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Estimating Supply, Demand, and Base Case Shortfalls for High Purity Chromium and High Purity Vanadium for U.S. Defense and Essential Civilian Applications in Support of the *Strategic and Critical Materials 2019 Report on Stockpile Requirements*

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IDA

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I N S T I T U T E F O R D E F E N S E A N A L Y S E S

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Foreword

This document presents the results of the study and related work performed by the Institute for Defense Analyses (IDA) for the Defense Logistics Agency–Strategic Materials (DLA-SM) under project DE-6-4333, "Comprehensive Assistance to DLA Strategic Materials in Preparing Biennial Reports of the DOD to the Congress on National Defense Stockpile Requirements." The purpose of the case study is to collect, develop, and assess data for use in estimating shortfalls of strategic and critical materials in support of the U.S. government's National Defense Stockpile (NDS) program. The NDS program assesses U.S. civilian and defense demand for strategic and critical non-fuel materials and mitigates the risk of potential shortfalls during a national emergency (Strategic and Critical Materials Stock Piling Act, SEC. 14).[1] The Under Secretary of Defense for Acquisition and Sustainment (USD(A&S)) is the Stockpile Manager. DLA-SM implements the NDS program for the Department of Defense (DOD), and NDS requirements are reported to the U.S. Congress biennially.

SEC. 14(b) of the Stock Piling Act requires the NDS program to "base the national emergency planning assumptions on a military conflict scenario consistent with the scenario used by the Secretary of Defense in budgeting and defense planning purposes."[2] Applying this guidance, the 2019 NDS program's "Base Case" was developed to specify the national emergency scenario, which includes a military conflict and a homeland defense event coupled with specific assumptions and planning factors. This scenario was developed in coordination with the Joint Staff, the military services, and the Office of the Secretary of Defense for Policy (OSD(P)) to ensure consistency with strategic guidance and access to the best available jointly developed attrition estimates.

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1 The Strategic and Critical Materials Stock Piling Act, 50 U.S.C. § 98 *et seq.*, SEC. 14, https://legcounsel.house.gov/Comps/Strategic%20And%20Critical%20Materials%20Stock%20Piling%20Act.pdf.

2 Ibid.

Base Case assumptions and planning factors are used to assess U.S. demand for materials and their supply and include the following considerations:

- Lack of available supply from adversary countries and foreign market dominators and various decrements to foreign supply (e.g., war damage, shipping losses, and country unreliability) and congressional requirements for DOD to consider risk to U.S. supply (i.e., a domestic single-point-of-failure).
- Decreased U.S. demand due to civilian austerity, increased emergency demands, and the use of Title I of the Defense Production Act (DPA)—the Defense Priorities and Allocation System (DPAS)—to prioritize U.S. defense demand.

Historically, the NDS program has focused on raw materials at the "upstream" of material supply chains (e.g., mined ores and concentrates). When Base Case U.S. essential civilian[3] and defense demands exceed supply, shortfalls are estimated. Various mitigation options may be considered to reduce the risk of shortfalls (e.g., traditional government stockpiling, vendor-held inventories, qualification of additional (domestic) suppliers, increased U.S. imports, ready substitutes, reduced U.S. exports, investing in increased U.S. capacity (DPA Title III), recycling, and foreign Security of Supply Arrangements (SOSAs)).

IDA supports DLA-SM and NDS reporting requirements through a risk-based analytic process, the Risk Assessment and Mitigation Framework for Strategic Materials (RAMF-SM), which

- Identifies study materials, gathers data, and sets planning case assumptions;
- Estimates shortfalls and assesses shortfall risk; and
- Identifies and prioritizes cost-effective mitigation options and recommends mitigation strategies.

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[3] The stockpile legislation mandates that essential civilian needs be provided for in the national emergency, without explicitly defining which civilian needs are essential. Historically, the determination of the subset of civilian demand that is essential was made via a working group composed of representatives from a number of different government agencies, including non-Defense agencies. For the 2019 Requirements Report, the Department of Homeland Security (DHS) critical infrastructure sectors identified in Presidential Policy Directive 21 (PPD-21) (The White House, *Critical Infrastructure Security and Resilience*, PPD-21 (Washington, DC: Office of the Press Secretary, February 12, 2013), https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil) were chosen as the most relevant characterization of what is deemed essential in both a civilian and government context. The essential civilian sectors include goods and services for general civilian use, excluding those considered nonessential for stockpile purposes.

DOD's latest biennial report, *Strategic and Critical Materials 2019 Report on Stockpile Requirements*,[4] was submitted to the U.S. Congress in January 2019.

In addition to estimating NDS Base Case shortfalls at the "upstream" of material supply chains, DLA-SM considers it important to assess the potential for "downstream" material shortfalls. Reasons for assessing potential downstream shortfalls include the following:

- Confirming that relevant U.S. and reliable foreign downstream material producers possess needed capabilities and capacities to process NDS stockpile materials during Base Case conditions, and
- Determining whether NDS Base Case downstream shortfalls exist when there are no upstream shortfalls or existing NDS inventories.

Base Case judgments are applied using the RAMF-SM construct to assess U.S. essential civilian and defense demands for downstream materials and their supply. RAMF-SM provides a framework for applying NDS Base Case judgments across downstream material flows within supply chain networks of multiple production nodes through to final products.

A three-step process was developed to help assess NDS Base Case downstream material supply chain shortfalls:

- Confirm the absence of downstream fragility/vulnerabilities;
- Identify the existence of apparent downstream fragility/vulnerabilities, if any; and
- Quantitatively model supply chains and calculate downstream shortfalls through supply-demand comparisons.

Downstream material supply chain analyses include the following activities:

- Depicting downstream material supply chains (production step by production step) for specific application areas and individual downstream end-items;
- Evaluating downstream material supply chains for the existence, or absence, of apparent downstream domestic fragility and foreign vulnerabilities;

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[4] Department of Defense, *Strategic and Critical Materials 2019 Report on Stockpile Requirements* (Washington, DC: Under Secretary of Defense for Acquisition and Sustainment (USD(A&S)), January 2019), SECRET//NOFORN. *Note:* In this document, the DOD report may also be referred to as the "2019 Requirements Report" or "RR19."

- Organizing the collection of initial qualitative and quantifiable supply and demand data for RAMF-SM Base Case shortfall calculations; and
- Focusing research on identifying and collecting other data for RAMF-SM modeling (substitutability, material requalification requirements, risk mitigation ideas, and other types of downstream fragility and vulnerabilities).

