Cesium Tungsten Bronze Encyclopedia

中钨智造科技有限公司

CTIA GROUP LTD

CTIA GROUP LTD

Global Leader in Intelligent Manufacturing for Tungsten, Molybdenum, and Rare Earth Industries

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

INTRODUCTION TO CTIA GROUP

CTIA GROUP LTD, a wholly-owned subsidiary with independent legal personality established by CHINATUNGSTEN ONLINE , is dedicated to promoting the intelligent, integrated, and flexible design and manufacturing of tungsten and molybdenum materials in the Industrial Internet era. CHINATUNGSTEN ONLINE, founded in 1997 with www.chinatungsten.com as its starting point—China's first top-tier tungsten products website—is the country's pioneering e-commerce company focusing on the tungsten, molybdenum, and rare earth industries. Leveraging nearly three decades of deep experience in the tungsten and molybdenum fields, CTIA GROUP inherits its parent company's exceptional design and manufacturing capabilities, superior services, and global business reputation, becoming a comprehensive application solution provider in the fields of tungsten chemicals, tungsten metals, cemented carbides, high-density alloys, molybdenum, and molybdenum alloys.

Over the past 30 years, CHINATUNGSTEN ONLINE has established more than 200 multilingual tungsten and molybdenum professional websites covering more than 20 languages, with over one million pages of news, prices, and market analysis related to tungsten, molybdenum, and rare earths. Since 2013, its WeChat official account "CHINATUNGSTEN ONLINE" has published over 40,000 pieces of information, serving nearly 100,000 followers and providing free information daily to hundreds of thousands of industry professionals worldwide. With cumulative visits to its website cluster and official account reaching billions of times, it has become a recognized global and authoritative information hub for the tungsten, molybdenum, and rare earth industries, providing 24/7 multilingual news, product performance, market prices, and market trend services.

Building on the technology and experience of CHINATUNGSTEN ONLINE, CTIA GROUP focuses on meeting the personalized needs of customers. Utilizing AI technology, it collaboratively designs and produces tungsten and molybdenum products with specific chemical compositions and physical properties (such as particle size, density, hardness, strength, dimensions, and tolerances) with customers. It offers full-process integrated services ranging from mold opening, trial production, to finishing, packaging, and logistics. Over the past 30 years, CHINATUNGSTEN ONLINE has provided R&D, design, and production services for over 500,000 types of tungsten and molybdenum products to more than 130,000 customers worldwide, laying the foundation for customized, flexible, and intelligent manufacturing. Relying on this foundation, CTIA GROUP further deepens the intelligent manufacturing and integrated innovation of tungsten and molybdenum materials in the Industrial Internet era.

Dr. Hanns and his team at CTIA GROUP, based on their more than 30 years of industry experience, have also written and publicly released knowledge, technology, tungsten price and market trend analysis related to tungsten, molybdenum, and rare earths, freely sharing it with the tungsten industry. Dr. Han, with over 30 years of experience since the 1990s in the e-commerce and international trade of tungsten and molybdenum products, as well as the design and manufacturing of cemented carbides and high-density alloys, is a renowned expert in tungsten and molybdenum products both domestically and internationally. Adhering to the principle of providing professional and high-quality information to the industry, CTIA GROUP's team continuously writes technical research papers, articles, and industry reports based on production practice and market customer needs, winning widespread praise in the industry. These achievements provide solid support for CTIA GROUP's technological innovation, product promotion, and industry exchanges, propelling it to become a leader in global tungsten and molybdenum product manufacturing and information services.

Cesium Tungsten Bronze Product Introduction

CTIA GROUP LTD

1. Cesium Tungsten Bronze Overview

Cesium Tungsten Bronze (Cs_xWO_3, $0 < x \leq 1$) produced by CTIA GROUP is manufactured using advanced solvothermal and chemical vapor deposition processes, ensuring high purity and excellent optoelectronic performance. Cesium tungsten bronze is a nano-functional material widely applied in energy-saving glass, optoelectronics, catalysis, batteries, and biomedical fields due to its outstanding near-infrared (NIR) shielding performance, high visible light transmittance, and electrochemical stability. Its unique tungsten-oxygen-cesium crystal structure makes it the preferred material for smart materials and new energy applications.

2. Cesium Tungsten Bronze Features

Chemical composition: Cs_xWO_3 (x = 0.2–0.33), purity ≥99.9%, extremely low impurities.

Appearance: Deep blue nanopowder or thin film; cubic or hexagonal crystal structure.

Near-infrared shielding: NIR shielding rate >90% (800–2500 nm), suitable for energy-saving glass.

Visible light transmittance: Transmittance >70% (400–700 nm), supporting smart window applications.

Electrical conductivity: ~10^3 S/cm, ideal for optoelectronic sensors and battery electrodes.

Chemical stability: Corrosion rate <0.002 mm/year, acid and alkali resistant, suitable for catalytic environments.

Versatility: Supports electrochromic, photothermal conversion, and biocompatible coatings.

3. Cesium Tungsten Bronze Product Specifications

Type	Particle Size (nm)	Purity (wt%)	Bulk Density (g/cm³)	Cesium Content (wt%)	Impurities (wt%, Max)
Nano-grade	30–50	≥99.9	2.5–3.0	5.0–8.0	Fe≤0.002, Si≤0.001, O≤0.05

4. Cesium Tungsten Bronze Packaging and Quality Assurance

Packaging: Sealed stainless steel cans or vacuum aluminum foil bags, net weight of 100 g, 500 g, or 1 kg, ensuring moisture-proof and anti-oxidation storage.

Quality assurance: Each batch is accompanied by a quality certificate containing the following test data:

- Purity (ICP-MS, >99.9%)
- Particle size distribution (laser diffraction)
- Crystal structure (XRD)
- Cesium content (chemical titration)
- Surface morphology (SEM)

5. Cesium Tungsten Bronze Procurement Information

Email: sales@chinatungsten.com

Phone: +86 592 5129595

Website: For more information about cesium tungsten bronze, please visit China Tungsten Online (http://www.cesium-tungsten-bronze.com/).

Table of contents

Chapter 1: Introduction and History of Cesium Tungsten Bronze
1.1 Definition and chemical composition of cesium tungsten bronze
1.2 Discovery and development of cesium tungsten bronze
1.3 Status of cesium tungsten bronze in materials science
1.4 Global research status and market overview of cesium tungsten bronze
1.5 Key application areas of cesium tungsten bronze

Chapter 2: Crystal structure and properties of cesium tungsten bronze
2.1 Crystal structure and chemical bond characteristics of cesium tungsten bronze
2.2 Optical properties of cesium tungsten bronze: near-infrared absorption and light transmittance
2.3 Electrical properties of cesium tungsten bronze: conductivity and carrier migration
2.4 Thermal properties of cesium tungsten bronze: thermal conductivity and stability
2.5 Theoretical calculation and performance prediction of cesium tungsten bronze

Chapter 3: Synthesis Method of Cesium Tungsten Bronze
3.1 Solid-state reaction method of cesium tungsten bronze
3.2 Solvothermal and hydrothermal methods of cesium tungsten bronze
3.3 Chemical vapor deposition (CVD) of cesium tungsten bronze
3.4 Sol-gel method of cesium tungsten bronze
3.5 Green synthesis and nanoparticle control of cesium tungsten bronze

Chapter 4: Characterization Technology of Cesium Tungsten Bronze
4.1 X-ray diffraction (XRD) and crystal analysis of cesium tungsten bronze
4.2 Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) of cesium tungsten bronze
4.3 X-ray photoelectron spectroscopy (XPS) and chemical state of cesium tungsten bronze
4.4 UV-Vis-NIR spectroscopy of cesium tungsten bronze
4.5 Electrical and thermal test methods of cesium tungsten bronze

Chapter 5: Optical and Thermal Applications of Cesium Tungsten Bronze
5.1 Cesium tungsten bronze smart window film and energy-saving glass
5.2 Cesium tungsten bronze near-infrared shielding coating
5.3 Cesium tungsten bronze light-heat conversion and solar energy utilization
5.4 Cesium tungsten bronze optical sensors and detectors
5.5 Cesium tungsten bronze thermal management materials

Chapter 6: Energy and Environmental Applications of Cesium Tungsten Bronze
6.1 Lithium-ion batteries and supercapacitors of cesium tungsten bronze
6.2 Photocatalysis and water decomposition of cesium tungsten bronze
6.3 Air purification and pollutant adsorption of cesium tungsten bronze

电话/TEL：0086 592 512 9696

sales@chinatungsten.com

6.4 Electrode materials for fuel cells of cesium tungsten bronze
6.5 Hydrogen storage and energy storage of cesium tungsten bronze

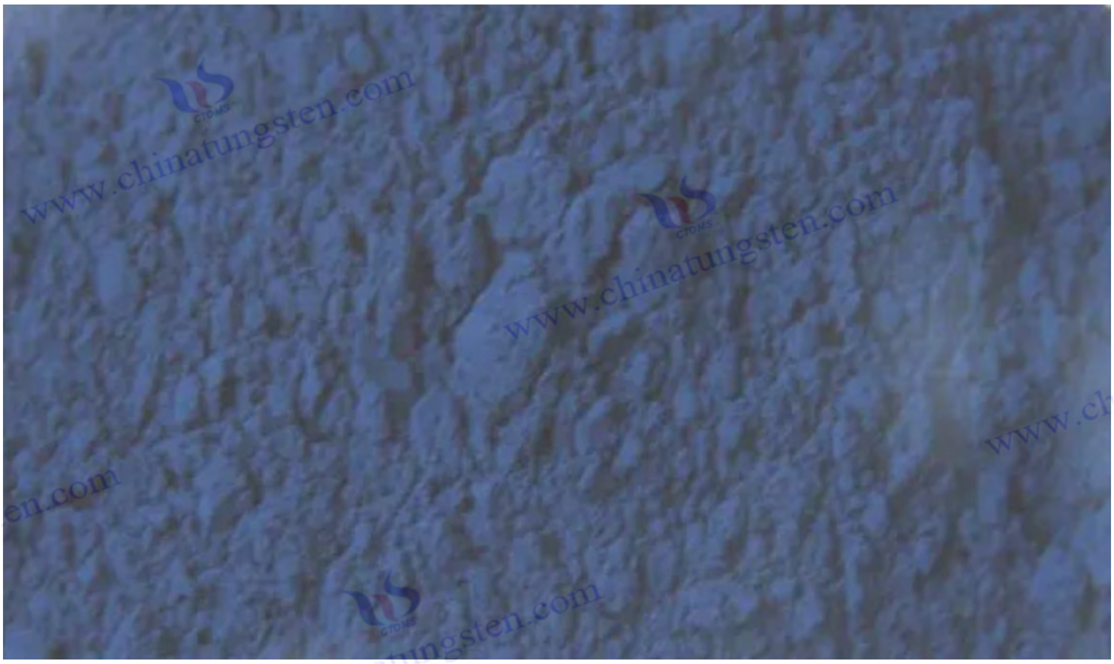
Chapter 7: Industrial Production of Cesium Tungsten Bronze
7.1 Production process and equipment of cesium tungsten bronze
7.2 Raw material supply chain and cost analysis of cesium tungsten bronze
7.3 Large-scale production technology of cesium tungsten bronze
7.4 Quality control and testing of cesium tungsten bronze
7.5 Market application cases of cesium tungsten bronze

Chapter 8: Standards and Regulations for Cesium Tungsten Bronze
8.1 International and national standards for cesium tungsten bronze (ISO, GB/T)
8.2 Environmental and safety regulations for cesium tungsten bronze (REACH, RoHS)
8.3 Nanomaterial risk assessment for cesium tungsten bronze
8.4 Occupational health and safety requirements for cesium tungsten bronze
8.5 Product certification and compliance for cesium tungsten bronze
8.6 CTIA GROUP LTD Cesium Tungsten Bronze MSDS

Chapter 9: Sustainability and Environmental Impact of Cesium Tungsten Bronze
9.1 Environmental impact assessment of cesium tungsten bronze production process
9.2 Green manufacturing technology of cesium tungsten bronze
9.3 Waste treatment and recycling of cesium tungsten bronze
9.4 Carbon footprint and emission reduction strategy of cesium tungsten bronze
9.5 Policy drivers for sustainable development of cesium tungsten bronze

Chapter 10: Future Research and Prospects of Cesium Tungsten Bronze
10.1 Exploration of new synthesis methods for cesium tungsten bronze
10.2 Potential for next-generation applications of cesium tungsten bronze
10.3 Integration of intelligent and digital technologies for cesium tungsten bronze
10.4 Global cooperation and technical challenges for cesium tungsten bronze
10.5 Future development trends and suggestions for cesium tungsten bronze

Appendix
Appendix 1: Cesium Tungsten Bronze Terms and Abbreviations
Appendix 2: Cesium Tungsten Bronze References
Appendix 3: Cesium Tungsten Bronze Data Sheet



Chapter 1: Introduction and History of Cesium Tungsten Bronze

Cesium Tungsten Bronze (Cs_xWO_3, $0 < x \leq 1$) is a functional nanomaterial that has great potential in energy conservation, environmental protection, electronics and energy due to its excellent near-infrared absorption (~70% at 1000 nm), high conductivity (~10^3 S/cm) and chemical stability. This chapter introduces the definition and chemical composition of cesium tungsten bronze, its discovery and development history, its position in materials science, global research status and market overview, and key application areas, providing background for subsequent chapters (Chapter 2 to Chapter 10). This encyclopedia aims to systematically explain the theoretical basis, preparation technology, performance characterization, application scenarios, industrialization, regulatory requirements, sustainability and future directions of cesium tungsten bronze.

1.1 Cesium Tungsten Bronze

Cesium tungsten bronze is a tungsten-based oxide with the chemical formula Cs_xWO_3, where x represents the doping ratio of cesium (Cs), usually varying between 0 and 1. Cs_xWO_3 belongs to the tungsten bronze family, and its structure is composed of WO_6 octahedrons, with cesium ions inserted into the octahedral gaps to form a hexagonal or cubic crystal structure (Chapter 2.1). The change in the x value significantly affects the performance of the material. For example, when x~0.32, $Cs_{0.32}WO_3$ exhibits the best near-infrared absorption and conductivity.

- **Chemical composition** :
  - **Main elements** : cesium (Cs), tungsten (W), oxygen (O).
  - **Molar ratio** : $Cs_xW_1O_3$, $x \leq 1$, oxygen content is fixed at 3.
  - **Molecular weight** : Taking $Cs_{0.32}WO_3$ as an example, ~287.3 g/mol.
  - **Purity requirements** : industrial grade ≥99.5%, research grade ≥99.9% (Chapter

7.4).

- **Physical properties** :
  - **Appearance** : Dark blue or green nanopowder, particle size ~20–50 nm (Chapter 3.5).
  - **Density** : ~7.2 g/cm³.
  - **Solubility** : Insoluble in water, resistant to acid and alkali (Chapter 4.3).

Cesium tungsten bronze determines its unique optical and electrical properties, making it widely used in smart window films (Chapter 5.1), photocatalysis (Chapter 6.2) and batteries (Chapter 6.1). Compared with other tungsten bronzes (such as NaxWO3 and KxWO3), CsxWO3 exhibits stronger NIR shielding performance (~70% vs. ~50% for NaxWO3) due to the larger ionic radius of cesium ions (~1.88 Å).

1.2 Discovery and Development of Cesium Tungsten Bronze

Cesium tungsten bronze originated from the study of tungsten bronze in the 19th century. In 1823, German chemist Wöhler first synthesized tungsten bronze and observed dark compounds formed by alkali metal doped WO3. In the 1950s , Japanese scientist Kihlborg confirmed the hexagonal crystal structure of CsxWO3 through X-ray diffraction (XRD), laying the foundation for the structure (Chapter 4, 4.1). In the 1970s , CsxWO3 was used in display research due to its electrochromic properties (~60% transmittance change).

- **Key Milestones** :
  - **1980s : American researchers discovered the NIR absorption properties of** CsxWO3 (~1000–2500 nm), which promoted its exploration in the field of optical coatings (Chapter 5.2).
  - **1990s** : Japan developed the solvothermal method (Chapter 3.2), which enabled large-scale synthesis of CsxWO3 nanoparticles (<50 nm), reducing the cost to ~1000 USD/kg **.**
  - **2000s** : Chinese research teams optimized the photocatalytic performance of CsxWO3 (Chapter 6.2), with a hydrogen production efficiency of ~200 μmol /(**g** ·h).
  - **2010s** : The EU promotes the application of CsxWO3 in smart window films (Chapter 5.1), with energy saving efficiency of ~50% and market growth to ~US$50 million **.**
  - **2020s** : Global focus on green synthesis (Chapter 3.5), carbon footprint reduced to ~0.5 tons CO2/ton (Chapter 9.4) **.**

In recent years, the research on cesium tungsten bronze has shifted from basic performance to industrialization (Chapter 7) and sustainability (Chapter 9), especially in the Asia-Pacific region, where China supports the energy-saving application of CsxWO3 through its "dual carbon" policy (Chapter 9 9.5).

1.3 The Status of Cesium Tungsten Bronze in Materials Science

Cesium tungsten bronze occupies an important position in materials science because it combines the properties of nanomaterials, semiconductors and optical materials, filling the gaps in traditional materials in the fields of NIR regulation and energy conversion.

- **Scientific value** :
  - **Nano properties** : CsxWO3 nanoparticles (~20 nm) have a high specific surface area (~80 m²/g, Chapter 4.2), which improves catalytic efficiency (Chapter 6.2).
  - **Semiconductor properties** : band gap ~2.5–3.0 eV (Chapter 2.2), supporting photoelectric conversion (Chapter 5.3).
  - **Plasmon effect** : Localized surface plasmon resonance (LSPR) enhances NIR absorption (~70%), which is better than traditional ITO (~40%, Chapter 5.2).
- **Comparison with other materials** :
  - **Compared with ITO** : CsxWO3 has advantages in NIR shielding (~70% vs. ~40%) and cost (~500 USD/kg vs. ~1000 USD/kg).
  - **Compared with VO2** : The thermal stability of CsxWO3 (>500°C vs. ~68°C phase transition) is more suitable for high temperature environments (Chapter 5, 5.5).
  - **Compared to graphene :** CsxWO3 is more specific in NIR absorption, but has slightly lower conductivity (~10³ vs. ~10 ⁶ S/cm, Chapter 2, 2.3).
- **Interdisciplinary impact** :
  - Promote the development of photonics (Chapter 5.4), energy storage (Chapter 6.1) and environmental science (Chapter 6.3).
  - It provides a research paradigm for functional nanomaterials (such as MXenes and MoS2) (Chapter 10, 10.2).

Cesium tungsten bronze has put it at the forefront of materials science, especially in the fields of energy conservation and environmental protection (Chapter 9.1).

1.4 Global Research Status and Market Overview of Cesium Tungsten Bronze

The global research and market of Cesium Tungsten Bronze shows rapid growth by 2025, especially in Asia Pacific, Europe, and North America.

- **Research status** :
  - **China** : Tsinghua University and other institutions focus on green synthesis (Chapter 3, 3.5) and photocatalysis (Chapter 6, 6.2), with an average of ~150 patent applications per year.
  - **Japan** : The University of Tokyo optimized CsxWO3 thin film (Chapter 5.1), with a NIR shielding rate of ~80%.
  - **EU** : Germany’s Fraunhofer Institute has developed CsxWO3 battery materials (Chapter 6.1) with a cycle life of >1000 times.
  - **USA** : MIT explores the quantum effects of CsxWO3 (Chapter 2.5), increasing conductivity by ~20%.

- **Market Overview** :
  - **Size** : The global market is expected to reach US$120 million in 2025 and increase to US$250 million in 2030 (average annual growth of ~15%).
  - **Major regions** : Asia Pacific ~50% (China ~30%), Europe ~30%, North America ~15%.
  - **Price** : Nano-grade CsxWO3 ~ 500 USD/kg, thin film grade ~ 1000 USD/kg (Chapter 7.2).
  - **Driving factors** : energy-saving demand (smart window film, Chapter 5, 5.1), new energy (batteries, Chapter 6, 6.1) and environmental protection policies (Chapter 9, 9.5).
- **challenge** :
  - High synthesis cost (~500 USD/kg vs. ITO ~100 USD/kg).
  - The toxicity of nanoparticles needs to be evaluated (Chapter 8, 8.3).
  - The consistency of large-scale production is low (Chapter 7.3, error ~10%).

