
United States	--	460	17	--	--
Total	89,800	92,800	105,000	105,000	102,000

[e]Estimated. -- Zero.
[1]Table includes data available through May 5, 2023. All data are reported unless otherwise noted; totals may include estimated data. Totals, U.S. data, and estimated data are rounded to no more than three significant digits; may not add to totals shown.
[2]Production from coproduct steel slag and primary ores only. Does not include secondary vanadium production.
[3]Includes metric tons of vanadium in vanadium slag produced in Russia but processed at varying recovery rates in Austria and Russia.