These analyses are supported by the identification of potential sources of Base Case downstream supply chain disruption, stemming from domestic fragility (i.e., no U.S. capacity or reliance on a U.S. single-point-of-failure producer) and/or foreign vulnerability (i.e., reliance on producers from adversary countries, foreign market dominators, and/or foreign single-point-of-failure producers).

The high purity chromium and high purity vanadium assessment reported in this document is one of a number of DOD downstream material supply chains assessed in support of the *Strategic and Critical Materials 2019 Report on Stockpiling Requirements*.[5] This research builds upon an ongoing body of work ("deep dive" assessments of U.S. supply chains for materials).

[5] Ibid.

Executive Summary

This document presents the results of work performed by the Institute for Defense Analyses (IDA) for the Defense Logistics Agency–Strategic Materials (DLA-SM) under project DE-6-4333, "Comprehensive Assistance to DLA Strategic Materials in Preparing Biennial Reports of the DOD to the Congress on National Defense Stockpile Requirements." The purpose of this case study was to collect, develop, and assess data for use in estimating Base Case shortfalls of high purity chromium and high purity vanadium for U.S. defense and essential civilian applications.

During this case study, IDA identified and assessed the uses of high purity chromium and high purity vanadium and mapped key elements of its supply chain. Key findings regarding IDA's assessment of high purity chromium and high purity vanadium are presented in this document. Additional data are available in DOD's biennial report to Congress, *Strategic and Critical Materials 2019 Report on Stockpile Requirements*.[1]

IDA attempted to assess demand, supply, and shortfalls for high purity chromium, high purity vanadium and vanadium-aluminum (V-Al) master alloys. High purity chromium and V-Al master alloys are used in superalloys for gas-turbine engines having military and commercial uses. A complete assessment was not possible due to limited supply and demand data found for these materials

Both chromium and vanadium are added to metal alloys to obtain desired properties, such as strength and stability at high temperatures, wear resistance, and corrosion resistance. High purity chromium (> 99.5%) and high purity vanadium—typically in the form of high purity V-Al master alloys—are used in alloys for gas-turbine engines used on military and commercial aircraft. High purity chromium is used in nickel-based superalloys. High purity vanadium is used in alloys for cooler sections of gas turbine engines, where the temperature does not exceed 400°F. Ultra-high purity chromium (> 99.95%) is used in manufacturing of semiconductors and of components such as computer disks and liquid crystal displays (LCDs). High purity vanadium is used in metal foils used for cladding airframe structure joints and in the production of components for infrared cameras. Vanadium redox flow batteries (VRBs) are an emerging application that will impact the supply of high purity vanadium pentoxide—a precursor used in the production of high purity vanadium and V-Al alloys. Limited supply and demand data were found for high purity chromium and high purity vanadium, including V-Al master alloys.

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[1] Department of Defense, *Strategic and Critical Materials 2019 Report on Stockpile Requirements* (Washington, DC: Under Secretary of Defense for Acquisition and Sustainment (USD(A&S)), January 2019), SECRET//NOFORN

Currently, no substitutions are known for these materials used in turbine engines or for the other uses discussed. Focused data collection efforts for these materials are needed to support future assessments. These efforts include obtaining (1) supply and demand data specific to the high purity chromium and high purity vanadium material forms of interest especially for military system uses, (2) demand data for emerging future application areas (e.g., high purity vanadium pentoxide used in VRBs), and (3) information on recycling and substitution efforts that would impact supply and demand.

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June 2019

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IDA | Summary of Key Findings

- DLA-SM requested an assessment of supply, demand, and Base Case shortfalls for high purity chromium and high purity vanadium used in U.S. defense and essential civilian applications
- Both high purity chromium and high purity vanadium—in the form of vanadium-aluminum (V-Al) master alloys—are used in the production of alloys used in gas-turbine engines that have military and commercial uses
- Other uses for high purity chromium include the following:
  - Ultra-high purity chromium (>99.95% chromium) used in electronic applications for military and commercial use
  - High strength stainless steels used in military and commercial systems (e.g., ships); however, these were not the focus of the assessment
- Other uses for high purity vanadium include the following:
  - Metal foil used in the cladding of steel to titanium and aluminum to titanium for airframe structure joints
  - Sputtering targets for production of vanadium oxide films used in bolometric application (e.g., infrared cameras)
- IDA found limited supply and demand data on high purity chromium, high purity vanadium, and V-Al alloys
- Substitution for high purity chromium or for high purity vanadium and V-Al alloys in superalloys or in uses listed above is largely unavailable
- Future efforts might include identifying additional data regarding the following:
  - Supply and demand information specific to high purity chromium and high purity vanadium commodities
  - Detailed information on military applications using these materials
  - Information regarding future application areas (e.g., for high purity vanadium, information on the vanadium redox flow battery (VRB) market and the high purity vanadium pentoxide (V_2O_5) supply)
  - Information on producer and end user efforts (e.g., recycling, alternative materials) that impact supply and demand

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1. Summary of Key Findings

The purpose of this case study was to collect, develop, and assess supply and demand data for use in estimating Base Case shortfalls of high purity chromium and high purity vanadium for U.S. defense and essential civilian applications. Both chromium and vanadium are added to metal alloys to obtain desired properties such as strength and stability at high temperatures, wear resistance, and corrosion resistance. Both high purity chromium and high purity vanadium—in the form of vanadium-aluminum (V-Al) master alloys—are used in the production of alloys used in gas-turbine engines for military and commercial aircraft.

Other uses of high purity chromium, in the form of ultra-high purity chromium (> 99.95%), include the manufacturing of semiconductors and of components such as computer disks and liquid crystal displays (LCDs). Also, high strength stainless steels—used in military and commercial systems such as ships—contain chromium, but these uses were not the focus of the assessment. Currently, no substitutes are identified for high purity chromium in these applications. Limited supply and demand data on high purity chromium were found. Consequently, an assessment of potential Base Case shortfalls for high purity chromium could not be performed.

Other uses of high purity vanadium include metal foils used for cladding in airframe structure joints and metal pieces used in the production of components for infrared cameras. Vanadium redox flow batteries (VRBs) are an emerging application that will impact the supply of high purity vanadium pentoxide—a precursor used in the production of high purity vanadium and V-Al alloys. Currently, there are no known substitutions for these materials used in turbine engines or for the other uses discussed. Limited supply and demand data was found for high purity vanadium and for V-Al master alloys. Consequently, an assessment of potential Base Case shortfalls for high purity vanadium or for V-Al master alloys could not be performed.