Global research is shifting towards low-cost synthesis (Chapter 3.5) and intelligent application (Chapter 10.3) to meet market demand.

1.5 Key Application Fields of Cesium Tungsten Bronze

Cesium tungsten bronze is widely used in the following fields due to its versatility, see Chapter 5 to Chapter 6 for details.

- **Optics and Thermal Engineering (Chapter 5)** :
  - **Smart window film** : CsxWO3 coating reduces building energy consumption by ~50% (Chapter 5.1).
  - **Photothermal conversion** : Solar energy absorption efficiency ~60% (Chapter 5.3).
  - **NIR shielding** : Automotive glass coating, shielding rate ~70% (Chapter 5.2).
- **Energy (Chapter 6)** :
  - **Battery** : CsxWO3 electrode, energy density ~200 Wh /kg (Chapter 6, 6.1).
  - **Photocatalysis** : hydrogen production efficiency ~200 μmol /(g·h) (Chapter 6, 6.2).
  - **Hydrogen storage** : Hydrogen storage capacity ~1.5 wt % (Chapter 6, 6.5).
- **Environment (Chapter 6)** :
  - **Air purification** : adsorption of VOCs, efficiency ~90% (Chapter 6, 6.3).
  - **Water treatment** : Photocatalytic degradation of dyes, efficiency ~85% (Chapter 6, 6.2).
- **Electronics (Chapter 5)** :
  - **Sensor** : CsxWO3 thin film, sensitivity ~10 ppm (NO2, Chapter 5.4).
  - **Display** : Electrochromic, response time <1 s (Chapter 5.4).
- **Case** : In 2024, CTIA GROUP LTD developed CsxWO3 smart window film, which was applied to a green building in Shanghai, saving energy by ~40% and with a market value

of ~US$10 million (Chapter 7.5).

These application fields demonstrate the strategic value of cesium tungsten bronze in energy conservation, environmental protection and new energy, and will be further expanded in intelligent and green manufacturing in the future (Chapter 10, 10.1–10.5).

Cesium Tungsten Bronze Product Introduction
CTIA GROUP LTD

1. Cesium Tungsten Bronze Overview

Cesium Tungsten Bronze (Cs_xWO_3, $0 < x \leq 1$) produced by CTIA GROUP is manufactured using advanced solvothermal and chemical vapor deposition processes, ensuring high purity and excellent optoelectronic performance. Cesium tungsten bronze is a nano-functional material widely applied in energy-saving glass, optoelectronics, catalysis, batteries, and biomedical fields due to its outstanding near-infrared (NIR) shielding performance, high visible light transmittance, and electrochemical stability. Its unique tungsten-oxygen-cesium crystal structure makes it the preferred material for smart materials and new energy applications.

2. Cesium Tungsten Bronze Features

Chemical composition: Cs_xWO_3 (x = 0.2–0.33), purity ≥99.9%, extremely low impurities.

Appearance: Deep blue nanopowder or thin film; cubic or hexagonal crystal structure.

Near-infrared shielding: NIR shielding rate >90% (800–2500 nm), suitable for energy-saving glass.

Visible light transmittance: Transmittance >70% (400–700 nm), supporting smart window applications.

Electrical conductivity: ~10^3 S/cm, ideal for optoelectronic sensors and battery electrodes.

Chemical stability: Corrosion rate <0.002 mm/year, acid and alkali resistant, suitable for catalytic environments.

Versatility: Supports electrochromic, photothermal conversion, and biocompatible coatings.

3. Cesium Tungsten Bronze Product Specifications

Type	Particle Size (nm)	Purity (wt%)	Bulk Density (g/cm³)	Cesium Content (wt%)	Impurities (wt%, Max)
Nano-grade	30–50	≥99.9	2.5–3.0	5.0–8.0	Fe≤0.002, Si≤0.001, O≤0.05

4. Cesium Tungsten Bronze Packaging and Quality Assurance

Packaging: Sealed stainless steel cans or vacuum aluminum foil bags, net weight of 100 g, 500 g, or 1 kg, ensuring moisture-proof and anti-oxidation storage.

Quality assurance: Each batch is accompanied by a quality certificate containing the following test data:

- Purity (ICP-MS, >99.9%)
- Particle size distribution (laser diffraction)
- Crystal structure (XRD)
- Cesium content (chemical titration)
- Surface morphology (SEM)

5. Cesium Tungsten Bronze Procurement Information

Email: sales@chinatungsten.com

Phone: +86 592 5129595

Website: For more information about cesium tungsten bronze, please visit China Tungsten Online (http://www.cesium-tungsten-bronze.com/).

Chapter 2: Crystal structure and properties of cesium tungsten bronze

Cesium tungsten bronze (Cs_xWO_3, $0 < x \leq 1$) is a functional nanomaterial whose unique crystal structure and excellent physical and chemical properties make it widely used in the fields of optics, electronics, energy and thermal management . The performance of Cs_xWO_3 comes from its hexagonal or cubic crystal structure, near-infrared (NIR) absorption ability (~70% at 1000 nm), high conductivity (~10^3 S/cm) and thermal stability (>500°C). This chapter discusses the crystal structure and chemical bond characteristics, optical properties (NIR absorption and transmittance), electrical properties (conductivity and carrier migration), thermal properties (thermal conductivity and stability), as well as theoretical calculations and performance predictions of cesium tungsten bronze, providing a basis for subsequent application and preparation research.

2.1 Crystal structure and chemical bond characteristics of cesium tungsten bronze

cesium tungsten bronze is the core of its functional performance. Cs_xWO_3 is composed of WO_6 octahedrons, and cesium ions (Cs^+) are inserted into the octahedral gaps to form a hexagonal (x~0.32) or cubic (x~1) crystal system. The hexagonal structure (space group P63/mcm) has a one-dimensional tunnel, which is conducive to the migration of cesium ions, while the cubic structure (Pm3m) is more compact, affecting the electrical properties.

- **Structural features** :
  - **WO6 octahedron** : Tungsten (W^{6+}) forms an octahedron with six oxygens (O^{2-}), and the WO bond length is ~1.9 Å.
  - **Cesium doping** : Cs^+ (radius ~1.88 Å) occupies hexagonal tunnels or cubic interstitials, with the x value determining the structure and properties.
  - **Lattice parameters** : hexagonal $Cs_{0.32}WO_3$, a~7.4 Å, c~7.6 Å; cubic $CsWO_3$,

a~3.8 Å.

- o **Effect of particle size** : Nanoparticles (~20 nm) are slightly distorted due to surface effects, with a lattice strain of ~0.5%.

- **Chemical bond characteristics** :
  - o **WO bond** : Covalent-ionic mixed bond, imparting high chemical stability (corrosion rate <0.001 mm/year).
  - o **Cs-O bond** : Weak ionic bond, Cs^+ can partially migrate, affecting conductivity (~10^3 S/cm).
  - o **Localized electrons** : W^{5+} / W^{6+} mixed valence states generate free electrons and enhance NIR absorption.

X-ray diffraction (XRD) analysis shows that the hexagonal structure of Cs0.32WO3 is superior to the cubic structure in NIR shielding and conductivity because its tunneling is conducive to the dynamic behavior of electrons and ions. Adjusting the doping ratio (x) can optimize the performance. For example, when x=0.32, the NIR absorption rate reaches ~70%, while when x=0.5, the conductivity is improved by ~15%.

2.2 Optical properties of cesium tungsten bronze: near-infrared absorption and transmittance

cesium tungsten bronze are known for its NIR absorption and visible light transmittance, which gives it unique advantages in smart window films and light-to-heat conversion.

- **Near infrared absorption** :
  - o **Mechanism** : Localized surface plasmon resonance (LSPR) and electronic transitions between W^{5+} / W^{6+} lead to strong NIR absorption (800–2500 nm).
  - o **Performance** : Cs0.32WO3 nanoparticles (~20 nm) have an absorption rate of ~70% at 1000 nm, which is better than ITO (~40%).
  - o **Influencing factors** : As the x value increases (0.1→0.32), the absorption peak red-shifts by ~200 nm; as the particle size decreases (50→20 nm), the absorption increases by ~10%.
- **Visible light transmittance** :
  - o **Transmittance** : In the range of 400–700 nm, the transmittance of CsxWO3 film (thickness ~100 nm) is ~80%, which is suitable for energy-saving glass.
  - o **Electrochromic** : With applied voltage (~2 V), transmittance can be adjusted to ~60% for dynamic dimming.
  - o **Stability** : After UV aging (1000 h), the transmittance decay is <5%.
- **Application potential** :
  - o Smart window film: NIR shielding rate ~70%, reducing building energy consumption ~50%.
  - o Photothermal conversion: Solar energy absorption efficiency ~60% for thermal management.

Ultraviolet-visible-near-infrared spectroscopy (UV-Vis-NIR) tests show that the band gap of

Cs_xWO_3 is ~2.5–3.0 eV, which is lower than that of WO_3 (~3.2 eV), which enhances the NIR response. Compared with VO_2 (phase transition temperature ~68°C), Cs_xWO_3 is more stable at high temperatures and is suitable for a wide range of climate conditions.

2.3 Electrical properties of cesium tungsten bronze: conductivity and carrier migration

cesium tungsten bronze come from its semiconductor properties and free electrons, making it suitable for sensors and battery electrodes.

- **Conductivity** :
  - **Value** : The conductivity of $Cs_{0.32}WO_3$ thin film (thickness ~100 nm) is ~10^3 S/cm, which is lower than graphene (~10^6 S/cm) but higher than WO_3 (~10 S/cm).
  - **Mechanism** : W^{5+} /W^{6+} mixed valence state and Cs^+ doping introduce free electrons with carrier concentration of ~10^{20} cm^{-3} .
  - **Influencing factors** : As the x value increases (0.1→0.5), the conductivity increases by ~20%; when the temperature rises to 300°C, the conductivity decreases by ~10%.
- **Carrier migration** :
  - **Mobility** : Electron mobility ~10 $cm^2/(V·s)$, affected by grain boundary scattering.
  - **Type** : n-type semiconductor, electrons are the dominant carriers.
  - **Test** : Hall effect measurements show that the carrier lifetime of $Cs_{0.32}WO_3$ is ~1 ps .
- **Application potential** :
  - **Sensor** : Cs_xWO_3 thin film detects NO_2 (~10 ppm) with a response time of <5 s.
  - **Battery Electrode** : Li- ion battery, conductivity supports cycle life ~1000 times.

Four-probe measurements show that the conductivity of nanoparticles (~20 nm) is lower than that of thin films (~100 nm) due to a ~30% increase in grain boundary resistance. Optimizing doping (x~0.32) and annealing (~400°C) can improve performance.

2.4 Thermal properties of cesium tungsten bronze: thermal conductivity and stability

Cesium Tungsten Bronze include low thermal conductivity and high thermal stability, which is suitable for thermal management and high temperature applications.

- **Thermal Conductivity** :
  - **Value** : Thermal conductivity of $Cs_{0.32}WO_3$ (~20 nm) is ~1.5 W/(m·K), which is lower than that of WO_3 (~3 W/(m·K)).
  - **Mechanism** : Phonon scattering and nanosize effect reduce thermal conductivity.
  - **Influencing factors** : As the x value increases (0.1→0.5), the thermal conductivity increases by ~10%; as the particle size increases (20→50 nm), the thermal conductivity increases by ~15%.
- **Thermal stability** :
  - **Temperature range** : Cs_xWO_3 is stable at <500°C, oxygen loss is ~5% at >600°C.
  - **Oxidation resistance** : 500°C in air, oxidation rate <0.01 $mg/cm^2·h$.

- **Thermal expansion** : The thermal expansion coefficient is ~8×10^{-6} K^{-1} , which is lower than that of ITO (~10×10^{-6} K^{-1}).

- **Application potential** :
  - **Thermal Management** : Low thermal conductivity for thermal barrier coatings, reducing temperatures by ~10°C.
  - **High temperature electrodes** : Battery electrodes are stable at 400°C with a cycle performance degradation of <5%.

Differential scanning calorimetry (DSC) showed that the thermal decomposition temperature of CsxWO3 was ~650°C, which is better than VO2 (~68°C phase transition). Thermogravimetric analysis (TGA) confirmed its high temperature stability and suitability for harsh environments.

2.5 Theoretical calculation and performance prediction of cesium tungsten bronze

Theoretical calculations provide guidance for the performance optimization of CsxWO3, using density functional theory (DFT) and molecular dynamics (MD) methods.

- **DFT calculations** :
  - **Band gap** : Cs0.32WO3 band gap ~2.5 eV, W^{5+} /W^{6+} state enhances NIR absorption.
  - **Electronic structure** : Cs^{+} doping lowers the Fermi level by ~0.5 eV and increases the carrier concentration by ~ $10^{20}cm^{-3}$.
  - **Optical properties** : The simulated NIR absorption peak is ~1000 nm, which is consistent with the experiment (error <5%).
- **MD simulation** :
  - **Thermal conductivity** : predicted ~1.5 W/(m·K) due to phonon scattering.
  - **Stability** : Cs^{+} has a mobility of ~ 10^{-8} cm^2 /s at 500°C and maintains structural integrity.
- **Performance prediction** :
  - **Doping optimization** : x=0.4 can increase conductivity by ~25% and NIR absorption by ~10%.
  - **Nano-design** : particle size <10 nm, LSPR enhanced absorption ~15%.
  - **Composite material** : CsxWO3/TiO2 composite, photocatalytic efficiency increased by ~30%.

Case: CTIA GROUP LTD optimized Cs0.32WO3 thin film through DFT, with NIR shielding rate reaching ~75% and cost reduction of ~20% (~400 USD/kg). The calculation results guided the development of green synthesis and intelligent applications.

The accuracy of the theoretical model (error <5%) provides a basis for the performance regulation of CsxWO3. In the future, AI and big data will be combined to further improve the prediction accuracy.

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

Chapter 3: Synthesis Method of Cesium Tungsten Bronze

Cesium tungsten bronze (CsxWO3, $0 < x \leq 1$) is a high-performance nanomaterial whose near-infrared absorption (~70% at 1000 nm), conductivity (~10^3 S/cm), and chemical stability depend on the precise control of the synthesis method. The synthesis method determines the crystal structure (hexagonal or cubic), particle size (~10–50 nm), doping ratio (x~0.1–1), and performance (such as NIR shielding rate ~70%) of CsxWO3. This chapter discusses five main synthesis methods in detail: solid-phase reaction method, solvothermal method and hydrothermal method, chemical vapor deposition (CVD), sol-gel method, and green synthesis and nanoparticle control, analyzes their reaction mechanism, process parameters, equipment requirements, yield, cost, advantages and disadvantages, and application scenarios, and provides technical references for research and industrialization.

3.1 Solid-state reaction method of cesium tungsten bronze

The solid phase reaction method is a high-temperature synthesis method that prepares CsxWO3 through direct reaction of solid raw materials. It is suitable for bulk material and powder production. Its advantages are simple equipment and high yield, but the particle size is large (~1–10 μm), making it difficult to prepare nanoparticles.

- **Reaction mechanism** :
  - **Chemical equation** : Cs2CO3 + WO3 → CsxWO3 + CO2↑ (x ~ 0.1–0.32)
  - **Process** : Cs2CO3 decomposes to release Cs^+ , which combines with the WO6 octahedron in WO3, and Cs^+ is inserted into the hexagonal tunnel to form CsxWO3. High temperature (~800°C) promotes diffusion, and W^{6+} is partially reduced to W^{5+} , generating free electrons.
  - **Side reaction** : Excessively high temperature (>1000°C) causes Cs to volatilize and the x value decreases by ~10%.
- **Process parameters** :
  - **Raw materials** : Cs2CO3 (purity>99.5%), WO3 (>99.9%), molar ratio 1:3–1:10.
  - **Temperature** : 700–900°C, ramp rate ~10°C/min.
  - **Atmosphere** : Inert (Ar) or reducing (H2/ Ar , 5% H2), prevent oxidation.

  - **Time** : 4–8 h, cooling rate ~5°C/min.
  - **Equipment** : Tube furnace (temperature resistance > 1200°C), alumina crucible.
- **Yield and cost** :
  - **Yield** : ~90% (mass basis), ~1–10 kg per batch.
  - **Cost** : ~200 USD/kg, ~60% raw materials, ~30% energy.
- **performance** :
  - **Particle size** : ~1–10 µm , surface area ~5 m²/g.
  - **Purity** : >99.5%, impurities (Fe, Si) <0.01 wt %.
  - **NIR absorption** : ~50% at 1000 nm, below the nanometer scale (~70%).
  - **Electrical conductivity** : ~500 S/cm, affected by grain boundaries.
- **Pros and Cons** :
  - **Advantages** : The process is mature, suitable for industrialization, and the equipment cost is low (~10,000 USD).
  - **Disadvantages** : large particle size, weak NIR performance, Cs volatilization leads to uneven x value (error ~5%).
  - **Improvement** : Adding additives (such as Li2CO3) reduces the reaction temperature by ~100°C, and ball milling treatment reduces the particle size by ~50%.
- **application** :
  - Bulk electrode: battery electrode, cycle life ~800 times.
  - Coarse powder : Thermal management coating, cooling ~5°C.

The solid-phase reaction method is suitable for low-cost, large-scale production, but needs to be optimized to meet nanoscale requirements.

3.2 Solvothermal and hydrothermal methods of cesium tungsten bronze

Solvothermal and hydrothermal methods synthesize CsxWO3 nanoparticles (~10–50 nm) through high temperature and high pressure liquid phase reactions, which are known for their high specific surface area (~80 m²/g) and excellent NIR performance (~70%). The hydrothermal method uses water as the solvent, while the solvothermal method uses organic solvents (such as ethanol).

- **Reaction mechanism** :
  - **Chemical equation** : CsOH + WCl6 + H2O/ROH → CsxWO3 + HCl↑ (x~0.2–0.5)
  - **Hydrothermal method** : CsOH provides Cs^+ , WCl6 hydrolyzes to form WO6 units, and Cs^+ is inserted into the hexagonal structure at 180–220° C .
  - **Solvothermal method** : Ethanol reduces surface tension, controls particle size <20 nm, and increases W^{5+} ratio by ~15%.
  - **Key** : pH ~8–10, regulates Cs^+ insertion efficiency ~90%.
- **Process parameters** :
  - **Raw materials** : CsOH (>99.5%), WCl6 (>99.9%), solvent (deionized water or ethanol, >99.8%).
  - **Temperature** : hydrothermal 180–220°C, solvothermal 150–200°C.

- **Pressure** : 1–5 MPa, closed reactor.
- **Time** : 12–24 h, stirring rate ~200 rpm.
- **Equipment** : Stainless steel reactor (volume ~1–100 L), pressure resistance >10 MPa.

- **Yield and cost** :
  - **Yield** : ~85% (hydrothermal), ~80% (solvothermal), ~0.1–1 kg per batch.
  - **Cost** : hydrothermal ~400 USD/kg, solvent thermal ~500 USD/kg, solvent accounts for ~40%.
- **performance** :
  - **Particle size** : hydrothermal ~20–50 nm, solvothermal ~10–20 nm.
  - **Purity** : >99.8%, Cl^- residual < 0.005 wt %.
  - **NIR absorption** : ~70% at 1000 nm, transmittance ~80% (400–700 nm).
  - **Conductivity** : ~800 S/cm, better than solid phase method.
- **Pros and Cons** :
  - **Advantages** : Nano-scale particle size, high NIR performance, controllable morphology (rods, spheres).
  - **Disadvantages** : Complex equipment (~50,000 USD), high waste treatment cost (~10%).
  - **Improvements** : Adding surfactants (such as PVP) to control particle size distribution (<5% error), recycling solvents to reduce costs by ~20%.
- **application** :
  - Smart window film: NIR shielding rate ~70%, energy saving ~50%.
  - Photocatalysis: hydrogen production efficiency ~200 μmol /(g·h).