Focused data collection efforts for these materials are needed to support future assessments. These efforts include obtaining (1) supply and demand data specific to the high purity chromium and high purity vanadium material forms of interest, especially for military system uses, (2) demand data for emerging future application areas (e.g., high purity vanadium pentoxide used in VRBs), and (3) information on recycling and substitution efforts that would impact supply and demand.

IDA | Outline

- Part I: High Purity Chromium Assessment
- Part II: High Purity Vanadium Assessment

2. Outline

This document consists of two parts: an assessment of high purity chromium and an assessment of high purity vanadium.

Part I: High Purity Chromium Assessment

3. Part I: High Purity Chromium Assessment

This chapter of the document presents the information gathered for the assessment of high purity chromium.

IDA | Summary – High Purity Chromium

- DLA-SM requested an assessment of supply, demand, and Base Case shortfalls for high purity chromium used in U.S. defense and essential civilian applications
  - High purity chromium (99.5 to 99.95% chromium) is used in nickel-based superalloys with military and commercial uses
    - Gas-turbine engines on military and civilian aircraft; ship propulsion; electrical power generation
  - Ultra-high purity chromium (>99.95% chromium) is used in electronic applications for military and commercial use
  - Other applications (e.g., high strength stainless steels) were not the focus of the assessment
- IDA found limited supply and demand data from open sources on high purity chromium
  - While USGS collects data on chromium, data on high purity chromium is not broken out separately
  - A 1995 study by the National Research Council's National Materials Advisory Board (under contract for DLA's National Defense Stockpile Center) reported approximately 2,500 metric tons annual consumption of higher grade or high purity chromium by the domestic aerospace industry for constructing aircraft engines
- Superalloys used in the high temperature sections of jet engines contain some high purity chromium. Currently, no substitutes are available for the high purity chromium in these superalloys
- Future efforts might include identifying additional data regarding the following:
  - Supply and demand information specific to high purity chromium commodities (aggregated data limit the ability to conduct necessary analyses)
  - Detailed information on military applications using these materials
  - Information regarding future application areas
  - Information on high purity chromium producer efforts (e.g., recycling) that will impact supply and determine how end-users' efforts (e.g., alternatives for applications) will impact demand

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A. Summary – High Purity Chromium

The purpose of this case study was to collect, develop, and assess supply and demand data for use in estimating Base Case shortfalls of high purity chromium for U.S. defense and essential civilian applications. Chromium is added to metal alloys to obtain desired properties such as strength and stability at high temperatures, wear resistance, and corrosion resistance. High purity chromium (> 99.5%) is used in nickel-based superalloys for gas-turbine engines used on military and commercial aircraft.

Other uses of high purity chromium, in the form of ultra-high purity chromium (> 99.95%), include the manufacturing of semi-conductors and of components such as computer disks and LCDs. Also, high strength stainless steels—used in military and commercial systems such as ships—contain chromium, but these uses do not necessarily require ultra-high purity and were not the focus of the assessment. Currently, no substitutes are identified for high purity chromium in these applications. Limited supply and demand data on high purity chromium were found. Consequently, an assessment of potential Base Case shortfalls for high purity chromium could not be performed.

Focused data collection efforts for high purity chromium are needed to support future assessments. These efforts include obtaining (1) supply and demand data specific to high purity chromium material forms of interest, especially for military system uses, (2) demand data for emerging future application areas, and (3) information recycling and substitution efforts that would impact supply and demand.

IDA | Outline: Part I – High Purity Chromium

- Purpose and scope – High purity chromium
- Basic description of high purity chromium
- High purity chromium supply information
- High purity chromium demand information
- High purity chromium demand information: Estimated demand for aerospace uses
- High purity chromium supply risk
- Potential future efforts – High purity chromium
- References – High purity chromium (see Appendix A)

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B. Outline: Part I – High Purity Chromium

This slide presents the outline for Part I – High Purity Chromium.

IDA | Purpose and Scope – High Purity Chromium

- This assessment informs DOD's 2019 biennial National Defense Stockpile Requirements Report (NDS RR) to Congress
- DLA-SM requested an assessment of supply, demand, and Base Case shortfalls for high purity chromium
  - Supply and demand data for chromium are collected at an aggregate level. Data specific to high purity chromium are not readily available
  - Due to the lack of specific data on high purity chromium supply and demand, quantitative shortfall data are not currently available
- The scope of the assessment includes the following:
  - Material background
  - Application areas
  - Key producers
  - Demand estimates
  - Next steps

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C. Purpose and Scope – High Purity Chromium

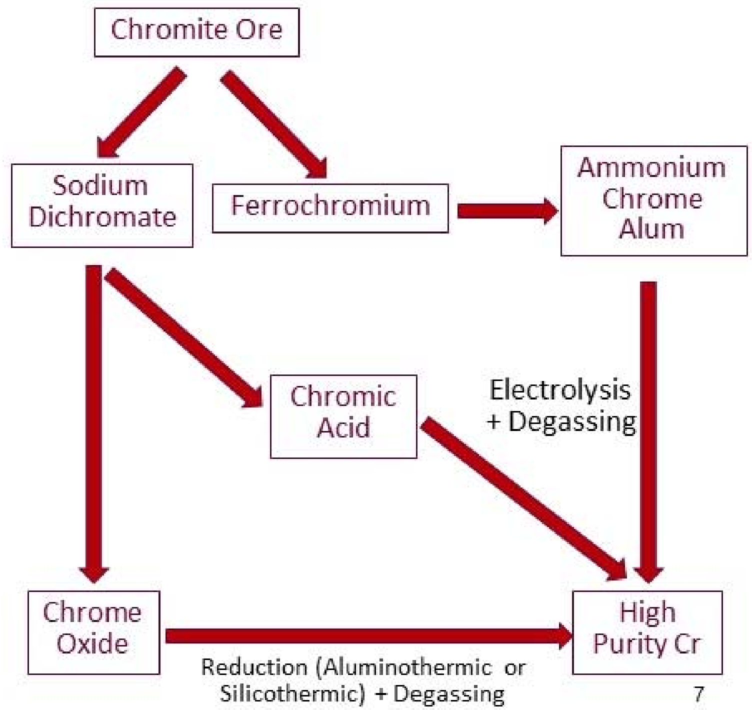
This slide addresses the purpose and scope of the assessment of high purity chromium.

Basic Description of High Purity Chromium Uses and Processing Steps (1 of 2)

- Chromium is a hard, bluish gray metal used in alloys to endow them with properties such as strength, hardness, and resistance to temperature, wear, and corrosion
- Chromium is refined by removing impurities (such as iron, silicon, and oxygen) to produce high purity chromium. High purity chromium contains between 99.5 and 99.95% chromium
- High purity chromium is produced via one of three production routes as illustrated on the right
- High purity chromium is used in superalloys for gas-turbine engines
- Aircraft gas-turbine engines are used to power military, commercial, and private airplanes and helicopters
- Other applications of turbines include ship propulsion, natural gas transmission, and electrical power generation
- Ultra high purity chromium (>99.95% chromium) is used in electronic applications such as sputtering targets for LCDs, photomasks, computer hard disks, and vapor deposition sources for semiconductor manufacture

Piece of Chromium

Superalloy Turbine Blade



D. Basic Description of High Purity Chromium Uses and Processing Steps

See page 17.

Basic Description of High Purity Chromium Uses and Processing Steps (2 of 2)

- High purity chromium contains the following impurities at or below the indicated levels:
  - 0. 005% nitrogen
  - 0.005% sulphur
  - 0.05% oxygen
  - 0.01% aluminum
  - 0.05% silicon
  - 0.35% iron
- High purity chromium is sold as briquettes, pellets, cubes, discs, and rods
- Typically, high purity chromium is sold under a trade name unique to a producer and is produced to meet individual customer specifications
- A 2005 United States International Trade Commission (USITC) report indicated that there are no industry-wide standard grades for high purity chromium

Chromium metal is added to metal alloys to impart properties such as strength and stability at high temperatures, wear resistance, and corrosion resistance. High purity chromium is used in nickel-based superalloys for gas turbine engines used in military and civilian aircraft. There are three production routes to obtain high purity chromium[1]:

- The first route involves converting chromite ore to ferrochromium. The ferrochromium is converted to an ammonium chromite alum from which high purity chromium is electrodeposited. To achieve higher purity chromium needed for superalloys the electro-deposited metal typically undergoes vacuum degassing. The electro-deposited chromium metal is removed from the electrodes. The metal is milled to a size appropriate for forming into briquettes containing chromium, carbon, tin and a polymeric binder. This briquette is heated in a vacuum during which impurities, such as nitrogen, lead, sulfur and oxygen, are removed.
- The second route consists of converting chromite ore to sodium dichromate. Chromic acid is produced from the dichromate, and chromium metal is electrodeposited from the chromic acid. Following the electrodeposition, the chromium metal will undergo additional refinement via a vacuum degassing process described in the previous bullet item.
- The third route involves converting chromite ore to sodium dichromate. Chromic oxide is leached, reduced, and precipitated from the dichromate. The oxide is then reduced to chromium metal in the presence of aluminum (aluminothermic) or silicon (silicothemric). The chromium metal is then vacuum degassed, sometimes more than once, to further reduce impurities.

There are no industry-wide accepted grades for high purity chromium.[2] Typically, it is produced to meet individual customer specifications.

Chromite ore is primarily produced in South Africa. The United States produces no chromite. The leading producers of ferrochromium are South Africa, India, and Kazakhstan. The major producers of chromium metal are located in France, Russia, China, and the United Kingdom.[3] The single U.S. producer of primary chromium metal is JMC (USA).[4] JMC (USA) produces high purity chromium metal for electronics applications. Its ultra-high purity chromium, a specialty niche market product, is the highest purity commercially produced chromium metal available in the world.

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1 National Research Council, *High-Purity Chromium Metal: Supply Issues for Gas-Turbine Superalloys*, NMAB-480 (Washington, DC: National Academy Press, 1995), https://www.nap.edu/read/9248.

2 United States International Trade Commission, *Superalloy Degassed Chromium from Japan*, Publication 3768 (Washington, DC: The U.S. International Trade Commission, April 2005), https://www.usitc.gov/publications/701_731/pub3768.pdf.

3 U.S. Geological Survey, "Chromium," in *Mineral Commodity Summaries*, 46–47 (Reston, VA: U.S. Department of the Interior, January 2018), https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/chromium/mcs-2018-chrom.pdf.

4 JMC (USA), Inc., "Company Profile," accessed March 29, 2019, https://www.jmcusa.com/chromium-supplier.html.

High Purity Chromium Supply Information

- The major producers of chromium metal are located in France, the United Kingdom, Russia, and China
- High purity chromium data are a subset of the total chromium metal supply data
- Data on high purity chromium are not collected separately
- Currently, information is not available regarding the fraction of chromium produced that is high purity
- JMC (USA) is the single domestic producer of chromium and high purity chromium. JMC (USA) produces high purity chromium that is at least 99.7% chromium. The majority of high purity chromium produced by JMC (USA) is for electronics applications
- Other high purity chromium producers found are as follows:
  - AMG Superalloys (United Kingdom – a business unit of AMG Advanced Metallurgical Group N.V.) produces a variety of chromium metal, including high purity briquettes with a minimum of 99.7% chromium
  - DCX Chrome (France – a wholly owned subsidiary of Delachaux group) produces a variety of chromium metal including high purity briquettes with a minimum of 99.75% chromium
  - JSC Polema (Russia) produces a few chromium metal products including high purity refined flakes with a minimum of 99.95% chromium

Briquette

Flakes

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E. High Purity Chromium Supply Information

High purity chromium supply data are a subset of the total chromium metal supply data. However, the high purity chromium data is not separated, or is not collected separately, from the total chromium metal supply data. Two of the main high purity chromium metal forms available are briquettes and flakes.

Major producers of chromium metal are located in France, the United Kingdom, Russia and China.[5] JMC (USA) is the single domestic producer of high purity chromium. The high purity chromium produced by JMC (USA) is at least 99.7% chromium. Most of the chromium produced by JMC (USA) is used for electronics applications. Foreign producers of high purity chromium found during research for this case study are AMG Superalloys (United Kingdom, a business unit of AMG Advanced Metallurgical Group N.V.),[6] DCX Chrome (France, a wholly owned subsidiary of Delachaux group),[7] and JSC Polema (Russia).[8] No information was found on the amount of high purity chromium produced by these suppliers.