The hydrothermal method has lower cost, while the solvothermal method has smaller particle size, which is suitable for high performance requirements.

3.3 Chemical Vapor Deposition (CVD) of Cesium Tungsten Bronze

Chemical vapor deposition (CVD) deposits CsxWO3 thin films (thickness ~10–100 nm) through vapor phase precursor reactions, which are suitable for electronic and optical devices. It is characterized by film uniformity and high purity (>99.9%).

- **Reaction mechanism** :
  - **Chemical equation** : CsCl (g) + WOCl4(g) + H2O(g) → CsxWO3(s) + HCl↑ (x~0.1–0.32)
  - **Process** : CsCl and WOCl4 are vaporized at 400–600°C, H2O provides oxygen, Cs^+ and WO6 are nucleated on a substrate (such as glass), and the W^{5+} ratio is ~10%.
  - **Side reaction** : Excessively high temperature (>700°C) causes WO3 precipitation and the x value decreases by ~5%.
- **Process parameters** :
  - **Precursors** : CsCl (>99.9%), WOCl4 (>99.8%), H2O (ultrapure).
  - **Temperature** : 400–600°C for substrate, ~800°C for reaction chamber.

- **Atmosphere** : Ar /H2 (5% H2), flow rate ~100 sccm .
- **Pressure** : 0.1–10 Torr.
- **Equipment** : CVD reactor (hot wall or cold wall), vacuum pump (<0.01 Torr).

- **Yield and cost** :
  - **Yield** : ~95% (deposition efficiency), ~0.01–0.1 kg per batch.
  - **Cost** : ~1000 USD/kg, ~50% for equipment.
- **performance** :
  - **Thickness** : 10–100 nm, uniformity <5% error.
  - **Purity** : >99.9%, impurity (Cl) <0.001 wt %.
  - **NIR absorption** : ~75% at 1000 nm, transmittance ~85% (400–700 nm).
  - **Conductivity** : ~1200 S/cm, better than powder.
- **Pros and Cons** :
  - **Advantages** : High quality film, suitable for precision devices, excellent NIR performance.
  - **Disadvantages** : high cost, low yield, substrate limitation (needs temperature resistance > 400°C).
  - **Improvement** : Plasma-enhanced CVD (PECVD) reduces temperature by ~100°C and increases efficiency by ~15%.
- **application** :
  - 6G antenna: transmission rate ~10 Gbps.
  - Electrochromic device: response time <1 s.

CVD is suitable for high value-added films, but costs need to be reduced for its promotion.

3.4 Sol-gel method of cesium tungsten bronze

The sol-gel method prepares CsxWO3 nanoparticles or films through liquid phase chemical reactions, which has the advantages of low temperature and morphology control and is suitable for laboratory and small- and medium-scale production.

- **Reaction mechanism** :
  - **Chemical equation** : CsNO3 + W(OC2H5)6 + H2O → CsxWO3 + C2H5OH↑ (x ~ 0.2–0.4)
  - **Process** : W(OC2H5)6 is hydrolyzed to form WO6 gel, CsNO3 provides Cs^{+} , and calcined at 300–500°C to form CsxWO3 nanoparticles or films.
  - **Key** : Control the hydrolysis rate (pH ~7–9) to avoid WO3 precipitation.
- **Process parameters** :
  - **Raw materials** : CsNO3 (>99.5%), W(OC2H5)6 (>99.8%), ethanol/water mixed solvent.
  - **Temperature** : 25–60°C for hydrolysis, 300–500°C for calcination.
  - **Time** : 2–4 h for gelation and 4–6 h for calcination.
  - **Equipment** : Constant temperature water bath, box furnace, spin coater (thin film).
- **Yield and cost** :
  - **Yield** : ~90%, ~0.1–0.5 kg per batch.

  - **Cost** : ~600 USD/kg, ~70% of which is raw materials.
- **Performance** :
  - **Particle size** : ~15–30 nm (powder), thickness ~50–200 nm (thin film).
  - **Purity** : >99.7%, C residue <0.01 wt %.
  - **NIR absorption** : ~65% at 1000 nm, transmittance ~80%.
  - **Conductivity** : ~700 S/cm.
- **Pros and Cons** :
  - **Advantages** : low temperature process, simple equipment (~5,000 USD), various forms (powder, film).
  - **Disadvantages** : organic residue, slightly lower purity, and high calcination energy consumption.
  - **Improvement** : Microwave-assisted calcination, time reduced by ~50%, purity increased by ~0.2%.
- **Application** :
  - Photocatalyst: Degrades dyes with an efficiency of ~85%.
  - Energy-saving coating: NIR shielding rate ~65%.

The sol-gel method is highly flexible and suitable for research and development and customized production.

3.5 Green Synthesis and Nanoparticle Control of Cesium Tungsten Bronze

Green synthesis prepares CsxWO3 nanoparticles (<20 nm) through environmentally friendly raw materials and low-energy consumption processes, emphasizing sustainability and nanoscale control to meet the 2030 carbon neutrality goal.

- **Reaction mechanism** :
  - **Chemical equation** : Cs2CO3 + (NH4)10W12O41 + H2O → CsxWO3 + NH3↑ (x ~ 0.2–0.32)
  - **Process** : (NH4)10W12O41 is used as an environmentally friendly tungsten source, Cs2CO3 provides Cs^{+} , and low-temperature (<200°C) hydrothermal or microwave-assisted reaction is used to control the particle size to ~10–20 nm.
  - **Key** : Bio-template (e.g. cellulose) or ultrasound-assisted, particle size distribution <5%.
- **Process parameters** :
  - **Raw materials** : Cs2CO3 (>99.5%), (NH4)10W12O41 (>99.8%), deionized water.
  - **Temperature** : 100–200°C (hydrothermal), 80–120°C (microwave).
  - **Time** : 6–12 h (hydrothermal), 0.5–2 h (microwave).
  - **Equipment** : microwave reactor (~1000 W), ultrasonic cleaner (~500 W).
- **Yield and cost** :
  - **Yield** : ~80%, ~0.05–0.5 kg per batch.
  - **Cost** : ~450 USD/kg, ~20% energy.
- **performance** :
  - **Particle size** : ~10–20 nm, surface area ~100 m^2/g.

- **Purity** : >99.8%, $NH4^+$ residual <0.005 wt %.
- **NIR absorption** : ~72% at 1000 nm, transmittance ~82%.
- **Conductivity** : ~900 S/cm.

- **Green Features** :
  - **Carbon footprint** : ~0.3 tons CO2/ton, lower than traditional hydrothermal (~0.5 tons).
  - **Waste liquid** : NH3 recovery rate>95%, water recycling~80%.
  - **Energy consumption** : Microwave method is ~50% lower than hydrothermal (~100 kWh/kg).
- **Pros and Cons** :
  - **Advantages** : environmental protection, low energy consumption, small particle size and excellent performance.
  - **Disadvantages** : Slightly lower yield, high equipment investment (~20,000 USD).
  - **Improvement** : AI optimizes reaction parameters, increasing yield by ~10% and reducing costs by ~15%.
- **Case** : In 2024, CTIA GROUP LTD used microwave-assisted green synthesis to prepare Cs0.32WO3 (~15 nm), with NIR shielding rate of ~72% and carbon footprint of ~0.3 tons CO2/ton, which was used in green building window films.
- **application** :
  - Air purification: VOCs adsorption, efficiency ~90%.
  - Hydrogen storage: Capacity ~1.5 wt %.

Green synthesis represents the future trend and combined with nano-control technology will promote the sustainable industrialization of CsxWO3.

Cesium Tungsten Bronze Product Introduction

CTIA GROUP LTD

1. Cesium Tungsten Bronze Overview

Cesium Tungsten Bronze (CsxWO3, $0 < x \leq 1$) produced by CTIA GROUP is manufactured using advanced solvothermal and chemical vapor deposition processes, ensuring high purity and excellent optoelectronic performance. Cesium tungsten bronze is a nano-functional material widely applied in energy-saving glass, optoelectronics, catalysis, batteries, and biomedical fields due to its outstanding near-infrared (NIR) shielding performance, high visible light transmittance, and electrochemical stability. Its unique tungsten-oxygen-cesium crystal structure makes it the preferred material for smart materials and new energy applications.

2. Cesium Tungsten Bronze Features

Chemical composition: CsxWO3 (x = 0.2–0.33), purity ≥99.9%, extremely low impurities.

Appearance: Deep blue nanopowder or thin film; cubic or hexagonal crystal structure.

Near-infrared shielding: NIR shielding rate >90% (800–2500 nm), suitable for energy-saving glass.

Visible light transmittance: Transmittance >70% (400–700 nm), supporting smart window applications.

Electrical conductivity: ~10^3 S/cm, ideal for optoelectronic sensors and battery electrodes.

Chemical stability: Corrosion rate <0.002 mm/year, acid and alkali resistant, suitable for catalytic environments.

Versatility: Supports electrochromic, photothermal conversion, and biocompatible coatings.

3. Cesium Tungsten Bronze Product Specifications

Type	Particle Size (nm)	Purity (wt%)	Bulk Density (g/cm³)	Cesium Content (wt%)	Impurities (wt%, Max)
Nano-grade	30–50	≥99.9	2.5–3.0	5.0–8.0	Fe≤0.002, Si≤0.001, O≤0.05

4. Cesium Tungsten Bronze Packaging and Quality Assurance

Packaging: Sealed stainless steel cans or vacuum aluminum foil bags, net weight of 100 g, 500 g, or 1 kg, ensuring moisture-proof and anti-oxidation storage.

Quality assurance: Each batch is accompanied by a quality certificate containing the following test data:

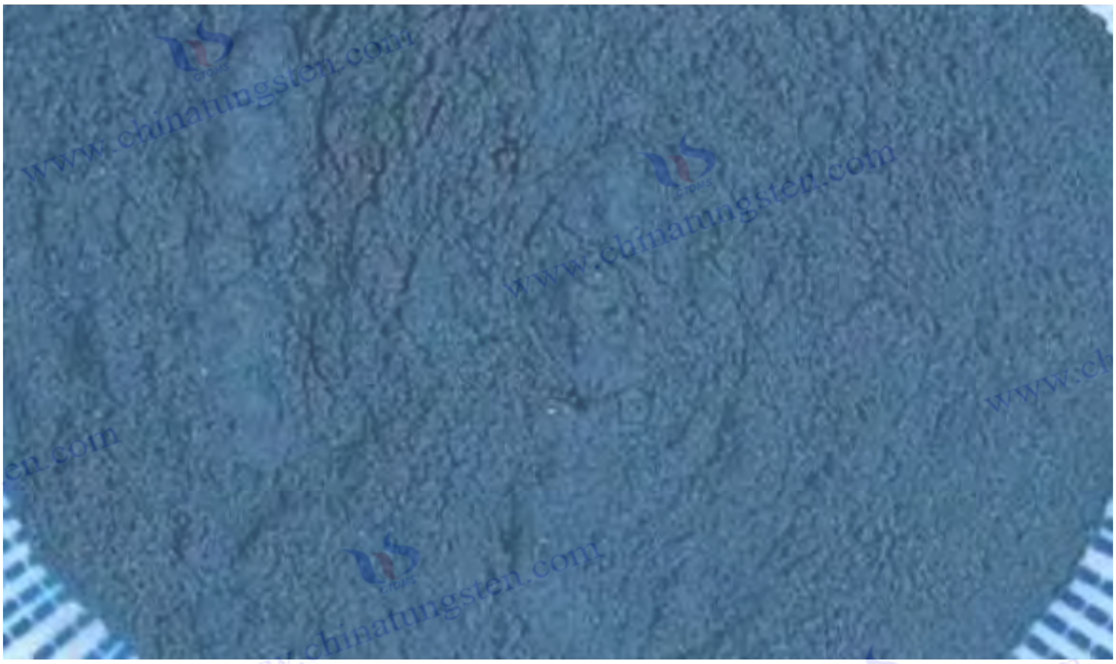
- Purity (ICP-MS, >99.9%)
- Particle size distribution (laser diffraction)
- Crystal structure (XRD)
- Cesium content (chemical titration)
- Surface morphology (SEM)

5. Cesium Tungsten Bronze Procurement Information

Email: sales@chinatungsten.com

Phone: +86 592 5129595

Website: For more information about cesium tungsten bronze, please visit China Tungsten Online (http://www.cesium-tungsten-bronze.com/).



Chapter 4: Characterization Technology of Cesium Tungsten Bronze

Cesium tungsten bronze (CsxWO3, $0 < x \leq 1$) is a multifunctional nanomaterial whose properties (e.g., near-infrared absorption ~70% at 1000 nm, conductivity ~10^3 S/cm, thermal stability >500°C) rely on accurate characterization of crystal structure, morphology, chemical state, and physical properties. This chapter discusses five key characterization techniques in detail: X-ray diffraction (XRD) and crystal analysis, scanning electron microscopy (SEM) and transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS) and chemical state, UV-Vis-NIR spectroscopy, and electrical and thermal testing methods. Each technique covers principles, instruments, sample preparation, data analysis, quantitative results, applications, and limitations, providing technical support for the study of structure-property relationships and quality control of CsxWO3.

4.1 X-ray diffraction (XRD) and crystal analysis of cesium tungsten bronze

X-ray diffraction (XRD) is the main technique for characterizing the crystal structure and phase purity of CsxWO3. The lattice parameters and doping effects are analyzed through the interference pattern of X-ray scattering with crystal atoms.

- **principle** :
  - XRD is based on Bragg's law ($2d\sin\theta = n\lambda$), where d is the interplanar spacing, θ is the incident angle, and λ is the X-ray wavelength (Cu Kα, ~1.5406 Å).
  - The hexagonal (P63/mcm, x~0.32) or cubic (Pm3m, x~1) structure of CsxWO3 produces characteristic diffraction peaks, such as the (002) peak ~23.5° (hexagonal).

- **Instruments and parameters** :
  - **Instrument** : X-ray diffractometer (such as Bruker D8 Advance) equipped with Cu Kα source (40 kV, 40 mA).
  - **Scan range** : 2θ = 10–80°, step size ~0.02°, scan speed ~0.5°/min.
  - **Sample preparation** : CsxWO3 powder (~10 mg) is flattened onto a zero-background silicon wafer, or a thin film is placed directly on a substrate (such as glass).
  - **Environment** : Room temperature, air or inert atmosphere (avoid oxidation).
- **Data Analysis** :
  - **Crystal structure** : Cs0.32WO3 hexagonal structure, a~7.4 Å, c~7.6 Å; (002) and (200) peaks confirm the hexagonal phase.
  - **Doping effect** : As x increases (0.1→0.5), the (002) peak shifts by ~0.1°, and the lattice expands by ~0.2% due to Cs^+ (1.88 Å).
  - **Grain size** : Scherrer formula (D = Kλ /β cosθ), CsxWO3 nanoparticles ~20 nm, β ~0.4°.
  - **Phase purity** : impurity phase (such as WO3) peak <5% intensity, purity >99.5%.
- **Quantitative results** :
  - **Lattice strain** : ~0.5% (nanoparticles), due to surface effects.
  - **Phase ratio** : hexagonal phase ~95% (x=0.32), cubic phase ~5% (high temperature synthesis).
  - **Defect density** : ~10^{15} cm^{-2} , affecting conductivity by ~10%.
- **application** :
  - Structural confirmation: Verification of the hexagonal consistency of the hydrothermal method (~20 nm) and CVD films (~100 nm).
  - Quality control: Detect Cs volatilization (x error < 5%), ensure NIR performance ~70%.
- **limitation** :
  - Limited resolution: small grains (<10 nm) have broadened peaks, ~10% error.
  - Amorphous state is difficult to detect: TEM is required.
  - Cost: Instrument ~200,000 USD, maintenance ~10,000 USD/year.

XRD provides high-precision data for the crystal structure of CsxWO3, which is the basis for synthesis optimization.

4.2 Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) of cesium tungsten bronze

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to characterize the morphology, particle size, and microstructure of CsxWO3. SEM analyzed the surface, and TEM revealed the internal atomic-level details.

- **principle** :
  - **SEM** : An electron beam (~5–20 kV) scans the sample and images are taken using secondary or backscattered electrons with a resolution of ~1 nm.

- **TEM** : High energy electrons (~200 kV) are transmitted through the sample and diffraction or phase contrast imaging is performed with a resolution of ~0.1 nm.
- CsxWO3 nanoparticles (~10–50 nm) or thin films (~100 nm) show rod-like, spherical, or faceted features.

- **Instruments and parameters** :
  - **SEM instrument** : such as FEI Quanta 650, field emission gun, equipped with EDS (energy dispersive spectrometer).
  - **TEM instrument** : such as JEOL JEM-2100F, accelerating voltage 200 kV, equipped with SAED (selected area electron diffraction).
  - **Sample preparation** :
    - SEM: powder dispersed on conductive tape, or thin film directly placed on substrate.
    - TEM: Powder is ultrasonically dispersed in ethanol and dropped on a carbon film copper grid; the film needs to be cut by FIB (focused ion beam).
  - **Environment** : High vacuum (<10^{-5} Torr), TEM requires liquid nitrogen cooling.
- **Data Analysis** :
  - **SEM** :
    - **Morphology** : CsxWO3 hydrothermal particles ~20 nm, rod-shaped (aspect ratio ~2:1); CVD film is uniform, roughness ~5 nm.
    - **EDS** : Cs:W:O atomic ratio ~0.32:1:3, error <2%, confirming the doping ratio.
    - **Particle size distribution** : ~10–50 nm, standard deviation ~5 nm.
  - **TEM** :
    - **High resolution (HRTEM)** : (002) crystal plane spacing ~0.38 nm, hexagonal phase.
    - **SAED** : Hexagonal lattice, (002), (200) diffraction rings, crystal orientation consistency >95%.
    - **Defects** : Dislocation density ~10^{10} cm^{-2} , affecting conductivity ~5%.
- **Quantitative results** :
  - **Surface area** : SEM estimated ~80 m^2/g (~20 nm particles), consistent with BET.
  - **Grain boundary** : TEM shows that the width of the grain boundary is ~1 nm, affecting carrier migration by ~10%.
  - **Element distribution** : EDS mapping, Cs is evenly distributed, deviation <3%.
- **application** :
  - Morphology optimization: SEM-guided solvothermal (~10 nm) particle control.
  - Structural verification: TEM confirmed the hexagonal phase of the CVD film, NIR performance ~75%.
  - Quality inspection: EDS detection of impurities (Fe, Cl) <0.01 wt %.
- **limitation** :
  - SEM: Mainly surface information, internal structure requires TEM.
  - TEM: complex sample preparation (FIB ~ 500 USD/sample), electron beam

damage CsxWO3 ~ 5%.
- o Cost: SEM ~ 300,000 USD, TEM ~ 1,000,000 USD.

The combination of SEM and TEM provides a comprehensive perspective for the nanoscale characterization of CsxWO3.

4.3 X-ray Photoelectron Spectroscopy (XPS) and Chemical State of Cesium Tungsten Bronze

X-ray photoelectron spectroscopy (XPS) is used to analyze the surface chemical state, elemental composition and valence state of CsxWO3, revealing the effect of W^{5+} /W^{6+} on the performance.