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5 U.S. Geological Survey, "Chromium."

6 AMG Superalloys, "Melted Products Delivery Programme and Applications" (England: Rotherham, South Yorkshire, AMG Superalloys UK Limited, 18 April 2018), https://amg-s.com/wp-content/uploads/2018/04/AMG-S-Chrome-Datasheet.pdf.

7 DCX Chrome, "Chrome Metal DDB – High Purity Grade," http://dcx-chrome.com/public/DCX_Fiche_Technique_ChromeMetal_DDB_HighPurityGrade.pdf.

8 JSC Polema, "Electrolytic Chromium Flakes," 2019, http://www.polema-rus.com/eng-page/electrolytic-chromium-flakes.html.

IDA | High Purity Chromium Demand Information

- The United States relies on imports to satisfy high purity chromium demands
- High purity chromium data are a subset of the total chromium metal demand data. Currently, information regarding the fraction of chromium that is high purity is not available
- Currently, information on the fraction of defense vs. commercial use of high purity chromium is not available
- To provide some indication of the demand for high purity chromium, the next slide provides an estimate of the amount of chromium used in aerospace applications. It is assumed that chromium in superalloys for aerospace require high purity chromium

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F. High Purity Chromium Demand Information

The United States currently relies upon imports to satisfy high purity chromium demands.[9] The demand data for high purity chromium is a subset of overall chromium demand data. Similar to the supply information, the demand data for high purity chromium is not tracked separately. In addition, information on the fraction of defense and commercial demand for high purity chromium is not available. The next slide describes the approach used to provide an indication of the demand for high purity chromium based on aerospace uses.

[9] U.S. Geological Survey, "Chromium."

High Purity Chromium Demand Information: Estimated Demand for Aerospace Uses

- In a 2015 publication, the International Chromium Development Association (ICDA) indicated that 65% of chromium used was for specialty steels and aerospace materials
- Assuming all aerospace chromium is high purity chromium used in superalloys for gas-turbine engines, the high purity chromium demand for aerospace applications accounts for, at most, 20% of total chromium demand

Aerospace chromium demand accounts for ~20% of overall demand (i.e., 65% * 33% ~ 20%)*

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G. High Purity Chromium Demand Information: Estimated Demand for Aerospace Uses

This slide attempts to provide an estimate of high purity chromium demand using information from a 2015 International Chromium Development Association (ICDA) brochure on chromium.[10] This brochure states that 65% of all chromium used was for specialty steels and aerospace materials. Aerospace uses account for 33% of the chromium used for specialty steels and aerospace materials. Therefore, chromium used in aerospace materials is about 20% of the total chromium used. If chromium used in aerospace materials is high purity, then high purity chromium would account for at most 20% of the total chromium demand.

[10] International Chromium Development Association (ICDA), "Chrome Chemicals and Chrome Metal," (brochure, Paris, France: ICDA, 2015).

IDA | High Purity Chromium Supply Risk

- All chromite ore needed to produce high purity chromium is imported
- The amount of high purity chromium that is imported is unknown
- The percentage of high purity chromium consumed that is imported is unknown
- The only domestic producer of high purity chromium identified is JMC (USA)
- The preceding observations lead to the following supply chain risks:
  - A disruption in one or more of the major sources of chromite ore could result in a reduction in the amount of high purity chromium available (imported or produced domestically)
  - A disruption in one or more of the major foreign sources of high purity chromium could significantly reduce the availability of high purity chromium
  - A disruption in the production capability at the single domestic producer would result in no domestic production capability for high purity chromium

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H. High Purity Chromium Supply Risk

As discussed previously, high purity chromium is produced from chromite ore. Currently, chromite ore is not mined domestically. All chromite ore needed to meet demand is imported. The amount of high purity chromium produced, imported, and consumed is unknown. Only one domestic supplier of high purity chromium, JMC (USA), was identified during this study.

There are supply chain risks given that all chromite ore is imported and that there is only one domestic producer of high purity chromium. A reduction in the amount of available high purity chromium could occur if there is a disruption in the major sources of chromite ore. Since the amount of imported high purity chromium is unknown, it is not possible to quantify the impact of any disruption of the foreign sources. Obviously, there would be a reduction in the amount available if there is a disruption in those sources. Also, the amount of high purity chromium produced domestically is unknown. Consequently, it is not possible to quantify the amount of reduction in the supply that would result if JMC (USA) experienced a disruption in production capability.

IDA | Potential Future Efforts – High Purity Chromium

To support future assessments of supply, demand, and Base Case shortfalls for high purity chromium, the following efforts might be considered:

- Obtain supply and demand information and data specific to high purity chromium
  - Conduct targeted outreach to companies that produce/use high purity chromium
- Obtain information and data on commercial and military applications and demand
  - Collect data from component or system suppliers (e.g., gas-turbine engine companies)
  - Obtain information on military systems using components that contain high purity chromium to better understand defense demand
- Better understand current and future application areas
- Obtain information and data on high purity chromium producer and end-user efforts (e.g., recycling) that will impact supply
- Obtain information and data on user efforts (e.g., development of alternative materials) that will impact demand for high purity chromium

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I. Potential Future Efforts – High Purity Chromium

As indicated previously, the supply and demand data for high purity chromium is insufficient to support assessments of future supply and demand risks, and of any Base Case shortfalls. Data specifically for high purity chromium need to be collected to support future assessments. One effort to obtain this data is to request information from companies that produce and use high purity chromium. In addition to supply and demand data, the approach should include an effort to obtain data on recycling and any other high purity chromium recovery efforts that may impact the supply. Also, data on any projects and programs to develop materials that would substitute for either high purity chromium in alloys or that would replace alloys that use high purity chromium should be collected. Finally, data supply and demand data specific to military and essential civilian uses should be collected by contacting service and joint program offices and defense contractors.

IDA

Part II: High Purity Vanadium Assessment

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4. Part II: High Purity Vanadium Assessment

This chapter of the document presents the information gathered for the assessment of high purity vanadium.