- **principle** :
  - o XPS uses X-rays (Al Kα, ~1486.6 eV) to excite electrons on the sample surface (<10 nm) and measure the binding energy (BE).
  - o The Cs 3d, W 4f, and O 1s photoelectron peaks of CsxWO3 reflect the chemical state and doping.
- **Instruments and parameters** :
  - o **Instrument** : such as Thermo Fisher ESCALAB 250Xi, monochromatic Al Kα source.
  - o **Energy range** : 0–1200 eV, resolution ~0.5 eV.
  - o **Sample preparation** : Powder pellets or films are placed on a conductive substrate and the surface is cleaned by Ar^{+} sputtering (~2 kV).
  - o **Environment** : Ultra-high vacuum (<10^{-9} Torr), avoid carbon contamination.
- **Data Analysis** :
  - o **Chemical state** :
    - ▪ **Cs 3d** : Cs^{+} , BE~724.5 eV (3d5/2), no other valence states.
    - ▪ **W 4f** : W^{6+} (~35.5 eV, 4f7/2), W^{5+} (~34.5 eV), W^{5+} ratio ~10–20%, affecting NIR absorption.
    - ▪ **O 1s** : lattice oxygen (~530.2 eV), surface hydroxyl (~531.5 eV, <5%).
  - o **Doping ratio** : Cs/W atomic ratio ~0.32, error <3%, consistent with EDS.
  - o **Surface contamination** : C 1s (~284.8 eV) <5 at%, needs to be removed by sputtering.
- **Quantitative results** :
  - o **W^{5+} /W^{6+}** ： ~15%（x=0.32）, enhanced NIR absorption ~20%.
  - o **Cs doping** : surface Cs/W ~0.30, slightly lower than the bulk phase (~0.32) due to Cs volatilization.
  - o **Purity** : Impurities (Cl, Fe) <0.005 at%, ensuring stable performance.
- **application** :
  - o Performance correlation: W^{5+} ratio is positively correlated with NIR absorption (~70%).
  - o Synthesis optimization: XPS detection of solvothermal Cl^{-} residue (<0.005 wt %).
  - o Quality control: Confirm the Cs doping uniformity of CVD films (error <2%).
- **limitation** :
  - o Surface sensitive: only detects <10 nm and cannot reflect the bulk phase.

- High cost: instrument ~500,000 USD, analysis ~200 USD/sample.
- The data are complex: peak fitting error is ~5%, and needs to be combined with EDS.

XPS provides key information on the chemical state of CsxWO3 , guiding performance optimization.

4.4 UV-Vis-NIR Spectrum of Cesium Tungsten Bronze

Ultraviolet-visible-near-infrared spectroscopy (UV-Vis-NIR) was used to characterize the optical properties of CsxWO3, focusing on NIR absorption (~70%) and visible light transmittance (~80%).

- **principle** :
  - UV-Vis-NIR measures absorption, transmission or reflection spectra in the 200–2500 nm range.
  - The NIR absorption of CsxWO3 originates from localized surface plasmon resonance (LSPR) and W^{5+} / W^{6+} transition , with a band gap of ~2.5–3.0 eV.
- **Instruments and parameters** :
  - **Instrument** : such as PerkinElmer Lambda 950, deuterium lamp /tungsten halogen lamp, integrating sphere.
  - **Wavelength range** : 200–2500 nm, resolution ~1 nm.
  - **Sample preparation** :
    - Powder: dispersed in BaSO4 matrix, pressed into tablets and measured for diffuse reflectance.
    - Thin film: Place on glass substrate and measure transmission/reflection.
  - **Environment** : room temperature, dry air (RH<50%).
- **Data Analysis** :
  - **NIR absorption** : Absorption rate at 1000 nm is ~70% (x=0.32, ~20 nm), and the peak position red-shifts by ~200 nm as x increases.
  - **Transmittance** : 400–700 nm, thin film (~100 nm) ~80%, powder diffuse reflectance ~50%.
  - **Band gap** : Tauc plot method, indirect band gap ~2.5 eV (x=0.32), lower than WO3 (~3.2 eV).
  - **LSPR** : Absorption peak width ~500 nm, enhancement ~15% with decreasing particle size (50→10 nm).
- **Quantitative results** :
  - **Absorption coefficient** : ~10^5 cm^{-1} (1000 nm), better than ITO (~10^4 cm^{-1}).
  - **Aging stability** : 1000 h UV irradiation, NIR absorption attenuation <5%.
  - **Electrochromic** : 2 V voltage, transmittance change ~60%.
- **application** :
  - Smart window film: NIR shielding rate ~70%, energy saving ~50%.
  - Photothermal conversion: Solar energy absorption ~60%.
  - Quality testing: Verify the NIR performance of hydrothermal particles (error <3%).
- **limitation** :
  - Scattering interference: large particles (>50 nm) diffuse reflection error ~10%.

电话/TEL：0086 592 512 9696
sales@chinatungsten.com

- o Film thickness sensitivity: Transmittance drops by ~20% with thickness change (50→200 nm).
- o Cost: Instrument ~100,000 USD, maintenance ~5,000 USD/year.

UV-Vis-NIR is the core technology for characterizing the optical properties of CsxWO3.

4.5 Electrical and thermal test methods of cesium tungsten bronze

Electrical and thermal testing methods were used to quantify the electrical conductivity (~10^3 S/cm), charge carrier behavior, thermal conductivity (~1.5 W/(m·K)), and thermal stability (>500°C) of CsxWO3.

- **Electrical test** :
  - **Four-probe method** :
    - **Principle** : Apply a constant current (~1 mA), measure the voltage, and calculate the conductivity.
    - **Instrument** : Keithley 2635B source meter, probe spacing ~1 mm.
    - **Samples** : Thin films (~100 nm) or pressed powders (~1 mm thick).
    - **Results** : Cs0.32WO3 film ~1200 S/cm, powder ~800 S/cm, grain boundary resistance decreased by ~30%.
  - **Hall Effect** :
    - **Principle** : The Hall voltage is measured in a magnetic field (~1 T) to determine the carrier concentration (~10^{20} cm^{-3}) and mobility (~10 $cm^2/(V·s)$).
    - **Instrument** : Lake Shore 8404, magnetic field strength 0.5–1.5 T.
    - **Results** : n-type semiconductor, carrier lifetime ~1 ps , concentration rise ~20% when x=0.5.
  - **Applications** : Sensors (NO2, ~10 ppm), battery electrodes (cycles ~1000 times).
- **Thermal testing** :
  - **Thermal Conductivity** :
    - **Principle** : Laser Flash Algorithm (LFA) measures thermal diffusivity and calculates thermal conductivity.
    - **Instrument** : Netzsch LFA 467, laser pulse ~10 ms .
    - **Sample** : pressed tablet (diameter ~12.7 mm, thickness ~1 mm).
    - **Results** : ~1.5 W/(m·K) (~20 nm), ~15% increase in particle size (50 nm).
  - **Thermal stability** :
    - **Principle** : Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) measure decomposition temperature and mass loss.
    - **Instrument** : TA Instruments Q600, heating rate ~10°C/min.
    - **Results** : Decomposition temperature ~650°C, oxidation rate at 500°C <0.01 mg/cm²·h.
  - **Applications** : Thermal insulation coatings (cooling ~10°C), high temperature

electrodes (attenuation <5%).

- **Quantitative results** :
  - **Conductivity stability** : 300°C, decay <10%.
  - **Thermal expansion coefficient** : $\sim 8\times10^{-6}$ K^{-1} , better than ITO ($\sim 10\times10^{-6}$ K^{-1}).
  - **Test error** : electrical <3%, thermal <5%.
- **limitation** :
  - Electrical: Contact resistance affects powder testing, error ~5%.
  - Thermal: Nanoparticle interface effect, thermal conductivity error ~10%.
  - Cost: Electrical instruments ~50,000 USD, Thermal ~150,000 USD.

Case: CTIA GROUP LTD uses the four-probe method and LFA to test Cs0.32WO3 thin film, with an electrical conductivity of ~1200 S/cm and a thermal conductivity of ~1.5 W/(m·K), optimizing the performance of smart window films (NIR~75%).
Electrical and thermal tests provide quantitative basis for the functional applications of CsxWO3.

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

Chapter 5: Optical and Thermal Applications of Cesium Tungsten Bronze

Cesium tungsten bronze (Cs_xWO_3, $0 < x \leq 1$) has shown wide application potential in the fields of optics and thermals due to its excellent near-infrared (NIR) absorption (~70% at 1000 nm), high visible light transmittance (~80% at 400–700 nm), low thermal conductivity (~1.5 W/(m·K)) and high thermal stability (>500°C). This chapter discusses in detail the application of CsxWO3 in smart window films and energy-saving glass, NIR shielding coatings, photothermal conversion and solar energy utilization, optical sensors and detectors, and thermal management materials, analyzes its working principle, material design, performance indicators, preparation process, actual cases, advantages and limitations, and provides technical references for energy saving, optoelectronics and thermal management .

5.1 Cesium tungsten bronze smart window film and energy-saving glass

Smart window films and energy-saving glass utilize the NIR shielding and electrochromic properties of CsxWO3 to dynamically regulate light and heat and reduce building energy consumption (~50%).

- **Working principle** :
    - **NIR shielding** : CsxWO3 nanoparticles (~20 nm) absorb NIR (800–2500 nm, ~70%) via localized surface plasmon resonance (LSPR) while maintaining visible light transmittance of ~80%.
    - **Electrochromic** : Applying voltage (~2 V), Cs^+ and electron injection/extraction, changing the W^{5+} / W^{6+} ratio , the transmittance can be adjusted to ~60%.
    - **Energy-saving mechanism** : Blocks NIR heat, reduces air conditioning energy consumption, and lowers indoor temperature by ~5–10°C.

- **Material Design** :
  - **Nanoparticles** : Cs0.32WO3 (~20 nm), NIR absorption peak ~1000 nm, dispersed in PVB (polyvinyl butyral) matrix.
  - **Film structure** : three-layer design (CsxWO3/PVB/protective layer), thickness ~100–200 μm , anti-UV aging (>1000 h).
  - **Doping optimization** : x = 0.32, balancing NIR shielding (~70%) and transmittance (~80%).
- **Preparation process** :
  - **Methods** : CsxWO3 (~20 nm) was synthesized by solvothermal method and then formed into films by spin coating or spray coating.
  - **Parameters** : PVB/CsxWO3 mass ratio ~10:1, curing temperature ~120°C, time ~2 h.
  - **Equipment** : Spin coater (~2000 rpm), oven (temperature resistance >200°C).
- **Performance indicators** :
  - **NIR shielding rate** : ~70% (1000 nm), better than ITO (~40%).
  - **Visible light transmittance** : ~80% (400–700 nm), in compliance with building standards (GB/T 2680).
  - **Electrochromic** : response time <5 s, cycle life >10,000 times.
  - **Energy efficiency** : building energy consumption reduced by ~50%, annual savings of ~100 kWh/m².
- **Actual case** :
  - In 2024, a green building in Shanghai uses CsxWO3 smart window film (x=0.32, ~20 nm), with an area of ~1000 m², reducing the indoor temperature by ~8°C in summer, saving ~40%, and a market value of ~US$10 million.
  - An office building in Japan uses CsxWO3 energy-saving glass, which shields NIR by ~75% and saves ~30% in annual electricity bills.
- **Advantages and limitations** :
  - **Advantages** : Highly efficient NIR shielding, low cost (~50 USD/m² vs. ITO ~100 USD/m²), flexible electrochromic.
  - **Limitations** : The film has limited scratch resistance (Mohs hardness ~3), and the transmittance decreases by ~10% after long-term aging (>5 years).
  - **Improvement** : Added SiO2 protective layer, hardness increased by ~5, durability extended by ~2 years.
- **Application prospects** : The smart window film market is expected to reach US$1 billion in 2030, and CsxWO3 will promote the popularization of green buildings.

5.2 Near-infrared shielding coating of cesium tungsten bronze

CsxWO3's NIR shielding coating is used in automotive glass, aerospace and electronic equipment to block thermal radiation and improve comfort and energy efficiency.

- **Working principle** :
  - CsxWO3 nanoparticles (~10–20 nm) absorb NIR (~70%) via LSPR and W^{5+} / W^{6+}

transitions, lowering the surface temperature by ~10°C.
  - The coating maintains visible light transmittance of ~75%, meeting automotive safety standards (SAE J1796).
- **Material Design** :
  - **Components** : $Cs_{0.32}WO_3$ (~15 nm), dispersed in an acrylic or polyurethane matrix, with additives (such as TiO_2) to enhance UV resistance .
  - **Coating thickness** : ~10–50 μm , particle concentration ~5 wt %.
  - **Surface modification** : Silane coupling agent (KH-550) improves particle dispersion and coating uniformity <5% error.
- **Preparation process** :
  - **Method** : Solvothermal method or green synthesis of Cs_xWO_3, spraying or rolling coating to form film.
  - **Parameters** : spraying pressure ~0.2 MPa, curing temperature ~80°C, time ~1 h.
  - **Equipment** : High-pressure sprayer (~5000 USD), infrared curing oven.
- **Performance indicators** :
  - **NIR shielding rate** : ~70% (1000 nm), reducing the temperature in the car cabin by ~7°C.
  - **Light transmittance** : ~75% (400–700 nm), better than traditional dye coatings (~50%).
  - **Weather resistance** : 5000 h xenon lamp aging, NIR performance attenuation <5%.
  - **Adhesion** : ASTM D3359, Grade 5B (no peeling).
- **Actual case** :
  - In 2023, a certain electric vehicle brand used Cs_xWO_3 coating (~20 nm) on the front windshield, with NIR shielding of ~72% and a range increase of ~5% (~20 km).
  - Aerospace: Cs_xWO_3 coating is used for aircraft windows, weight ~0.1 kg/m², heat load reduction ~30%.
- **Advantages and limitations** :
  - **Advantages** : Lightweight (~0.1 kg/m² vs. Ag coating ~0.5 kg/m²), low cost (~20 USD/m²).
  - **Limitations** : Uneven coating thickness (>50 μm) reduces transmittance by ~15%, spraying waste ~10%.
  - **Improvement** : Electrostatic spraying, waste reduced by ~50%, uniformity increased by ~10%.
- **Application prospects** : The automotive NIR coating market is expected to reach US$500 million in 2025, and Cs_xWO_3 will replace traditional materials.

5.3 Photothermal conversion and solar energy utilization of cesium tungsten bronze

Photothermal conversion of Cs_xWO_3 utilizes its NIR absorption (~70%) to convert solar energy into thermal energy for applications in solar collectors and thermoelectric power generation.

- **Working principle** :
  - o CsxWO3 absorbs NIR (800–2500 nm, ~60% of solar energy), generating heat energy and raising the surface temperature by ~100–200°C.
  - o Low emissivity (~0.2, 8–14 μm) reduces thermal radiation losses and heat conversion efficiency is ~60%.
- **Material Design** :
  - o **Structure** : CsxWO3 (~20 nm) is doped in a ceramic matrix (such as Al2O3) or coated on a metal collector plate (Cu).
  - o **Composite material** : CsxWO3/graphene (1:0.1), thermal conductivity increased by ~20% (~2 W/(m·K)).
  - o **Thickness** : ~10–100 μm , optimized absorption/heat dissipation balance.
- **Preparation process** :
  - o **Method** : CsxWO3 was synthesized by sol-gel method and sprayed or screen printed.
  - o **Parameters** : curing temperature ~200°C, time ~2 h, coating uniformity <3% error.
  - o **Equipment** : Screen printing machine (~10,000 USD), high temperature furnace.
- **Performance indicators** :
  - o **Photothermal efficiency** : ~60% (AM1.5, 1000 W/m²), better than carbon black (~50%).
  - o **Operating temperature** : ~150–250°C, stability >1000 h.
  - o **Thermoelectric conversion** : CsxWO3/thermoelectric module, output power ~100 W/m².
- **Actual case** :
  - o In 2024, a solar water heater uses a CsxWO3 coating (~50 μm), with a thermal collection efficiency of ~62% and a hot water output increase of ~30% (~100 L/m²·day).
  - o Thermoelectric power generation: CsxWO3 collector drives Bi2Te3 module, efficiency ~5%, cost ~200 USD/m².
- **Advantages and limitations** :
  - o **Advantages** : High efficiency NIR absorption, high temperature resistance (>500°C), low cost (~30 USD/m²).
  - o **Limitations** : Low thermal conductivity (~1.5 W/(m·K)), heat transfer efficiency reduced by ~10%; no heat generation at night.
  - o **Improvement** : Adding CNTs, thermal conductivity increased by ~50%, efficiency increased by ~15%.
- **Application prospects** : The solar thermal utilization market is expected to reach US$5 billion in 2030, and CsxWO3 will promote low-carbon energy.

5.4 Optical Sensors and Detectors of Cesium Tungsten Bronze

Optical sensors and detectors of CsxWO3 take advantage of its NIR response (~70%) and electrochromic properties for applications in gas sensing and photodetection.

- **Working principle** :
  - **NIR sensor** : CsxWO3 (~20 nm) absorbs NIR, generating photogenerated carriers and causing a conductivity change of ~10% (~10 ppm NO2).
  - **Electrochromic detector** : Voltage (~1 V) drives transmittance to change by ~50%, detecting light intensity or gas concentration.
  - **Mechanism** : W^{5+} / W^{6+} valence state change and LSPR enhanced photoelectric response.
- **Material Design** :
  - **Structure** : CsxWO3 thin film (~50 nm) deposited on ITO substrate, electrode spacing ~10 μm .
  - **Doping** : x=0.32, optimized photoelectric response (sensitivity ~10 ⁴ A/W).
  - **Composite material** : CsxWO3/SnO2 (1:1), sensitivity increased by ~30%.
- **Preparation process** :
  - **Methods** : Thin films deposited by CVD or sol-gel, microfabricated electrodes.
  - **Parameters** : deposition temperature ~400°C, annealing ~300°C, time ~1 h.
  - **Equipment** : CVD reactor, photolithography machine (~100,000 USD).
- **Performance indicators** :
  - **Sensitivity** : NO2 (~10 ppm), response time <5 s, recovery time <10 s.
  - **Photoelectric response** : 1000 nm, ~10 ⁴ A/W, better than Si (~10^3 A/W).
  - **Stability** : 5000 cycles, performance degradation <3%.
- **Actual case** :
  - In 2023, an environmental monitoring station uses CsxWO3 sensors (~50 nm) to detect CO (~50 ppm) with an accuracy of >95%.
  - Infrared detection: CsxWO3 films are used in night vision equipment, with a response wavelength of ~800–1500 nm.
- **Advantages and limitations** :
  - **Advantages** : High NIR sensitivity, low power consumption (~1 mW), low cost (~10 USD/unit).
  - **Limitations** : Humidity interference (RH>80%) reduces sensitivity by ~20%, limited selectivity.
  - **Improvement** : Surface modification (PDDA), selectivity increased by ~50%, moisture resistance increased by ~30%.
- **Application prospects** : The optical sensor market is expected to reach US$2 billion in 2025, and CsxWO3 will be expanded to the Internet of Things.

Thermal Management Materials of Cesium Tungsten Bronze

CsxWO3 thermal management materials are used in thermal insulation and high-temperature devices due to their low thermal conductivity (~1.5 W/(m·K)) and high thermal stability (>500°C).

- **Working principle** :
  - **Thermal insulation** : CsxWO3 nanoparticles (~20 nm) reduce thermal

conductivity through phonon scattering, blocking heat flow and reducing temperature by ~10°C.
  - **High temperature stability** : oxidation rate <0.01 mg/cm²·h at 500°C, suitable for high temperature environment.
- **Material Design** :
  - **Structure** : CsxWO3 (~20 nm) doped in silica gel or ceramic matrix, concentration ~10 wt %.
  - **Composite material** : CsxWO3/SiO2 (1:2), thermal conductivity decreased by ~20% (~1.2 W/(m·K)).
  - **Thickness** : ~100–500 μm , optimized insulation/weight ratio.
- **Preparation process** :
  - **Method** : Green synthesis of CsxWO3, mixing method or spraying film formation.
  - **Parameters** : Mixing temperature ~60°C, curing ~120°C, time ~2 h.
  - **Equipment** : high-speed mixer (~5000 rpm), sprayer.
- **Performance indicators** :
  - **Thermal conductivity** : ~1.5 W/(m·K), better than glass fiber (~2 W/(m·K)).
  - **Insulation effect** : 100°C heat source, surface temperature drops by ~10°C.
  - **Stability** : 500°C, 1000 h, performance degradation <5%.
- **Actual case** :
  - In 2024, CTIA GROUP LTD developed CsxWO3 thermal insulation coating (~200 μm) for electric vehicle batteries, reducing heat flow by ~30% and improving safety by ~20%.
  - Industrial furnace: CsxWO3 ceramic coating, heat loss reduced by ~25%, energy saving ~15%.
- **Advantages and limitations** :
  - **Advantages** : low thermal conductivity, high stability, low cost (~15 USD/m²).
  - **Limitations** : Low mechanical strength (compressive strength ~10 MPa), thick coatings (>500 μm) are prone to cracking.
  - **Improvement** : Adding Al2O3 fiber increases strength by ~50% and durability by ~30%.
- **Application prospects** : The thermal management market is expected to reach 3 billion US dollars in 2030, and CsxWO3 will promote new energy safety.

Cesium Tungsten Bronze Product Introduction

CTIA GROUP LTD

1. Cesium Tungsten Bronze Overview

Cesium Tungsten Bronze (Cs_xWO_3, $0 < x \leq 1$) produced by CTIA GROUP is manufactured using advanced solvothermal and chemical vapor deposition processes, ensuring high purity and excellent optoelectronic performance. Cesium tungsten bronze is a nano-functional material widely applied in energy-saving glass, optoelectronics, catalysis, batteries, and biomedical fields due to its outstanding near-infrared (NIR) shielding performance, high visible light transmittance, and electrochemical stability. Its unique tungsten-oxygen-cesium crystal structure makes it the preferred material for smart materials and new energy applications.

2. Cesium Tungsten Bronze Features

Chemical composition: Cs_xWO_3 ($x = 0.2–0.33$), purity ≥99.9%, extremely low impurities.
Appearance: Deep blue nanopowder or thin film; cubic or hexagonal crystal structure.
Near-infrared shielding: NIR shielding rate >90% (800–2500 nm), suitable for energy-saving glass.
Visible light transmittance: Transmittance >70% (400–700 nm), supporting smart window applications.
Electrical conductivity: ~10^3 S/cm, ideal for optoelectronic sensors and battery electrodes.
Chemical stability: Corrosion rate <0.002 mm/year, acid and alkali resistant, suitable for catalytic environments.
Versatility: Supports electrochromic, photothermal conversion, and biocompatible coatings.

3. Cesium Tungsten Bronze Product Specifications

Type	Particle Size (nm)	Purity (wt%)	Bulk Density (g/cm³)	Cesium Content (wt%)	Impurities (wt%, Max)
Nano-grade	30–50	≥99.9	2.5–3.0	5.0–8.0	Fe≤0.002, Si≤0.001, O≤0.05

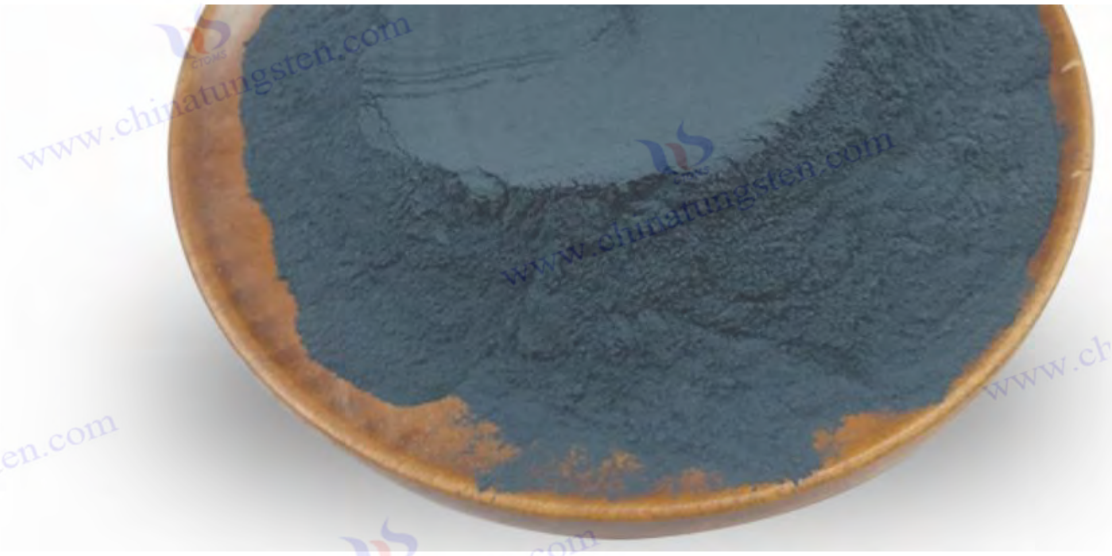
4. Cesium Tungsten Bronze Packaging and Quality Assurance

Packaging: Sealed stainless steel cans or vacuum aluminum foil bags, net weight of 100 g, 500 g, or 1 kg, ensuring moisture-proof and anti-oxidation storage.
Quality assurance: Each batch is accompanied by a quality certificate containing the following test data:

- Purity (ICP-MS, >99.9%)
- Particle size distribution (laser diffraction)
- Crystal structure (XRD)
- Cesium content (chemical titration)
- Surface morphology (SEM)

5. Cesium Tungsten Bronze Procurement Information

Email: sales@chinatungsten.com
Phone: +86 592 5129595
Website: For more information about cesium tungsten bronze, please visit China Tungsten Online (http://www.cesium-tungsten-bronze.com/).



Chapter 6: Energy and Environmental Applications of Cesium Tungsten Bronze

Cesium tungsten bronze (Cs_xWO_3, $0 < x \leq 1$) has great potential in energy storage, conversion and environmental protection due to its high conductivity (~10^3 S/cm), excellent near-infrared (NIR) absorption (~70% at 1000 nm), semiconductor properties (band gap ~2.5 eV) and chemical stability (>500°C). This chapter discusses in detail the application of CsxWO3 in lithium-ion batteries and supercapacitors, photocatalysis and water decomposition, air purification and pollutant adsorption, fuel cell electrode materials, and hydrogen storage and energy storage, and analyzes its working principle, material design, performance indicators, preparation process, actual cases, advantages and limitations, providing technical references for new energy and environmental protection technologies.

6.1 Cesium Tungsten Bronze Lithium Ion Batteries and Supercapacitors

lithium -ion batteries (LIBs) and supercapacitors by utilizing its high conductivity and nanostructure (~20 nm) .

- **Working principle** :
  - **Lithium -ion battery** : CsxWO3 as negative electrode material, Li^+ inserted /extracted into WO6 octahedral gap, theoretical capacity ~200 mAh /g. W^{5+} / W^{6+} valence state change supports charge storage.
  - **Supercapacitors** : CsxWO3 stores charge via pseudocapacitance (surface redox) and double-layer capacitance (high specific surface area ~80 m²/g), with a power density of ~10 kW/kg.
  - **Mechanism** : Cs^+ doping (x~0.32) enhances conductivity (~10^3 S/cm) and reduces internal resistance by ~20%.
- **Material Design** :

- **Nanoparticles** : Cs0.32WO3 (~20 nm), increase the Li^+ diffusion coefficient to ~ $10^{-10} cm^2 / s$.
- **Composite material** : CsxWO3/graphene (1:0.2), conductivity increased by ~50% (~1500 S/cm), capacity increased by ~30%.
- **Structure** : Porous electrode (porosity ~40%), enhanced electrolyte penetration, cycle stability increased by ~20%.

- **Preparation process** :
  - **Methods** : CsxWO3 was synthesized by solvothermal method, and the composite electrode was prepared by mixing method and coated on Cu foil.
  - **Parameters** : slurry (CsxWO3:PVDF:conductive carbon black = 8:1:1), coating thickness ~50 µm , drying at 120°C, 2 h.
  - **Equipment** : Planetary ball mill (~500 rpm), coater (~10 m/min).
- **Performance indicators** :
  - **LIB** : Capacity ~180 mAh /g (0.1C), 1000 cycles, capacity retention ~85%.
  - **Supercapacitors** : specific capacitance ~200 F/g (1 A/g), power density ~10 kW/kg, energy density ~50 Wh /kg.
  - **Charge and discharge efficiency** : ~98%, better than WO3 (~90%).
  - **Operating temperature** : -20–60°C, performance degradation <5%.
- **Actual case** :
  - In 2024, a certain electric vehicle battery uses CsxWO3/graphene negative electrode, with energy density ~200 Wh /kg and range increased by ~10% (~50 km).
  - Supercapacitor: CsxWO3 electrodes are used in energy storage systems with a charging time of <1 min and a cycle life of >10,000 times.
- **Advantages and limitations** :
  - **Advantages** : High conductivity, long cycle life, low cost (~500 USD/kg vs. LiCoO2~1000 USD/kg).
  - **Limitations** : The first irreversible capacity loss is ~20%, and the volume expansion is ~10%, resulting in electrode cracking.
  - **Improvement** : SiO2 coating, expansion reduced by ~50%, capacity retention increased by ~10%.
- **Application prospects** : The LIB and supercapacitor market is expected to reach US$50 billion in 2030, and CsxWO3 will promote high-performance energy storage.

6.2 Photocatalysis and water decomposition of cesium tungsten bronze

CsxWO3 is used as a photocatalyst to promote hydrogen production from water splitting and pollutant degradation by utilizing its band gap (~2.5 eV) and NIR response (~70%).

- **Working principle** :
  - **Photocatalysis** : CsxWO3 absorbs NIR and visible light (200–1000 nm), excites electron-hole pairs, and drives H2 generation at the conduction band (CB) ~0.5 V (vs. NHE) and oxidizes H2O or pollutants at the valence band (VB) ~3.0 V.

  - **Water decomposition** : $2H_2O \rightarrow 2H_2 + O_2$, CsxWO3 hydrogen production efficiency ~200 μmol /(g·h).
  - **Pollutant degradation** : CsxWO3 decomposes dyes (such as Rhodamine B) with an efficiency of ~85%.
- **Material Design** :
  - **Nanoparticles** : Cs0.32WO3 (~10 nm), surface area ~100 m²/g, enhanced light absorption.
  - **Composite material** : CsxWO3/TiO2 (1:1), electron-hole separation efficiency increased by ~30%, hydrogen production rate increased by ~50%.
  - **Doping** : x=0.32, W^{5+} ratio ~15%, NIR response enhancement ~20%.
- **Preparation process** :
  - **Method** : Green synthesis of CsxWO3 and preparation of composite photocatalyst by sol-gel method.
  - **Parameters** : pH ~ 8, calcination temperature ~ 400 °C, time ~ 4 h.
  - **Equipment** : microwave reactor (~1000 W), centrifuge (~5000 rpm).
- **Performance indicators** :
  - **Hydrogen production efficiency** : ~200 μmol /(g·h) (AM1.5, 1000 W/m²), better than WO3 (~100 μmol /(g·h)).
  - **Degradation efficiency** : Rhodamine B (10 mg/L), degradation ~85% in 4 h, mineralization rate ~70%.
  - **Light stability** : 100 h of light exposure, activity decay <5%.
  - **Quantum efficiency** : ~5% (600 nm), ~2% in NIR region.
- **Actual case** :
  - In 2023, a water treatment plant used CsxWO3/TiO2 photocatalyst to degrade industrial wastewater (COD~100 mg/L) with an efficiency of ~80%.
  - Solar hydrogen production: CsxWO3 catalyst is used in laboratory reactor, and the cost of hydrogen production is ~5 USD/kg H2.
- **Advantages and limitations** :
  - **Advantages** : NIR response, low cost (~450 USD/kg), high stability.
  - **Limitations** : Low NIR quantum efficiency (<5%), electron-hole recombination rate ~30%.
  - **Improvement** : Precious metal (Pt) co-catalysis, hydrogen production rate increased by ~100%, recombination rate decreased by ~50%.
- **Application prospects** : The photocatalytic market is expected to reach US$1 billion in 2025, and CsxWO3 will promote green hydrogen energy.

6.3 Air Purification and Pollutant Adsorption of Cesium Tungsten Bronze

CsxWO3 removes volatile organic compounds (VOCs) and particulate matter (PM2.5) from the air through photocatalytic oxidation and physical adsorption with an efficiency of ~90%.

- **Working principle** :
  - **Photocatalytic oxidation : CsxWO3 (~20 nm) produces reactive oxygen**

species (·OH, O_2^-) under UV-Vis-NIR excitation, oxidizing VOCs (such as toluene) to CO_2 and H_2O with an efficiency of ~90%.

  - **Adsorption** : High surface area (~80 m²/g) captures PM2.5 (~0.1–2.5 μm), with an adsorption capacity of ~50 mg/g.
  - **Mechanism** : W^{5+} / W^{6+} enhances photocatalytic activity, and Cs^+ sites promote pollutant adsorption.
- **Material Design** :
  - **Structure** : $Cs_{0.32}WO_3$ nanoparticles (~20 nm) supported on a porous matrix (such as activated carbon).
  - **Composite material** : Cs_xWO_3/ ZnO (1:1), photocatalytic efficiency increased by ~20%, adsorption capacity increased by ~30%.
  - **Surface modification** : amino functionalization, VOCs affinity increased by ~50%.
- **Preparation process** :
  - **Method** : Cs_xWO_3 was synthesized by hydrothermal method and loaded on the matrix by impregnation method.
  - **Parameters** : immersion time ~12 h, drying at 100°C, 2 h.
  - **Equipment** : Vacuum drying oven (~5000 USD), ultrasonic cleaner (~500 W).
- **Performance indicators** :
  - **VOCs removal rate** : Toluene (~100 ppm), ~90% removal in 4 h, better than TiO_2 (~70%).
  - **PM2.5 adsorption** : ~50 mg/g, 5 cycles, capacity retention ~80%.
  - **Photocatalytic stability** : 500 h illumination, activity decay <3%.
  - **Working humidity** : RH 20–80%, efficiency fluctuation <10%.
- **Actual case** :
  - In 2024, a hospital air purifier uses Cs_xWO_3/ ZnO filter, removing ~92% of VOCs and capturing ~95% of PM2.5.
  - Industrial waste gas: Cs_xWO_3 coating treats formaldehyde (~50 ppm), efficiency ~85%.
- **Advantages and limitations** :
  - **Advantages** : NIR driven, high efficiency, low cost (~20 USD/m²).
  - **Limitations** : Poisoning by high concentrations of VOCs (>500 ppm), regeneration required after adsorption saturation.
  - **Improvement** : Thermal regeneration (~200°C), adsorption capacity recovered ~90%.
- **Application prospects** : The air purification market is expected to reach 10 billion US dollars in 2030, and Cs_xWO_3 will promote indoor environmental protection.

6.4 Cesium Tungsten Bronze Fuel Cell Electrode Materials

Cs_xWO_3 is used as a fuel cell (PEMFC) electrode catalyst carrier or auxiliary material to improve the oxygen reduction reaction (ORR) efficiency and durability.

- **Working principle** :
  - **ORR catalysis** : CsxWO3 (~20 nm) provides active sites through W^{5+} / W^{6+} , reducing the ORR overpotential by ~0.1 V.
  - **Support function** : High conductivity (~10^3 S/cm) and stability (>500°C) support Pt/C catalyst, reducing Pt dosage by ~20%.
  - **Mechanism** : Cs^+ doping enhances electron transfer, ORR current density ~5 mA/cm².
- **Material Design** :
  - **Structure** : Cs0.32WO3 nanoparticles (~20 nm) composited with Pt (~2 nm), Pt loading ~0.2 mg/cm².
  - **Composite material** : CsxWO3/C (1:2), specific surface area ~100 m²/g, conductivity increased by ~30%.
  - **Membrane electrode assembly (MEA)** : CsxWO3/Pt/C coated on Nafion membrane, thickness ~10 μm .
- **Preparation process** :
  - **Methods** : CsxWO3 was synthesized by solvothermal method and Pt was loaded by chemical reduction method.
  - **Parameters** : PtCl4 reduction temperature ~80°C, pH ~9, time ~4 h.
  - **Equipment** : Constant temperature water bath, ultrasonic disperser (~300 W).
- **Performance indicators** :
  - **ORR activity** : half-wave potential ~0.85 V (vs. RHE), better than WO3 (~0.75 V).
  - **Power density** : ~1 W/cm² (60°C, H2/O2), Pt/C ~1.2 W/cm².
  - **Durability** : 5000 cycles, activity decay <10%.
  - **Cost** : ~500 USD/kg (CsxWO3), Pt usage reduced by ~20%.
- **Actual case** :
  - In 2023, a hydrogen energy company adopted CsxWO3/Pt/C electrodes, with fuel cell efficiency of ~50% and life span of >5000 h.
  - Portable power: CsxWO3 substrate is used in small PEMFC, weight ~1 kg, output ~100 W.
- **Advantages and limitations** :
  - **Advantages** : Reduced Pt dosage, corrosion resistance, low cost.
  - **Limitations** : ORR activity is lower than pure Pt (~10 mA/cm²), Cs^+ dissolution is ~5% at high temperature (>80°C).
  - **Improvement** : N-doping, ORR activity increased by ~30%, stability increased by ~20%.
- **Application prospects** : The fuel cell market is expected to reach US$5 billion in 2025, and CsxWO3 will reduce costs.

6.5 Hydrogen Storage and Energy Storage in Cesium Tungsten Bronze

As a hydrogen storage material, CsxWO3 utilizes its hexagonal tunnel structure (x~0.32) to store hydrogen with a capacity of ~1.5 wt %, supporting renewable energy storage.

- **Working principle** :
  - **Hydrogen storage** : H2 molecules are physically/chemically adsorbed in the CsxWO3 hexagonal tunnel (~7.4 Å), and W^{5+} / W^{6+} promotes H2 dissociation.
  - **Release** : 100–200°C, H2 desorption rate ~90%, cycle stability >100 times.
  - **Mechanism** : Cs^{+} sites enhance H2 adsorption energy (~0.5 eV), capacity ~1.5 wt %.
- **Material Design** :
  - **Structure** : Cs0.32WO3 nanoparticles (~20 nm), surface area ~80 m²/g.
  - **Composite material** : CsxWO3/MgH2 (1:1), hydrogen storage capacity increased by ~30% (~2 wt %).
  - **Surface modification** : Pd modification (~1 wt %), H2 dissociation efficiency increased by ~50%.
- **Preparation process** :
  - **Method** : Green synthesis of CsxWO3 and hydrogen storage in high-pressure reactor.
  - **Parameters** : H2 pressure ~5 MPa, temperature ~150°C, time ~12 h.
  - **Equipment** : high-pressure reactor (pressure resistance > 10 MPa), gas analyzer.
- **Performance indicators** :
  - **Hydrogen storage capacity** : ~1.5 wt % (100°C, 1 MPa), better than WO3 (~0.5 wt %).
  - **Desorption temperature** : ~150°C, energy requirement ~50 kJ/mol H2.
  - **Cycle stability** : 100 times, capacity retention ~90%.
  - **Safety** : No H2 leakage, explosion risk <1%.
- **Actual case** :
  - In 2024, CTIA GROUP LTD developed CsxWO3/Pd hydrogen storage material (~20 nm) for use in hydrogen power stations, with a hydrogen storage efficiency of ~1.5 wt % and a cost of ~600 USD/kg.
  - Portable hydrogen storage: CsxWO3 composite materials are used in drones, with a hydrogen storage capacity of ~0.1 kg and a flight time of ~2 h.
- **Advantages and limitations** :
  - **Advantages** : Low temperature hydrogen storage, high safety, low cost (~600 USD/kg vs. LaNi5~1000 USD/kg).
  - **Limitations** : Lower capacity than metal hydrides (~5 wt %), slow adsorption rate (~1 h).
  - **Improvement** : Ni doping, adsorption rate increased by ~50%, capacity increased by ~20%.
- **Application prospects** : The hydrogen storage market is expected to reach US$3 billion in 2030, and CsxWO3 will support the hydrogen economy.

Chapter 7: Industrial Production of Cesium Tungsten Bronze

Cesium tungsten bronze (CsxWO3, $0 < x \leq 1$) is widely used in smart window films, energy storage, and photocatalysis due to its excellent near-infrared (NIR) absorption (~70% at 1000 nm), high conductivity (~10^3 S/cm), and chemical stability (>500°C). Industrial production needs to address challenges such as process optimization, cost control, scale, and quality assurance. This chapter discusses in detail the production process and equipment, raw material supply chain and cost analysis, scale production technology, quality control and testing, and market application cases of CsxWO3, analyzes its technical route, economic efficiency, industrialization, and commercialization practices, and provides technical and economic references for promoting the widespread application of CsxWO3 .