IDA | Summary – High Purity Vanadium

- DLA-SM requested an assessment of supply, demand, and Base Case shortfalls for high purity vanadium material used in U.S. defense and essential civilian applications
- Uses of high purity vanadium include the following:
  - Metal foil used in the cladding of steel to titanium and of aluminum to titanium for airframe structure joints
  - Metal discs used in sputtering targets for production of vanadium oxide films used in bolometric application (e.g., IR cameras)
  - V-Al master alloys used in production of aerospace alloys (e.g., Ti-6Al-4V alloys) for aircraft structures and gas-turbine engines used on military and civilian aircraft
- IDA found limited supply and demand data on high purity vanadium and V-Al master alloys
- Currently, no substitutions are available for high purity vanadium and V-Al alloys in the applications listed above
- The emerging vanadium redox flow battery (VRB) market will impact the supply of high purity V_2O_5 used to produce high purity vanadium and V-Al master alloys
- Future efforts might include the following:
  - Identifying supply and demand data specific to high purity vanadium commodities
  - Obtaining detailed data on military application areas and demand
  - Better understanding the VRB market and related efforts to increase V_2O_5 supplies
  - Better understanding producer and end user efforts (e.g., recycling, alternative materials) that will impact supply and demand

A. Summary – High Purity Vanadium

The purpose of this case study was to collect, develop, and assess supply and demand data for use in estimating Base Case shortfalls of high purity vanadium for U.S. defense and essential civilian applications. Vanadium is added to metal alloys to obtain desired properties such as strength and stability at high temperatures, wear resistance, and corrosion resistance. High purity vanadium—typically in the form of high purity V-Al master alloys—is used in alloys for cooler sections of gas turbine engines, where the temperature does not exceed 400°F, for engines used on military and commercial aircraft.

Other uses of high purity vanadium include metal foils used for cladding in airframe structure joints and metal pieces used in the production of components for infrared cameras. VRBs are an emerging application that will impact the supply of high purity vanadium pentoxide—a precursor used in the production of high purity vanadium and of V-Al master alloys. Currently, there are no known substitutions for these materials used in turbine engines or for the other uses discussed. Limited supply and demand data were found for high purity vanadium and for V-Al master alloys. Consequently, an assessment of potential Base Case shortfalls for high purity vanadium or for V-Al master alloys could not be performed.

Focused data collection efforts for these materials are needed to support future assessments. These efforts include obtaining (1) supply and demand data specific to the high purity vanadium material forms of interest, especially for military system uses, (2) demand data for emerging future application areas (e.g., high purity vanadium pentoxide used in VRBs), and (3) information recycling and substitution efforts that would impact supply and demand.

Outline: Part II – High Purity Vanadium

- Purpose and scope – High purity vanadium
- Basic description of high purity vanadium
- High purity vanadium supply information
- High purity vanadium demand information
- High purity vanadium supply risk
- Potential future efforts – High purity vanadium
- References – High purity vanadium (see Appendix A)

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B. Outline: Part II – High Purity Vanadium

This slide presents the outline for Part II – High Purity Vanadium.

IDA | Purpose and Scope – High Purity Vanadium

- This assessment informs the DOD's 2019 biennial National Defense Stockpile Requirements Report (NDS RR) to Congress
- DLA-SM requested an assessment of supply, demand, and Base Case shortfalls for high purity vanadium
  - Supply and demand data for high purity vanadium are not collected separately. Data are available at an aggregate level
  - Limited supply data are available for a single V-Al master alloy
  - Due to the lack of data regarding high purity vanadium and V-Al master alloy supply and demand, quantitative shortfall data are not currently available
- The scope of the assessment includes the following:
  - Material background
  - Application areas
  - Key producers
  - Demand estimates
  - Next steps

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C. Purpose and Scope – High Purity Vanadium

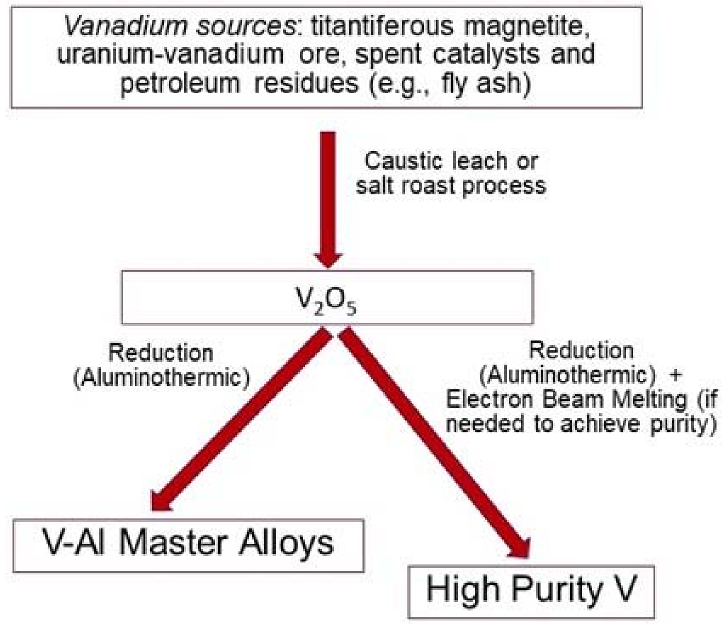
This slide addresses the purpose and scope of the assessment of high purity vanadium.

IDA | Basic Description of High Purity Vanadium

- Vanadium is a hard, yet ductile, silvery grey transition metal
- The majority of vanadium is produced from magnetite
- High purity vanadium (>99.8% vanadium) and V-Al master alloys are produced from high purity V_2O_5 as illustrated in the figure on the right
- Uses of high purity vanadium include the following:
  - As foil used in the cladding of steel to titanium and of aluminum to titanium for airframe structure joints
  - As sputtering targets for production of vanadium oxide films used in bolometric applications (e.g., infrared cameras)
- High purity V-Al master alloys are used in the production of titanium alloys used in airframe structures and in jet turbine engines
- VRBs represent an emerging market for high purity vanadium pentoxide


Vanadium Crystals


Airframe Structures



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D. Basic Description of High Purity Vanadium

Vanadium is a transition metal found in many natural and some secondary sources such as petroleum residues. The majority of vanadium is produced from the mineral magnetite that is one of the main iron ores. High purity vanadium (> 99.8% vanadium) and V-Al master alloys are produced through the reduction of vanadium pentoxide (V_2O_5). High purity V-Al master alloys are used in the production of titanium aerospace alloys used in airframes and gas turbine engines. High purity vanadium foil is used in cladding steel to titanium for airframes. Also, metal pieces are used as sputtering targets for the production of vanadium oxide films used in infrared cameras. VRBs represent an emerging market for high purity V_2O_5 use that will have an unknown impact on supply of high purity V_2O_5.