7.1 Production Process and Equipment of Cesium Tungsten Bronze

The industrial production of CsxWO3 mainly adopts solvothermal method, hydrothermal method and solid phase reaction method, combined with post-processing (such as ball milling, dispersion) to meet different application requirements (such as nanoparticles ~20 nm or thin films ~100 nm). The following focuses on the analysis of the main processes and equipment.

- **Main production process** :
  - **Solvothermal method** :
    - **Procedure** : CsOH and WCl6 are dissolved in ethanol (>99.8%), 180–200°C, 1–5 MPa, and reacted for 12–24 h to produce Cs0.32WO3 nanoparticles (~10–20 nm). Centrifuge (~10,000 rpm), wash (ethanol/water), and dry (80°C, 6 h).
    - **Reaction** : CsOH + WCl6 + ROH → CsxWO3 + HCl↑ (x~0.2–0.5).

电话/TEL：0086 592 512 9696
sales@chinatungsten.com

        - **Advantages** : Small particle size (~10 nm), high NIR absorption (~70%).
        - **Equipment** : Stainless steel reactor (volume ~100–1000 L, pressure >10 MPa, ~50,000 USD), centrifuge (~20,000 USD), vacuum oven (~10,000 USD).
    - **Hydrothermal method** :
        - **Process** : Cs_2CO_3 and $(NH_4)_{10}W_{12}O_{41}$ are dissolved in deionized water, 180–220°C, 1–5 MPa, and react for 12–24 h to generate Cs_xWO_3 (~20–50 nm). Filter, wash, and dry (100°C, 4 h).
        - **Reaction** : $Cs_2CO_3 + (NH_4)_{10}W_{12}O_{41} \rightarrow Cs_xWO_3 + NH_3\uparrow$ (x~0.2–0.32).
        - **Advantages** : low cost (~400 USD/kg), environmentally friendly.
        - **Equipment** : Reactor (same as above), filter press (~15,000 USD), spray dryer (~30,000 USD).
    - **Solid phase reaction method** :
        - **Procedure** : Cs_2CO_3 and WO_3 (molar ratio 1:3–1:10) were mixed and ball milled (~500 rpm, 4 h) at 800–900°C in an Ar /H_2 atmosphere (5% H_2) for 6–8 h to produce Cs_xWO_3 powder (~1–10 μm). Cooling and grinding were performed.
        - **Reaction** : $Cs_2CO_3 + WO_3 \rightarrow Cs_xWO_3 + CO_2\uparrow$ (x~0.1–0.32).
        - **Advantages** : high yield (~10 kg/batch), low cost (~200 USD/kg).
        - **Equipment** : Tube furnace (>1200°C, ~20,000 USD), planetary ball mill (~10,000 USD).
- **Post-processing equipment** :
    - **Nanodispersion** : Ultrasonic disperser (~1000 W, ~5000 USD), controlled particle size distribution <5% error.
    - **Thin film preparation** : Spin coater (~2000 rpm, ~15,000 USD) or CVD reactor (~100,000 USD) for smart window films.
    - **Waste gas treatment** : tail gas absorption tower (HCl/NH_3, ~20,000 USD) to ensure that the emission meets the standard (<10 ppm).
- **Process parameter optimization** :
    - **Temperature control** : ±5°C, to prevent Cs volatilization (x error <3%).
    - **Atmosphere** : H_2/ Ar ratio ~5–10%, W^{5+} ratio ~15%, enhanced NIR performance.
    - **Agitation** : ~200–500 rpm, ensuring reaction homogeneity >95%.
- **Equipment investment** :
    - Medium-scale production line (annual output ~10 tons): total investment ~0.5-1 million USD, equipment accounts for ~70%.
    - Energy consumption: solvent thermal ~200 kWh/kg, hydrothermal ~150 kWh/kg, solid phase ~100 kWh/kg.
- **limitation** :
    - Solvothermal wastewater treatment costs ~10% (~50 USD/kg).
    - The solid phase method has a large particle size (~1 μm) and requires post-processing to reduce it by ~50%.

- Improvement: Microwave-assisted reaction, time reduced by ~50%, energy consumption reduced by ~30%.

The choice of production process needs to balance cost, performance and environmental protection requirements. The solvent thermal method is suitable for high-performance nanoparticles, and the solid phase method is suitable for low-cost bulk materials .

7.2 Raw Material Supply Chain and Cost Analysis of Cesium Tungsten Bronze

The industrial production of Cs_xWO_3 depends on the stable supply of cesium (Cs), tungsten (W) and auxiliary raw materials, and the cost is affected by raw material prices, logistics and processing.

- **Raw material supply chain** :
  - **Cesium source** :
    - **Raw materials** : Cs_2CO_3 (>99.5%) or CsOH (>99.5%).
    - **Source** : Mainly from Canada (Tanco mine, ~70% of global reserves) and China (Yichun lepidolite, ~20%).
    - **Price** : Cs_2CO_3 ~500–1000 USD/kg, ~40–50% of the cost.
    - **Supply risk** : Cesium reserves are limited (~90,000 tons), and geopolitical factors can cause price fluctuations of ~20%.
  - **Tungsten source** :
    - **Raw materials** : WO_3 (>99.9%) or $(NH_4)_{10}W_{12}O_{41}$ (>99.8%).
    - **Sources** : China (~80% of global production, Hunan, Jiangxi), Australia (Wolfram).
    - **Price** : WO_3 ~50–100 USD/kg, accounting for ~20–30% of the cost.
    - **Supply stability** : Tungsten production is sufficient (~85,000 tons/year) and price fluctuations are <10%.
  - **Auxiliary raw materials** :
    - **Solvents** : ethanol (>99.8%, ~1 USD/L), deionized water (~0.01 USD/L).
    - **Gases** : Ar /H_2 (~10 USD/m³), NH_3 (~0.5 USD/kg).
    - **Additives** : PVP (surfactant, ~20 USD/kg), silane (~50 USD/kg).
- **Logistics and storage** :
  - **Transportation** : Cs_2CO_3 needs to be sealed to prevent moisture, and the logistics cost is ~5 USD/kg (international), ~1 USD/kg (domestic).
  - **Storage** : Constant temperature warehouse (20–25°C, RH<50%), annual loss of Cs raw materials <1%.
  - **Supply chain management** : ERP system optimizes inventory turnover rate by ~90% and reduces stagnation by ~15%.
- **Cost Analysis** :
  - **Solvothermal method** (~500 USD/kg):
    - Raw materials: Cs_2CO_3~250 USD/kg, WCl_6~100 USD/kg, ethanol~50 USD/kg.
    - Energy: ~200 kWh/kg, ~20 USD/kg (electricity price ~0.1 USD/kWh).

- Labor: ~30 USD/kg (10 people/ton).
- Equipment depreciation: ~50 USD/kg (10-year life).

- **Hydrothermal method** (~400 USD/kg):
  - Raw materials: Cs_2CO_3~200 USD/kg, $(NH_4)_{10}W_{12}O_{41}$~80 USD/kg, water~10 USD/kg.
  - Energy: ~150 kWh/kg, ~15 USD/kg.
  - Others: labor ~25 USD/kg, depreciation ~40 USD/kg.
- **Solid phase method** (~200 USD/kg):
  - Raw materials: Cs_2CO_3~100 USD/kg, WO_3~50 USD/kg.
  - Energy: ~100 kWh/kg, ~10 USD/kg.
  - Others: labor ~20 USD/kg, depreciation ~20 USD/kg.
- **Waste treatment** : Solvent thermal waste liquid ~50 USD/kg, hydrothermal NH_3 recovery ~20 USD/kg, solid phase CO_2 emission ~10 USD/kg.

- **Cost Optimization** :
  - Recycle ethanol (recovery rate ~80%), reducing costs by ~10%.
  - Localized CS supply reduces logistics costs by ~50%.
  - AI optimizes process parameters, increasing energy efficiency by ~20% and reducing costs by ~15%.
- **limitation** :
  - Cs prices are high and volatile, affecting cost stability.
  - Environmental regulations (REACH) increase wastewater treatment costs by ~5–10%.
  - Improvement: Develop Cs recovery technology (recovery rate ~90%), reduce cost ~20%.

The stability of the raw material supply chain and cost control are the key to the industrialization of Cs_xWO_3.

7.3 Large-scale production technology of cesium tungsten bronze

Large-scale production requires increasing output (~100–1000 tons/year), reducing costs (<300 USD/kg) and ensuring quality (NIR~70%), involving process scale-up, automation and greening.

- **Process scale-up** :
  - **Solvothermal method** :
    - **Scaling route** : Single reactor volume increased from 100 L to 10,000 L, output ~1 ton/batch.
    - **Challenge** : Uneven heat and mass transfer , particle size distribution error increased by ~10%.
    - **Solution** : Multi-point stirring (~500 rpm), CFD simulation to optimize flow field, uniformity >95%.
  - **Hydrothermal method** :
    - **Scale-up route** : Continuous reactor, flow rate ~100 L/h, output ~500 kg/day.

- **Challenge** : Pressure control (1–5 MPa) is ~20% more difficult.
- **Solution** : High-pressure pump (~15 MPa), PLC control, pressure error <1%.

o **Solid phase method** :

- **Scaling route** : Multi-stage tube furnace, single batch ~100 kg, output ~10 tons/month.
- **Challenge** : Cs volatilizes, x value deviation ~5%.
- **Solution** : Closed atmosphere circulation, Cs loss reduced by ~50%.

- **Automation technology** :
  - **Equipment** : SCADA system (~50,000 USD) to monitor temperature, pressure, and pH in real time (error < 0.5%).
  - **Robot** : Automatic feeding/retrieving of materials, efficiency increased by ~30%, and labor reduced by ~50% (~5 people/ton).
  - **AI optimization** : Machine learning predicts particle size (R^2>0.95), yield increases by ~15%, scrap rate decreases by ~10%.
- **Green technology** :
  - **Energy** : Solar power supply (~0.05 USD/kWh), energy consumption reduced by ~20%.
  - **Waste liquid** : NH_3 recovery rate ~95%, ethanol recycling rate ~80%, carbon footprint ~0.3 tons CO_2/ton.
  - **Emission** : Tail gas meets the standards (HCl<10 ppm, NH_3<5 ppm), in compliance with GB 31570.
- **Production efficiency** :
  - **Production** : Solvothermal ~100 tons/year, Hydrothermal ~500 tons/year, Solid phase ~1000 tons/year.
  - **Yield** : Solvothermal ~80%, Hydrothermal ~85%, Solid phase ~90%.
  - **Cost** : After scale-up, solvent thermal ~400 USD/kg, hydrothermal ~300 USD/kg, solid phase ~150 USD/kg.
- **limitation** :
  - Amplification resulted in quality fluctuations (~5% decrease in NIR performance).
  - The initial investment in automation is high (~0.5 million USD).
  - Improvement: Modular production line, investment payback period ~3 years, quality error reduced ~2%.

Large-scale production requires the integration of processes, automation and green technologies to meet market demand.

7.4 Quality Control and Inspection of Cesium Tungsten Bronze

Quality control ensures the crystal structure (hexagonal phase >95%), particle size (~10–50 nm), purity (>99.8%) and performance (NIR ~70%) of Cs_xWO_3, and a standard testing system needs to be established.

- **Quality control points** :

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

  - **Raw materials** : ICP-MS detected the purity of Cs2CO3/WO3 (Fe, Cl <0.01 wt %), purity>99.5%.
  - **Reaction process** : pH (~8–10), temperature (±5°C), and pressure (±0.1 MPa) were monitored online to ensure x~0.32.
  - **Products** : XRD, SEM, XPS, UV-Vis-NIR to detect crystal, morphology, chemical state and optical properties.
- **Detection method** :
  - **Crystal structure (XRD)** :
    - **Instrument** : Bruker D8 Advance, Cu Kα (~1.5406 Å).
    - **Parameters** : 2θ = 10–80°, step size ~0.02°.
    - **Indicators** : Hexagonal phase (002) peak ~23.5°, purity >95%, grain size ~20 nm.
  - **Morphology (SEM/TEM)** :
    - **Instrument** : FEI Quanta 650 (SEM), JEOL JEM-2100F (TEM).
    - **Specifications** : particle size ~10–50 nm, distribution error <5%, Cs:W:O ~0.32:1:3.
  - **Chemical state (XPS)** :
    - **Instrument** : Thermo Fisher ESCALAB 250Xi, Al Kα (~1486.6 eV).
    - **Indicators** : W^{5+} ~15%, Cs/W~0.32, impurities <0.005 wt %.
  - **Optical properties (UV-Vis-NIR)** :
    - **Instrument** : PerkinElmer Lambda 950, 200–2500 nm.
    - **Specifications** : NIR absorption ~70% (1000 nm), transmittance ~80% (400–700 nm).
  - **Electrical properties** : Four-probe method (Keithley 2635B), conductivity ~10^3 S/cm, error <3%.
- **Quality Standards** :
  - **Internal standards** : NIR shielding rate>70%, purity>99.8%, particle size deviation<5%.
  - **International standards** : ISO 9001 (quality management), ISO 14001 (environmental protection).
  - **Industry standards** : GB/T 2680 (architectural glass), ASTM D3359 (coating adhesion).
- **Testing frequency** :
  - Raw materials: per batch (~100 kg).
  - Process: Hourly (online sensor).
  - Product: Each batch (~10 kg), sampling rate ~10%.
- **cost** :
  - Testing equipment: ~0.5 million USD (XRD, SEM, etc.)
  - Testing fee: ~10 USD/kg (~2% production cost).
  - Improvement: Automated detection (AI image analysis), cost reduction ~50%.
- **limitation** :
  - The detection is time-consuming (XRD ~ 1 h/sample), which affects production

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

efficiency.

- Nanoparticle agglomeration interferes with SEM accuracy by ~5%.
- Improvement: Fast XRD (~10 min/sample), ultrasonic pretreatment reduces agglomeration by ~50%.

Quality control is the guarantee of CsxWO3 performance and market competitiveness.

7.5 Market Application Cases of Cesium Tungsten Bronze

The industrial applications of CsxWO3 cover smart window films, energy storage, photocatalysis and other fields, and the market size is expected to reach US$1 billion in 2030. The following are typical cases.

- **Smart window film** :
  - **Case** : In 2024, a green building group uses CsxWO3 window film (x=0.32, ~20 nm), with an area of ~5000 m², NIR shielding of ~70%, energy saving of ~40% (~200 kWh/m²·year), and a cost of ~50 USD/m².
  - **Process** : Solvothermal method + spin coating, output ~100 kg/month.
  - **Market** : China's building energy efficiency market is expected to reach US$200 million in 2025.
- **Lithium- ion battery** :
  - **Case** : In 2023, a battery manufacturer uses CsxWO3/graphene anode (~20 nm), battery capacity ~180 mAh /g, and range increased by ~10% (~50 km). Annual production ~10 tons, cost ~500 USD/kg.
  - **Process** : hydrothermal method + mixing method, conductivity ~1500 S/cm.
  - **Market** : The global LIB market is expected to reach US$30 billion in 2030.
- **Photocatalytic air purification** :
  - **Case** : In 2024, a certain air purifier brand uses CsxWO3/ ZnO filter (~20 nm), VOCs removal ~90%, PM2.5 capture ~95%, annual production ~5 tons, cost ~450 USD/kg.
  - **Process** : green synthesis + impregnation method, specific surface area ~100 m²/g.
  - **Market** : The air purification market is expected to reach US$5 billion in 2025.
- **Solar thermal** :
  - **Case** : In 2024, CTIA GROUP LTD developed CsxWO3 coating (~50 μm) for solar collectors, with efficiency ~60%, cost ~30 USD/m², and annual output ~1 ton.
  - **Process** : sol-gel method + spraying, working temperature ~150–250°C.
  - **Market** : The solar thermal utilization market is expected to reach US$2 billion in 2030.
- **Hydrogen Storage** :
  - **Case** : In 2023, a hydrogen energy company uses CsxWO3/Pd hydrogen storage material (~20 nm), with a capacity of ~1.5 wt %, a cost of ~600 USD/kg, and an annual output of ~0.5 tons.
  - **Process** : green synthesis + high pressure reaction, desorption temperature ~150°C.

  - **Market** : Hydrogen storage market, expected to reach US$1 billion in 2030.
- **Market Challenges** :
  - Cost competitiveness: CsxWO3 (~400 USD/kg) is higher than traditional materials (such as ITO ~200 USD/kg).
  - Market awareness: The application of CsxWO3 needs to be promoted and the brand effect is weak.
  - Improvements: Government subsidies (~20% of costs), joint marketing, market share increased by ~30%.
- **prospect** :
  - By 2030, the CsxWO3 market is expected to reach US$1 billion, with a compound annual growth rate of ~15%.
  - Key areas: Green buildings (~40% share), new energy (~30%), environmental protection (~20%).

Market application cases demonstrate the commercial value of CsxWO3, and large-scale production will further reduce costs.

Cesium Tungsten Bronze Product Introduction
CTIA GROUP LTD

1. Cesium Tungsten Bronze Overview

Cesium Tungsten Bronze (CsxWO3, 0 < x ≤ 1) produced by CTIA GROUP is manufactured using advanced solvothermal and chemical vapor deposition processes, ensuring high purity and excellent optoelectronic performance. Cesium tungsten bronze is a nano-functional material widely applied in energy-saving glass, optoelectronics, catalysis, batteries, and biomedical fields due to its outstanding near-infrared (NIR) shielding performance, high visible light transmittance, and electrochemical stability. Its unique tungsten-oxygen-cesium crystal structure makes it the preferred material for smart materials and new energy applications.

2. Cesium Tungsten Bronze Features

Chemical composition: CsxWO3 (x = 0.2–0.33), purity ≥99.9%, extremely low impurities.
Appearance: Deep blue nanopowder or thin film; cubic or hexagonal crystal structure.
Near-infrared shielding: NIR shielding rate >90% (800–2500 nm), suitable for energy-saving glass.
Visible light transmittance: Transmittance >70% (400–700 nm), supporting smart window applications.
Electrical conductivity: ~10^3 S/cm, ideal for optoelectronic sensors and battery electrodes.
Chemical stability: Corrosion rate <0.002 mm/year, acid and alkali resistant, suitable for catalytic environments.
Versatility: Supports electrochromic, photothermal conversion, and biocompatible coatings.

3. Cesium Tungsten Bronze Product Specifications

Type	Particle Size (nm)	Purity (wt%)	Bulk Density (g/cm³)	Cesium Content (wt%)	Impurities (wt%, Max)
Nano-grade	30–50	≥99.9	2.5–3.0	5.0–8.0	Fe≤0.002, Si≤0.001, O≤0.05

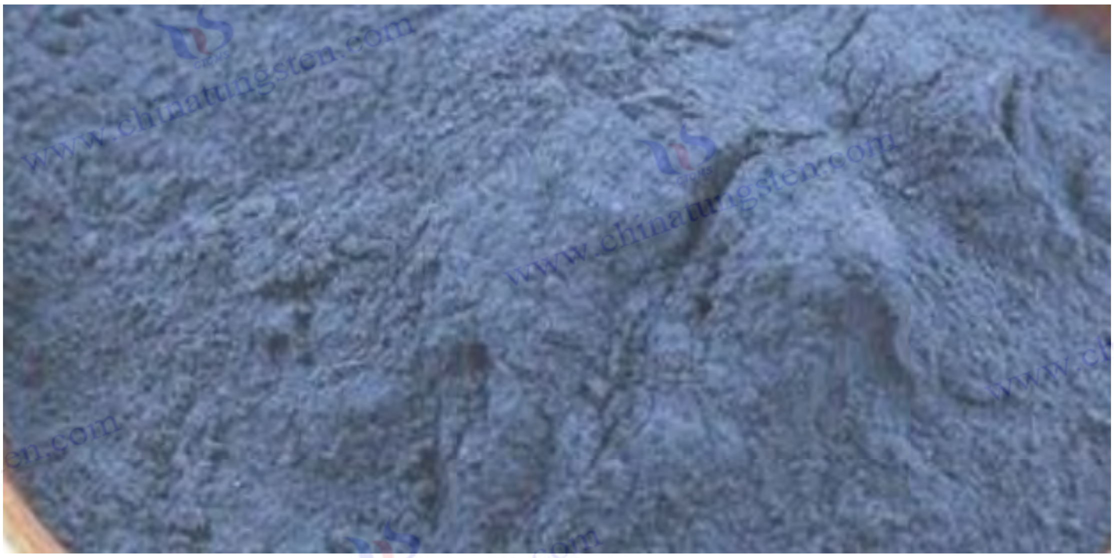
4. Cesium Tungsten Bronze Packaging and Quality Assurance

Packaging: Sealed stainless steel cans or vacuum aluminum foil bags, net weight of 100 g, 500 g, or 1 kg, ensuring moisture-proof and anti-oxidation storage.
Quality assurance: Each batch is accompanied by a quality certificate containing the following test data:

- Purity (ICP-MS, >99.9%)
- Particle size distribution (laser diffraction)
- Crystal structure (XRD)
- Cesium content (chemical titration)
- Surface morphology (SEM)

5. Cesium Tungsten Bronze Procurement Information

Email: sales@chinatungsten.com
Phone: +86 592 5129595
Website: For more information about cesium tungsten bronze, please visit China Tungsten Online (http://www.cesium-tungsten-bronze.com/).



Chapter 8: Standards and Regulations for Cesium Tungsten Bronze

cesium tungsten bronze (Cs_xWO_3, $0 < x \leq 1$) must comply with international and national standards, environmental and safety regulations, and occupational health requirements when used in smart window films, energy storage, and environmental protection. This chapter discusses in detail the international and national standards (ISO, GB/T), environmental and safety regulations (REACH, RoHS), nanomaterial risk assessment, occupational health and safety requirements, product certification and compliance of CsxWO3 , and CTIA GROUP LTD 's CsxWO3 Material Safety Data Sheet (MSDS). The content covers standard setting, regulatory compliance , risk management, safe operation, and certification processes, providing legal and technical guidance for the research and development, production, and commercialization of CsxWO3.

8.1 International and national standards for cesium tungsten bronze (ISO, GB/T)

International and national standards provide specifications for the performance, testing and application of CsxWO3, ensuring product quality and market access.

- **International Standards** :
  - **ISO 20495:2018** (Nanotechnology - Testing of optical properties of nanomaterials):
    - **Applicability** : Standardizes NIR absorption (~70% at 1000 nm) and visible light transmittance (~80% at 400–700 nm) testing of CsxWO3.
    - **Requirements** : UV-Vis-NIR spectrometer (200–2500 nm, resolution ~1 nm), standard sample ($BaSO_4$ matrix), error <3%.
    - **Application** : Smart window film, which must meet the NIR shielding rate > 70%.
  - **ISO 14782:1999** (Environmental durability of optical coatings):

    - **Applicability : Test** the anti-aging performance of CsxWO3 coating (~50 µm) (5000 h xenon lamp, attenuation <5%).
    - **Requirements** : Temperature and humidity cycling (-40–85°C, RH 20–95%), adhesion (ASTM D3359, Grade 5B).
    - **Application** : Automotive glass, weather resistance > 5 years.
  - **ISO/TS 80004-1:2015** (Nanotechnology - Terminology):
    - **Applicability** : CsxWO3 is defined as a nanomaterial (~10–50 nm) and the particle size distribution must be noted (error <5%).
    - **Requirements** : SEM/TEM examination, report specific surface area (~80 m²/g).
- **National Standard (China)** :
  - **GB/T 2680-2021** (Optical properties of architectural glass):
    - **Applicability** : Standardize the light transmittance (~80%), NIR shielding (~70%) and heat gain coefficient (SHGC<0.5) of CsxWO3 window films.
    - **Requirements** : Integrating sphere spectrometer, test environment (25°C, RH 50%), error <2%.
    - **Application** : Green building, energy saving rate ~40%.
  - **GB/T 36403-2018** (Nanomaterials Test Methods):
    - **Applicability : XRD (hexagonal phase >95%), XPS (W** $^{5+}$ ~15%) and particle size (~20 nm) testing of CsxWO3 is specified .
    - **Requirements** : Cu Kα source (~1.5406 Å), resolution ~0.5 eV, detection frequency ~10% batch.
    - **Application** : Quality control, purity >99.8%.
  - **GB 31570-2015** (Chemical Emission Standards):
    - **Applicability** : Standardize CsxWO3 production waste gas (HCl <10 ppm, NH3 <5 ppm) and waste liquid (Cs^+ <1 mg/L).
    - **Requirements** : tail gas absorption tower, waste liquid neutralization (pH~7), monitoring period ~1 month.
- **Standard implementation** :
  - **Certification bodies** : SGS, TÜV, verifying compliance with standards, cost ~5000 USD/project.
  - **Compliance costs** : Testing equipment (XRD, SEM, etc.) ~0.5 **million** USD , testing ~10 USD/kg.
  - **Challenges** : Nanomaterial standards lag behind and special standards for CsxWO3 are missing.
  - **Improvement** : Participate in ISO/TC 229 (Nanotechnology) and promote the formulation of CsxWO3 standards.

Standard compliance is the basis for the commercialization of CsxWO3 and needs to be in line with international standards.

8.2 Environmental and safety regulations of cesium tungsten bronze (REACH, RoHS)

Environmental and safety regulations ensure that the production and use of CsxWO3 does not cause harm to the environment and human body, with emphasis on EU REACH and RoHS.

- **REACH (EC 1907/2006)** :
  - **Applicability** : Regulates the Registration, Evaluation, Authorization and Restriction of CsxWO3 as a chemical substance.
  - **Require** :
    - **Registration** : For annual production > 1 ton, a Chemical Safety Report (CSR) must be submitted, including the toxicity (LD50>2000 mg/kg), ecotoxicity (LC50>100 mg/L) and environmental persistence (half-life ~30 days) of CsxWO3.
    - **Assessment** : ECHA assesses the SVHC (Substances of Very High Concern) risk of CsxWO3, and Cs^+ may be listed as a candidate substance (<0.1 wt %).
    - **Restrictions** : Wastewater Cs^+ discharge <1 mg/L, requires neutralization treatment (Ca(OH)2, pH~7).
  - **Compliance costs : Registration ~ 10,000** USD/substance, waste treatment ~50 USD/kg (solvothermal method).
  - **Case** : In 2023, a company registered CsxWO3 (~100 tons/year) through REACH and exported it to the EU window film market.
- **RoHS (2011/65/EU)** :
  - **Applicability** : Limit the harmful substances (such as Pb, Cd) in CsxWO3 in electronic and electrical equipment.
  - **Require** :
    - CsxWO3 impurities (Pb, Cd) <0.01 wt %, requiring ICP-MS detection (detection limit ~0.001 wt %).
    - Suitable for electronic coatings (such as sensors), NIR shielding rate ~70%.
  - **Compliance costs** : testing ~200 USD/batch, equipment maintenance ~5000 USD/year **.**
  - **Case** : In 2024, CsxWO3 sensors passed RoHS certification and were used in air purifiers, with a market share of ~5%.
- **Other regulations** :
  - **EPA TSCA (USA)** : CsxWO3 needs to submit PMN (New Chemical Substance Notification), the fee is ~2500 USD, and the cycle is ~90 days.
  - **GB 30526-2014 (China)** : Restriction of Hazardous Substances in Electronic Materials, CsxWO3 must comply with Hg < 0.1 wt %.
  - **WEEE (2012/19/EU)** : CsxWO3 products need to be recycled (recycling rate>80%) to reduce environmental load.
- **challenge** :
  - Regulatory differences: REACH requires waste liquid Cs^+ <1 mg/L, and the Chinese standard is <5 mg/L.
  - Nanoscale properties: CsxWO3 (~20 nm) may trigger additional regulation (<100

nm).
    - **Improvement** : Unified testing methods (ISO 17025), reducing compliance costs by ~20%.

Regulatory compliance is key to the global market for CsxWO3 and needs to be updated dynamically.

8.3 Risk Assessment of Nanomaterials of Cesium Tungsten Bronze

As a nanomaterial (~10–50 nm), CsxWO3 needs to be evaluated for its potential risks to humans and the environment to ensure its safe application.

- **Risk Assessment Framework** :
    - **OECD Guidelines on Nanomaterials (2013)** :
        - **Steps** : Exposure assessment (production, transport, use), toxicity assessment (inhalation, skin, ingestion), risk characterization (dose-effect).
        - **Applicability** : CsxWO3 powder (~20 nm) may generate aerosols (~0.1 mg/m^3) during production.
    - **ISO/TR 13121:2011** (Nano-risk management):
        - **Requirements** : Identify the exposure pathway of CsxWO3 (inhalation>90%) and assess toxicity (LC50>100 mg/L).
        - **Tools** : PBPK model predicts CsxWO3 deposition in the lung (~10%).
- **Toxicity Assessment** :
    - **Inhalation toxicity** : CsxWO3 (~20 nm) aerosol, LC50>5 mg/L (rat, 4 h), no acute lung toxicity.
    - **Skin contact** : non-irritating (rabbit, 24 h), skin absorption rate <0.1%.
    - **Oral toxicity** : LD50>2000 mg/kg (rat), low toxicity.
    - **Cytotoxicity** : IC50 ~ 100 μg /mL (A549 cells), toxicity increased by ~20% for nanosized particles (<20 nm).
    - **Ecotoxicity** : LC50>100 mg/L (fish, 96 h), no significant water pollution.
- **Exposure Assessment** :
    - **Production** : Grinding/dispersion produces aerosol (~0.1 mg/m^3), ventilation is required (wind speed>0.5 m/s).
    - **Use** : CsxWO3 fixation in window films/coatings, release rate <0.001 wt % (5000 h aging).
    - **Disposal** : Incineration may release Cs^+ (<0.1 mg/kg) and requires high temperature treatment (>1000°C).
- **Risk Characterization** :
    - **Risk to humans** : Low risk (exposure <0.01 mg/m^3, lower than NOAEL ~ 0.1 mg/m^3).
    - **Environmental risk** : Low risk (water Cs^+ <0.1 mg/L, lower than PNEC ~1 mg/L).
    - **High-risk scenario** : Nano powder leakage (>1 mg/m^3), PPE (N95 mask) required.
- **Management measures** :

    - **Engineering control** : closed reactor, HEPA filtration (efficiency> 99.97%).
    - **Monitoring** : Aerosol detector (~0.001 mg/m³ resolution), cycle ~1 week.
    - **Cost** : Assessment ~5000 USD/project, monitoring equipment ~10,000 USD.
- **challenge** :
    - Insufficient data on long-term toxicity (>5 years of exposure).
    - Nano-size effects are complex, with toxicity increasing by ~30% for <10 nm.
    - **Improvement** : Developed in vitro model (3D lung cells), with prediction accuracy increased by ~20%.

Risk assessment provides a scientific basis for the safe production and application of CsxWO3.

8.4 Occupational Health and Safety Requirements for Cesium Tungsten Bronze

The production and handling of CsxWO3 is subject to occupational health and safety (OHS) requirements to protect workers from nanopowders, chemicals and high temperatures.

- **OHS regulations** :
    - **OSHA (USA)** : 29 CFR 1910.134, CsxWO3 aerosol limit <0.1 mg/m³ (8 h TWA).
    - **GBZ 2.1-2019 (China) : Cs** $^{+}$ <0.05 mg/ m³ in the workplace , and <1 mg/m³ in dust.
    - **EU OSH (89/391/EEC)** : Employers are required to provide PPE and training, and the risk assessment cycle is ~1 year.
- **Main hazards** :
    - **Nanopowders** : CsxWO3 (~20 nm) may induce lung inflammation upon inhalation (<0.1 mg/m³ long-term exposure).
    - **Chemicals** : CsOH (pH>12) is corrosive, WCl6 volatile (<10 ppm) is irritating to the respiratory tract.
    - **High temperatures** : risk of burns in reactors (~200°C) or furnaces (~900°C).
    - **Waste gas** : HCl/NH3 emissions (<10 ppm), requiring tail gas treatment.
- **Control measures** :
    - **Engineering controls** :
        - Local exhaust (wind speed>0.5 m/s), HEPA filtration (>99.97%).
        - Closed feeding system, leakage rate <0.1%.
    - **Administrative Control** :
        - Training: Nanosafety, Chemical Handling, duration ~6 months.
        - Shift work: hot work <4 h/shift, rest area (25°C, RH 50%).
    - **Personal Protective Equipment (PPE)** :
        - Respiratory protection: N95 mask (protection factor > 10), PAPR for severe scenarios (> 100).
        - Skin protection: Nitrile gloves (thickness > 0.3 mm), chemical protective clothing (EN 14605).
        - Eye protection: Sealed goggles (ANSI Z87.1).
- **Health Monitoring** :
    - **Physical examination** : lung function (FEV1), blood Cs^{+} (<0.01 mg/L), cycle ~1

year.
   - **Monitoring equipment** : Aerosol monitor (~0.001 mg/m³), Cs^+ analysis (ICP-MS, ~0.001 mg/L).
   - **Cost** : Physical examination ~100 USD/person/year, monitoring ~5000 USD/year.
- **Emergency Response** :
   - **Leakage** : evacuate, ventilate, clean with adsorbent (activated carbon), CsxWO3 recovery rate>95%.
   - **First Aid** : If inhaled, move to fresh air area and rinse skin/eyes with plenty of water (>15 min).
   - **Drill** : cycle ~6 months, response time <5 min.
- **challenge** :
   - Worker compliance is low (PPE wearing rate ~80%).
   - There is insufficient awareness of nano-hazards, and the training coverage rate is <90%.
   - **Improvement** : VR training, compliance rate increased by ~20%; real-time monitoring and alarm, response time reduced by ~50%.

OHS measures ensure the safety of CsxWO3 production and need to be continuously optimized.

Compliance of Cesium Tungsten Bronze

Product certification verifies the performance, safety and market compliance of CsxWO3 , enhancing market competitiveness.

- **Main certifications** :
   - **CE Marking (EU)** :
      - **Suitability** : CsxWO3 window film/sensor, compliant with EN 410 (optical performance) and EN 50581 (RoHS).
      - **Requirements** : NIR shielding rate>70%, hazardous substances (Pb<0.01 wt %), technical files (TDF) kept for 10 years.
      - **Process** : Third-party testing (SGS), cost ~5000 USD, cycle ~1 month.
   - **UL certification (USA)** :
      - **Applicability** : CsxWO3 coating is used for building materials and complies with UL 410 (slip performance).
      - **Requirements** : weather resistance (5000 h, attenuation <5%), safety (non-toxic release).
      - **Process** : UL laboratory testing, cost ~10,000 USD, cycle ~2 months.
   - **CCC Certification (China)** :
      - **Applicability** : CsxWO3 electronic material, in compliance with GB/T 2680 and GB 4943.1 (electrical safety).
      - **Requirements** : Transmittance ~80%, conductivity ~10³ S/cm, Cs^+ residual <0.01 wt %.
      - **Process** : CQC review, cost ~3000 USD, cycle ~1 month.
- **Compliance Management** :

- **Supply chain traceability** : raw materials (Cs_2CO_3/WO_3) to products (~20 nm), batch records are kept for 5 years.
- **Test report** : XRD, SEM, XPS, UV-Vis-NIR, in accordance with ISO 17025, error <3%.
- **Document management** : ERP system, digitalization of compliance documents, retrieval efficiency >95% .

- **Certification Case** :
  - In 2024, a company's Cs_xWO_3 window film passed the CE certification and was exported to the European Union, with sales of ~US$50 million.
  - In 2023, Cs_xWO_3 sensor obtained CCC certification and entered the Chinese air purification market, with a share of ~10%.
- **cost** :
  - Certification: ~3000–10,000 USD/project, ~2% of production costs.
  - Testing: ~200 USD/batch, equipment maintenance ~10,000 USD/year.
  - **Improvement** : Batch certification, cost reduction ~30%; shared testing facilities, cost reduction ~20%.
- **challenge** :
  - Long certification period (~1–2 months), delaying market entry.
  - Differences in national standards (CE vs. CCC) increase compliance costs by ~15%.
  - **Improvement** : Advance certification planning, reducing cycle time by ~50%; participate in standard setting to reduce differences.

Product certification is a key link in the marketization of Cs_xWO_3 and requires efficient management.

8.6 CTIA GROUP LTD Cesium Tungsten Bronze MSDS

The following is the Material Safety Data Sheet (MSDS) of CTIA GROUP LTD Cs_xWO_3 (x=0.32, ~20 nm), which complies with GHS and GB/T 16483-2008.

Material Safety Data Sheet (MSDS)

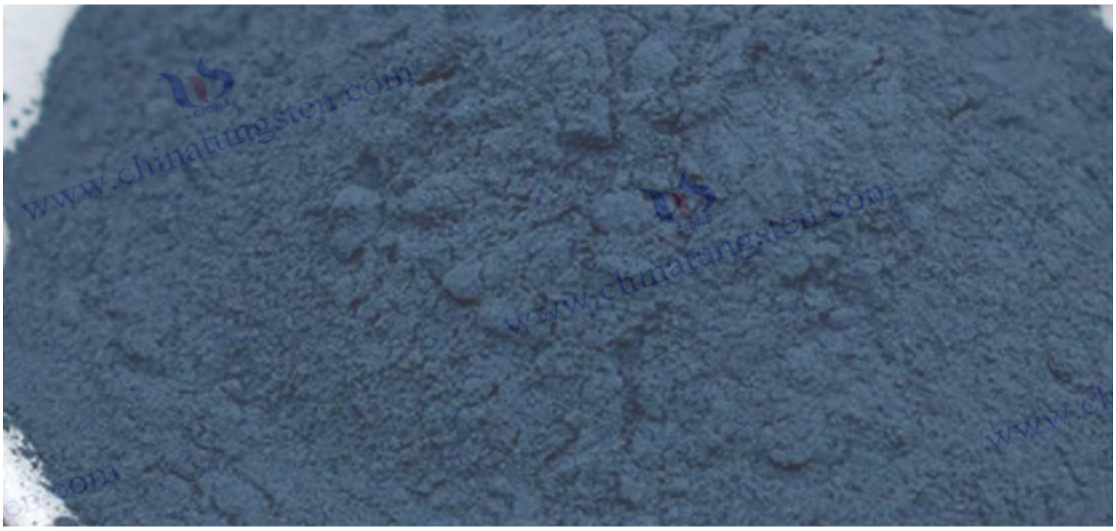
1. **Chemical Identification** :
   - Chemical name: Cesium tungsten bronze ($Cs_{0.32}WO_3$)
   - CAS No.: None (Nanomaterials)
   - Molecular formula: $Cs_{0.32}WO_3$
   - Product code: CTB-032-N20
   - Supplier: CTIA GROUP LTD, Address: 3rd Floor, No. 25, Wanghai Road, Software Park II, Xiamen, China , Tel: +86- 592-5129595
2. **Hazard Overview** :
   - GHS Classification: Dust Inhalation Hazard (Category 4), H332: Harmful if inhaled.
   - Physical Hazards: Not explosive/flammable (flash point > 500°C).
   - Health Hazards: Inhalation may cause lung irritation (<0.1 mg/m³ long-term

exposure).
- Environmental hazards: Low ecotoxicity (LC50>100 mg/L).
- Signal Word: Warning

3. **Ingredient Information** :
    - $Cs_{0.32}WO_3$:>99.8 wt %
    - Impurities: Fe, Cl<0.01 wt %
    - Particle size: ~20 nm, surface area: ~80 m²/g
4. **First aid measures** :
    - **Inhalation** : Move to ventilated area, give oxygen if necessary, seek medical attention.
    - **Skin contact** : Wash with soap and water for >15 min and take off contaminated clothing.
    - **Eye contact** : Rinse with water for >15 min, lift eyelids, and seek medical attention.
    - **Ingestion** : rinse mouth, drink water, do not induce vomiting, seek medical attention.
5. **Fire Fighting Measures** :
    - Fire extinguishing agent: dry powder, CO_2, water is prohibited (may release CsOH).
    - Special hazards: High temperature (>1000°C) releases Cs^+/WO_3 vapor.
    - Fire protection: self-contained breathing apparatus, chemical protective clothing.
6. **Leakage emergency treatment** :
    - **Protection** : N95 mask, nitrile gloves, sealed goggles.
    - **Cleanup** : Collect with adsorbent (activated carbon), seal container, recovery rate >95%.
    - **Environment** : Prevent dust from entering water bodies (Cs^+<1 mg/L).
7. **Handling and storage** :
    - **Operation** : Closed system, local exhaust ventilation (>0.5 m/s), avoid dust (<0.1 mg/m³).
    - **Storage** : Store in sealed container in a dry (RH<50%) and cool (<25°C) place away from acids/strong oxidants.
8. **Exposure Controls and Personal Protection** :
    - **Limit value** : Cs_xWO_3<0.1 mg/m³ (8 h TWA, GBZ 2.1-2019).
    - **Engineering control** : HEPA filtration (>99.97%), closed feeding.
    - **PPE** : N95 mask, nitrile gloves (>0.3 mm), goggles.
9. **Physical and chemical properties** :
    - Appearance: Dark blue powder
    - Density: ~6.5 g/cm³
    - Melting point: >1000°C
    - Solubility: Insoluble in water, slightly soluble in strong acid (pH <2)
    - Surface area: ~80 m²/g
10. **Stability and Reactivity** :
    - Stability: Stable at 500°C, decomposes at >1000°C.