IDA | High Purity Vanadium Supply Information

- High purity vanadium metal and high purity V-Al master alloys are produced from high purity V_2O_5
- The major producers of V_2O_5 from primary sources (ores, minerals) are located in South Africa, Russia, and China
- As of January 2018, all domestic demand for V_2O_5 is met by foreign sources
- Imports of V-Al master alloy (containing 35% aluminum and 64.5% vanadium) exceeds exports
- Data on high purity vanadium are not collected separately
- Currently, information is not available regarding the fraction of vanadium produced that is high purity
- Domestic secondary production through processing of waste materials (spent catalysts and petroleum residues) may be used to make vanadium pentoxide, vanadium metals, and metal alloys that contain vanadium
- Domestic vanadium commodity suppliers include the following:
  - Strategic Materials Corp (Stratcor, Inc.) – V_2O_5, vanadium metal, V-Al master alloys
  - Reading Alloys (a business of Ametek Specialty Metal Products) – V-Al master alloys
  - Kennametal International Specialty Alloys, Inc. – V-Al master alloys
- Other high purity vanadium commodity producers are as follows:
  - Vanadium Corp. Resources Inc. (Canada) – V_2O_5
  - Largo Resources, Inc. (Canada; mine in Brazil) – high purity V_2O_5
  - Bushveld Minerals: Bushveld Vanadium (South Africa) – V_2O_5

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E. High Purity Vanadium Supply Information

V_2O_5 is the precursor in the production of high purity vanadium and V-Al master alloys. The supply information gathered focused mainly on sources of V_2O_5.[11] The major producers of V_2O_5 from primary sources (i.e., ores and minerals) are located in South Africa, Russia, and China. All domestic demand for V_2O_5 is met through imports. The amount of high purity vanadium metal produced internationally and domestically is unknown. Import and export data on one V-Al alloy containing 64.5% vanadium and 35% aluminum is available.[12] Imports of this master alloy exceeds exports, so one might conclude that domestic demand for this master alloy is met by foreign sources. It is unknown what amount of this master alloy is used in the production of aerospace alloys, including those used in turbine engines.

Domestic secondary production—via processing of waste materials such as spent catalysts and petroleum residues—may be used to make V_2O_5, vanadium metal, and specialty alloys.[13] The amount of V_2O_5 and vanadium metal, let alone high purity vanadium, produced using secondary production is not known.

Domestic producers of vanadium commodities include Strategic Materials Corporation (Stratcor, Inc.),[14] Reading Alloys (a business unit of Ametek Specialty Metal Products),[15] and Kennametal International Specialty Alloys, Inc.[16] Each of these domestic suppliers produces V-Al alloys. Based on information found, Stratcor, Inc. is the only supplier that produces V_2O_5 and vanadium metal.

Foreign producers of vanadium commodities include Vanadium Corp. Resources Inc. (Canada), Largo Resources, Inc. (Canada; mined in Brazil) and Bushveld Minerals: Bushveld Vanadium (South Africa). Each of these suppliers produces V_2O_5. Only Largo Resources, Inc. reported producing high purity V_2O_5.

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[11] Henry Hillard, "The Materials Flow of Vanadium in the United States," Bureau of Mines Information Circular 9409 (Washington, DC: Department of the Interior, 1994), https://pubs.usgs.gov/usbmic/ic-9409/9409.pdf.

[12] U.S. Geological Survey, "Vanadium," *Mineral Commodity Summaries*, 182–183 (Reston, VA: U.S. Department of the Interior, 2017), https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/mcs/mcs2017.pdf.

[13] Ibid.

[14] Evraz Stratcor, Inc., "EVRAZ Vanadium," vanadium.evraz.com/facilities/evraz-stratcor/.

[15] AMETEK ReadingAlloys, "Vanadium Alloy," https://www.readingalloys.com/products/master-alloys/vanadium.

[16] U.S. Geological Survey. "Vanadium."

IDA | High Purity Vanadium Demand Information

- In 2016, USGS estimated that metallurgical uses accounted for 95% of the vanadium consumed in the United States in for
  - Steels, in the form of ferrovanadium (FeV)
  - Aerospace alloys, mainly in the form of V-Al master alloys
  - Foil and sputtering targets, as vanadium metal
- Other sources estimate 91 to 92% of vanadium consumption for steels and 4 to 4.5% in aerospace alloys (V-Al master alloys used in aerospace typically require high purity vanadium)
- Vanadium metal used in foil for cladding and in sputtering targets most likely requires high purity vanadium
- Aerospace consumption of high purity vanadium has been estimated to be 50% of all high purity vanadium consumed. Chemical catalysts and VRB applications also consume high purity vanadium

Based on these data, it appears that a reasonable starting estimate for domestic consumption for high purity vanadium metal commodities is about 4% of total vanadium consumption

F. High Purity Vanadium Demand Information

In 2016, the United States Geological Survey (USGS) estimated that 95% of the vanadium consumed in the United States was for metallurgical uses. The vanadium consumed include ferrovanadium used in the production of steels, V-Al alloys used in the production of aerospace alloys, and vanadium metal used as foil or in sputtering targets.[17] Other sources[18,19] estimated vanadium consumed worldwide in steel production was between 91% and 92% of all vanadium consumed. The vanadium consumed in aerospace alloys was between 4% and 4.5%. Based on these estimates, it appears reasonable that domestic consumption of high purity vanadium metal commodities is around 4% of the total domestic consumption of vanadium. Vanadium foil and sputtering target metals most likely require high purity as introduction of impurities would adversely impact the performance of the foil and of products (e.g., infrared cameras), where sputtering of vanadium is a part of the production process.

[17] U.S. Geological Survey, *2016 Minerals Yearbook – Vanadium [Advance Release]* (Washington, DC: Department of the Interior, 2016), https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/vanadium/myb1-2016-vanad.pdf.

[18] Prophecy Development Corp., "Developing First Major Vanadium Mine in Nevada" (Canada: Vancouver, BC, October 10, 2018).

[19] Largo Resources, "Corporate Presentation" (Canada: Toronto, Ontario, May 2019), https://s22.q4cdn.com/197308373/files/doc_presentations/2019/05/LGO_Corporate-Presentation_May2019-(1).pdf.

High Purity Vanadium Supply Risk

- V_2O_5 is refined to produce high purity vanadium and V-Al master alloys
- All domestic demand for V_2O_5 is met by foreign sources
- Based on USGS, reported V-Al master alloy import/export data for 2016, 59% of the imported master alloy is consumed domestically (not accounting for domestic production of the master alloy)*
- The supply of V_2O_5 will be impacted by its use in VRBs
  - Efforts are underway to increase the supply of V_2O_5 (e.g., American Vanadium Corp Gibellini Project)
  - Future V_2O_5 supplies will be determined by many factors, including the VRB market growth rate, the opening dates of additional mines, and reductions in existing supply chains
- Future supply chain risks may include the following:
  - Disruption of existing V_2O_5 sources, causing a reduction in the available amount of high purity vanadium and V-Al alloys
  - A reduction in availability of V_2O_5 due to growth in the VRB market without an accompanying increase in sources of V_2O_5

* Apparent domestic consumption = (Imports – exports)/imports * 100%

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G. High Purity Vanadium Supply Risk

As discussed previously, V_2O_5 is the precursor in the production of high purity vanadium metal and V-Al master alloys. All domestic demand for V_2O_5 is met by foreign sources.[20] Any reduction in the availability of V_2O_5, due to a reduction in production of or increased uses for V_2O_5 may impact the supply of high purity vanadium metal or the V-Al master alloys. If the VRB market grows, the demand for V_2O_5 will increase. Efforts are underway increase the V_2O_5 supply, but future supplies will be determined by many factors, including the size of the VRB market, the VRB market growth rate, the rate of increase in V_2O_5 sources and supplies, and any reductions in existing sources.[21,22]

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[20] U.S. Geological Survey, "Vanadium."

[21] U.S. Geological Survey, *2016 Minerals Yearbook – Vanadium [Advance Release]*.

[22] Prophecy Development Corp., "Gibellini (Vanadium)," https://www.prophecydev.com/projects/gibellini-vanadium/.

IDA | Potential Future Efforts – High Purity Vanadium

To support future assessments of supply, demand, and Base Case shortfalls for high purity vanadium, the following efforts might be considered:

- Obtain supply and demand information and data specific to high purity vanadium commodities
  - Conduct targeted outreach to companies that produce/use high purity vanadium, V-Al master alloys (aerospace-grade Ti Al alloy sheet and plate)
- Obtain information and data on commercial and military application areas and demand
  - Collect data from component or system suppliers (e.g., gas- turbine engine companies, airframe producers)
  - Obtain information on military systems using high purity vanadium and V-Al master alloys to better understand defense
- Obtain information on VRB market and related efforts to increase V_2O_5 supplies
- Obtain information and data on high purity vanadium and V-Al master alloy producer and end-user efforts (e.g., recycling) that will impact supply
- Obtain information and data on user efforts (e.g., development of alternative materials) that will impact the demand for high purity vanadium

H. Potential Future Efforts – High Purity Vanadium

As indicated previously, the supply and demand data for high purity vanadium commodities—mainly V_2O_5, metal and V-Al master alloys—is insufficient to support assessments of future supply and demand risks and any Base Case shortfalls. Data specifically for high purity vanadium commodities need to be collected to support future assessments. One effort to obtain this data is to request information from companies that produce and that use high purity vanadium commodities. In addition to supply and demand data, the approach should include an effort to obtain data on recycling and any other high purity vanadium recovery efforts that may impact the supply. Also, data on any projects and programs to develop materials that would substitute for either high purity vanadium in alloys or that would replace alloys that use high purity vanadium should be collected. Finally, supply and demand data specific to military and essential civilian uses should be collected by contacting service and joint program offices and defense contractors.

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Appendix A.
References

This appendix presents the key data sources that were used in the assessment of high purity chromium and high purity vanadium, the sources of the images that were used in the slides for the assessment of high purity chromium and high purity vanadium, and a list of sources that were cited in the Executive Summary of this document.

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IDA | Sources of Slide Images and Tables – High Purity Chromium

Slide	Source
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9	Briquette: "Chrome Metal DDB – High Purity Grade," http://dcx-chrome.com/public/DCX_Fiche_Technique_ChromeMetal_DDB_HighPurityGrade.pdf Flakes: "Electrolytic Chromium Flakes," Polema, http://www.polema-rus.com/eng-page/electrolytic-chromium-flakes.html/print
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IDA | Sources of Slide Images and Tables– High Purity Vanadium

Slide	Source
18	Vanadium crystals: "Critical Elements—A Virtual Museum: 23 V Vanadium," http://images-of-elements.com/vanadium.php Airframe structures: "Vanadium: The Metal We Can't Do Without and Don't Produce," *Mining.com*, October 24, 2017

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Appendix B.
Abbreviations

DHS	Department of Homeland Security
DLA-SM	Defense Logistics Agency–Strategic Materials
DOD	Department of Defense
DPA	Defense Production Act
DPAS	Defense Priorities and Allocation System
FeV	ferrovanadium
ICDA	International Chromium Development Association
IDA	Institute for Defense Analyses
LCD	liquid crystal display
NMAB	National Materials Advisory Board
NDS	National Defense Stockpile
NDS RR	National Defense Stockpile Requirements Report
OSD(P)	Office of the Secretary of Defense for Policy
PPD	Presidential Policy Directive
RAMF-SM	Risk Assessment and Mitigation Framework for Strategic Materials
RR	Requirements Report
SOSA	Security of Supply Arrangement
U.S.	United States
U.S.C.	United States Code
USD(A&S)	Under Secretary of Defense for Acquisition and Sustainment
USGS	United States Geological Survey
USITC	United States International Trade Commission
V_2O_5	vanadium pentoxide
V-Al	vanadium-aluminum
VRB	vanadium redox flow battery

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This assessment was prepared in support of the National Defense Stockpile Program's 2019 biennial report to Congress, *Strategic and Critical Materials 2019 Report on Stockpile Requirements*, which estimates the demand and supply of strategic and critical materials under a statutorily mandated national emergency planning scenario. An assessment of high purity chromium and high purity vanadium (mainly in the form of vanadium-aluminum master alloys) used in applications such as gas-turbine engines was performed. The purpose of the supply chain assessment is to provide a comprehensive qualitative and quantitative analysis of the military and strategic dependence of the United States on this material.

15. SUBJECT TERMS

Superalloys, turbine engines, high purity chromium, high purity vanadium, vanadium-aluminum master alloys, vanadium redox flow battery

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