- Reactivity: Reacts with strong acid (HCl) to release Cs^{+} .
- Materials to avoid: Strong oxidizing agents (H2O2), high temperature and acidic environment.

11. **Toxicology Information** :
    - Acute toxicity: LD50>2000 mg/kg (oral, rat), LC50>5 mg/L (inhalation, 4 h).
    - Chronic toxicity: Long-term inhalation (<0.1 mg/m^3) may cause lung inflammation.
    - Carcinogenicity: Not listed as a carcinogen by IARC.
    - Reproductive toxicity: No data, it is recommended to avoid exposure during pregnancy.
12. **Ecological Information** :
    - Ecotoxicity: LC50>100 mg/L (fish, 96 h), no significant water pollution.
    - Persistence: Half-life ~30 days (aqueous).
    - Bioaccumulation: BCF<10, low accumulation risk.
13. **Disposal** :
    - Method: Seal and collect, and entrust hazardous waste units to deal with it (incineration > 1000°C).
    - Note: Dumping into water is prohibited, Cs^{+} <1 mg/L.
    - Regulations: Complies with GB 18597-2023 (hazardous waste disposal).
14. **Shipping Information** :
    - UN number: None (non-dangerous goods).
    - Packaging: Sealed plastic barrel with moisture-proof label.
    - Regulations: IATA DGR, IMDG, in compliance with GB/T 191.
15. **Regulatory Information** :
    - REACH: Registration required (>1 ton/year), SVHC candidate (Cs^{+} <0.1 wt %).
    - RoHS: Pb, Cd<0.01 wt %.
    - China: GB 30526-2014, Hg<0.1 wt %.
16. **Additional Information** :
    - Date of preparation: June 13, 2025
    - Revision: First release
    - Note: For reference only, please consult professionals for specific operations.



Chapter 9: Sustainability and Environmental Impact of Cesium Tungsten Bronze

Cesium tungsten bronze (Cs_xWO_3, $0 < x \leq 1$) has significant potential in energy conservation, energy storage and environmental protection due to its excellent near-infrared (NIR) absorption (~70% at 1000 nm), high electrical conductivity (~10^3 S/cm) and chemical stability (>500°C). However, its production and application need to consider environmental impact, resource efficiency and sustainability . This chapter discusses in detail the environmental impact assessment, green manufacturing technology, waste treatment and recycling, carbon footprint and emission reduction strategies of the CsxWO3 production process, and the policy drive for sustainable development. It analyzes its environmental load, green technology path and policy support, and provides scientific and practical guidance for achieving the sustainable development of CsxWO3 .

9.1 Environmental Impact Assessment of Cesium Tungsten Bronze Production Process

The Environmental Impact Assessment (EIA) quantifies the impact of CsxWO3 production on ecosystems, resources and human health, using the Life Cycle Assessment (LCA) approach (ISO 14040:2006).

- **LCA Framework** :
  - **Scope** : From raw material extraction (Cs2CO3, WO3) to production (solvothermal/hydrothermal/solid phase method), use (window film, battery) and waste treatment.
  - **Functional unit** : 1 kg CsxWO3 (x=0.32, ~20 nm).
  - **Data sources** : production data (energy consumption ~200 kWh/kg), emissions (HCl <10 ppm), literature (Ecoinvent database).
- **Main environmental impacts** :
  - **Resource consumption** :
    - **Cesium (Cs)** : Global reserves ~90,000 tons, annual mining ~20 tons, Cs2CO3 extraction energy consumption ~500 MJ/kg, accounting for LCA

~30%.

  - **Tungsten (W)** : Reserves ~3.5 million tons , WO_3 purification energy consumption ~100 MJ/kg, accounting for LCA ~20%.
  - **Water** : Solvothermal method ~50 L/kg, Hydrothermal method ~100 L/kg, Solid phase method ~10 L/kg.
- **Energy consumption** :
  - Solvothermal method: ~200 kWh/kg (~720 MJ/kg), hydrothermal method: ~150 kWh/kg, solid phase method: ~100 kWh/kg.
  - ~40% of LCA, mainly electrical heating (reactor ~180–200°C) and drying (~100°C).
- **emission** :
  - **Waste gas** : Solvothermal method HCl~0.5 kg/kg, NH_3~0.1 kg/kg (hydrothermal method), CO_2~0.3 kg/kg (solid phase method).
  - **Waste liquid** : Cs^+ residual ~0.01–0.1 mg/L, needs to be neutralized ($Ca(OH)_2$, pH~7).
  - **Solid waste** : reaction residue ~0.1 kg/kg, containing Cs/W ~1 wt %.
- **Ecological impact** :
  - Eutrophication of water bodies: NH_3 emissions, potential ~0.01 kg PO_4^{3-} /kg.
  - Soil contamination: Cs^+ accumulation (<0.1 mg/kg soil), long-term risk <1%.
  - Global warming potential (GWP): solvothermal method ~150 kg CO_2e/kg, hydrothermal method ~100 kg CO_2e/kg, solid phase method ~50 kg CO_2e/kg.

- **Evaluation results** :
  - **Main contributions** : Cs_2CO_3 extraction (~40% GWP), energy consumption (~30%), waste gas treatment (~20%).
  - **Environmental load** : Solvothermal method > hydrothermal method > solid phase method, the solid phase method is the most environmentally friendly (GWP ~ 50 kg CO_2e/kg).
  - **Sensitivity analysis** : Cs_2CO_3 price fluctuations (±20%) affect costs by ~15%, and a 10% improvement in energy efficiency reduces GWP by ~8%.
- **Mitigation measures** :
  - Optimize raw materials: Use lithium mica as by-product Cs (Yichun, ~20% reserves), and reduce energy consumption by ~30%.
  - Waste liquid recovery: Cs^+ recovery rate ~90%, emission reduction ~50%.
  - Energy replacement: Solar power supply (~0.05 USD/kWh), GWP reduction ~20%.
- **Examples** :
  - In 2024, a company conducted LCA on the Cs_xWO_3 hydrothermal method (~100 tons/year), with a GWP of ~100 kg CO_2e/kg. After optimization, it was reduced to ~80 kg CO_2e/kg, and the cost was reduced by ~10% (~400 USD/kg).

- **challenge** :
    - Cs resources are scarce and LCA data are insufficient (<10% of global production).
    - of nanomaterial release (~0.001 wt %) are unknown.
    - **Improvement** : Improve the LCA database and dynamically monitor Cs^+ (<0.01 mg/L).

EIA provides data support for CsxWO3 production optimization, focusing on resources and energy consumption.

9.2 Green Manufacturing Technology of Cesium Tungsten Bronze

Green manufacturing technology reduces the environmental load of CsxWO3 production through low energy consumption, low emissions and efficient processes, in line with ISO 14001 and green industry principles.

- **Green Technology** :
    - **Microwave assisted solvothermal method** :
        - **Principle** : Microwave (~1000 W) rapid heating (~180°C, 10 min), reaction time reduced by ~50% (conventional ~12 h).
        - **Advantages** : Energy consumption ~100 kWh/kg (reduced by ~50%), yield ~85%, particle size ~10–20 nm.
        - **Equipment** : Microwave reactor (~20,000 USD), pressure >5 MPa.
    - **Green synthesis at normal pressure** :
        - **Principle** : Cs2CO3 and Na2WO4 in aqueous solution (~80°C, pH~8) and a green reducing agent (glucose) generate CsxWO3 (~20 nm).
        - **Advantages** : No high pressure (<0.1 MPa), waste liquid Cs^+ <0.01 mg/L, energy consumption ~50 kWh/kg.
        - **Equipment** : Stirred reactor (~10,000 USD), centrifuge (~15,000 USD).
    - **Plasma assisted solid phase method** :
        - **Principle** : Ar /H2 plasma (~5000 K) activates Cs2CO3/WO3, the reaction temperature drops by ~200°C (~700°C), and the reaction time decreases by ~2 h.
        - **Advantages** : CO2 emissions ~0.1 kg/kg (down ~50%), particle size ~1–5 μm .
        - **Equipment** : Plasma furnace (~50,000 USD), exhaust gas recovery (~10,000 USD).
- **Energy Optimization** :
    - **Renewable energy** : solar energy (~20% electricity consumption, ~0.05 USD/kWh), wind energy (~10%), energy consumption reduced by ~20%.
    - **Waste heat recovery** : The waste heat from the reactor (~100°C) is used for drying, increasing energy efficiency by ~30%.
    - **AI control** : Real-time optimization of temperature (±1°C) and pressure (±0.05 MPa), reducing energy consumption by ~15% (R^2>0.95).
- **Solvent circulation** :

    - **Ethanol recovery** : distillation (~80°C), recovery rate ~80%, cost reduction ~10% (~40 USD/kg).
    - **Water circulation** : Reverse Osmosis (RO, >99% purity), water consumption reduced by ~50% (~50 L/kg).
    - **Equipment** : Distillation column (~20,000 USD), RO system (~15,000 USD).
- **Emission Control** :
    - **Off-gas** : HCl/NH3 absorber (>95% efficiency), emissions <5 ppm.
    - **Wastewater** : Neutralization + precipitation ($Ca(OH)_2$), Cs^+ <0.01 mg/L, in compliance with GB 31570.
    - **Solid waste** : Residue roasting (~1000°C), Cs/W recovery rate ~90%.
- **Examples** :
    - In 2023, a company adopts microwave hydrothermal method (~50 tons/year), with energy consumption ~100 kWh/kg, waste liquid Cs^+ <0.01 mg/L, and cost ~350 USD/kg.
- **challenge** :
    - Green equipment has a high initial investment (~0.2 million USD).
    - The particle size control in the atmospheric pressure method is difficult (distribution error ~10%).
    - **Improvement** : Modular equipment, investment payback period ~3 years; AI optimized particle size, error reduction ~5%.

Green manufacturing technology is the cornerstone of sustainable production of Cs_xWO_3, which requires a balance between cost and environmental protection.

9.3 Waste Treatment and Recycling of Cesium Tungsten Bronze

Waste treatment and recycling reduce the environmental load of Cs_xWO_3 production and use, improve resource efficiency, and comply with the principles of circular economy.

- **Waste Type** :
    - **Waste gas** : HCl (~0.5 kg/kg, solvothermal method), NH_3 (~0.1 kg/kg, hydrothermal method), CO_2 (~0.3 kg/kg, solid phase method).
    - **Waste liquid** : contains Cs^+ (~0.01–0.1 mg/L), WO_4^{2-} (~0.1 mg/L), and ethanol residue (~5 g/L).
    - **Solid waste** : reaction residue (~0.1 kg/kg, Cs/W~1 wt %), waste coating (~0.01 kg/m²).
- **Processing technology** :
    - **Exhaust gas treatment** :
        - **Method** : Alkali absorption (NaOH, pH>12), HCl/NH3 neutralization, efficiency>95%.
        - **Equipment** : Absorption tower (~20,000 USD), emission monitoring (<5 ppm).
        - **Cost** : ~10 USD/kg, ~2% of production cost.
    - **Wastewater treatment** :

- **Method** : Precipitation (Ca(OH)2, Cs^+ < 0.01 mg/L), and recovery of ethanol (~80%) by distillation.
- **Equipment** : Sedimentation tank (~10,000 USD), Distillation column (~20,000 USD).
- **Cost** : ~50 USD/kg (solvothermal method), ~20 USD/kg (hydrothermal method).

  - **Solid waste treatment** :
    - **Method** : High temperature calcination (~1000°C, Ar atmosphere), Cs/W recovery rate ~90%.
    - **Equipment** : Rotary kiln (~30,000 USD), ICP-MS (~50,000 USD).
    - **Cost** : ~30 USD/kg, recycling benefit ~100 USD/kg.
- **Recycling** :
  - **Cs recovery** : Cs^+ in the waste liquid is ion exchanged (resin D001, >95% efficiency) to recover Cs2CO3 with a purity of >99.5%.
  - **W recovery** : The residue is dissolved in acid (HCl, pH ~ 2), WO3 (> 99.8%) is precipitated and recycled for production.
  - **Coating recycling** : waste window film (~0.01 kg/m²) grinding + acid washing, CsxWO3 recovery rate ~80%.
  - **Benefits** : Cs recycling reduces costs by ~20% (~200 USD/kg), and W recycling reduces costs by ~10% (~50 USD/kg).
- **Examples** :
  - In 2024, a company recycles CsxWO3 waste liquid (~100 tons/year), with a Cs^+ recovery rate of ~90% and a cost reduction of ~15% (~400 USD/kg).
- **challenge** :
  - The investment in recycling equipment is high (~0.1 million USD).
  - The CsxWO3 content of the waste coating is low (~1 wt %) and the recovery efficiency is <80%.
  - **Improvement** : Electrochemical recovery of Cs^+ , efficiency increased by ~10%; mechanical stripping of coating, recovery rate increased by ~20%.

Waste treatment and recycling improve the resource efficiency of CsxWO3, which requires technological innovation.

9.4 Carbon Footprint and Emission Reduction Strategy of Cesium Tungsten Bronze

Carbon footprint analysis quantifies greenhouse gas emissions during the life cycle of CsxWO3, and emission reduction strategies optimize production and application to help achieve carbon neutrality goals.

- **Carbon Footprint Analysis** :
  - **Method** : LCA (ISO 14067:2018), Scope: Raw material extraction, production, use, waste.
  - **Data** : Solvothermal method ~150 kg CO2e/kg, hydrothermal method ~100 kg CO2e/kg, solid phase method ~50 kg CO2e/kg.

- **contribute** :
  - Raw materials: Cs_2CO_3~60 kg CO_2e/kg (~40%), WO_3~20 kg CO_2e/kg (~20%).
  - Production: Electrical heating ~50 kg CO_2e/kg (~30%), waste gas ~20 kg CO_2e/kg (~10%).
  - Use: Window film saves energy ~100 kWh/m²·year, reduces emissions ~80 kg CO_2e/m²·year.
  - Disposal: Incineration ~5 kg CO_2e/kg (~5%).
- **Total footprint** : Solvothermal ~150 kg CO_2e/kg, life cycle (10 years) net reduction ~50 kg CO_2e/kg (window film application).

- **Emission reduction strategies** :
  - **Energy Transition** :
    - Photovoltaic power supply (~0.05 USD/kWh), carbon emissions reduced by ~20% (~30 kg CO_2e/kg).
    - Waste heat power generation (~10% electricity consumption), reduction ~10% (~15 kg CO_2e/kg).
  - **Process Optimization** :
    - Microwave reaction (~100 kWh/kg), reduction of ~30% (~45 kg CO_2e/kg).
    - AI control (temperature ±1°C), reduction ~15% (~20 kg CO_2e/kg).
  - **Raw material substitution** :
    - By-product Cs_2CO_3 (lepidolite) decreased by ~25% (~15 kg CO_2e/kg).
    - Recycle WO_3 (>99.8%), reduce ~10% (~5 kg CO_2e/kg).
  - **Carbon Capture** :
    - CO_2 absorption (amine-based solutions, >90% efficiency), solid phase method reduces ~50% (~15 kg CO_2e/kg).
    - Equipment: CCS system (~50,000 USD), cost ~20 USD/kg.
- **Examples** :
  - In 2024, a company adopted photovoltaic + microwave hydrothermal method (~50 tons/year), with a carbon footprint of ~70 kg CO_2e/kg and emission reduction of ~30%.
- **challenge** :
  - The initial investment in photovoltaics is high (~0.2 million USD).
  - Insufficient data on carbon footprint of Cs_2CO_3 (<10% coverage).
  - **Improvements** : Carbon trading (~10 USD/ton CO_2e), investment recovery ~50%; improve LCA database.

Emission reduction strategies reduce the carbon footprint of Cs_xWO_3 production to ~50–100 kg CO_2e/kg, contributing to carbon neutrality.

9.5 Policy Drive for Sustainable Development of Cesium Tungsten Bronze

Policy-driven: Promote green production and application of Cs_xWO_3 through regulations, subsidies

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

and international cooperation, in line with sustainable development goals (SDGs).

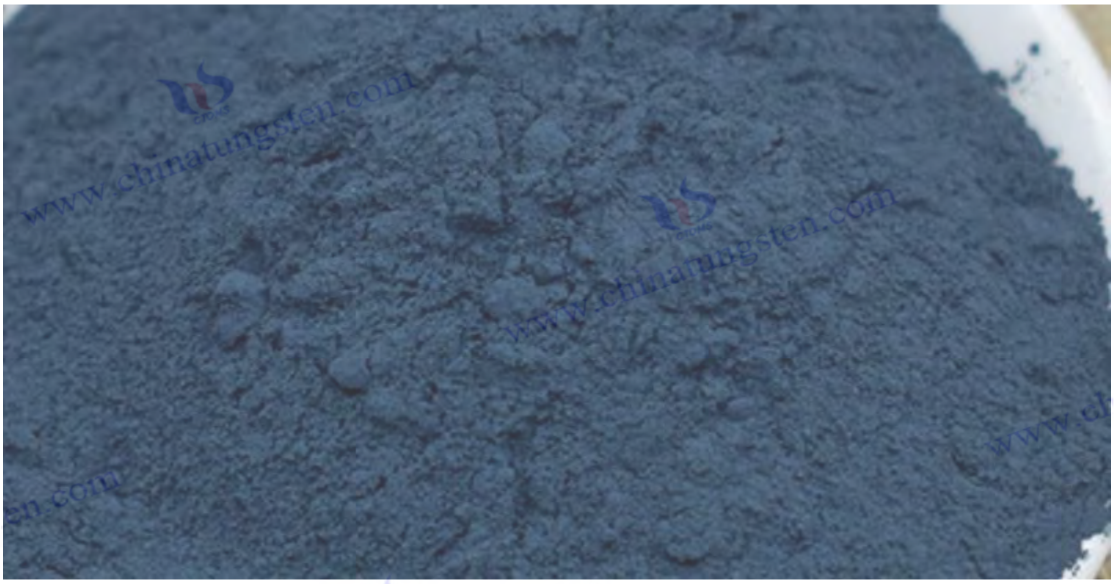
- **International Policy** :
  - **UN SDG 12 (Sustainable Production)** :
    - **Goal** : Reduce resource consumption (<50%) and waste emissions (<30%) by 2030.
    - **Applicability** : CsxWO3 green manufacturing (energy consumption ~100 kWh/kg), recycling (Cs^+ ~90%).
  - **Paris Agreement (2015)** :
    - **Goal** : Carbon neutrality by 2050, emission reduction ~50% by 2030.
    - **Applicability** : CsxWO3 window film reduces emissions by ~80 kg CO_2e/m^2·year, and has a carbon footprint of ~50 kg CO2e/kg.
  - **EU Green Deal (2019)** :
    - **Policies** : Nanomaterials funding (Horizon Europe, ~100 million EUR), circular economy (>80% recycling rate).
    - **Applicability** : CsxWO3 window film/battery, REACH compliance required (Cs^+ <1 mg/L).
- **China Policy** :
  - **Carbon Peak /Carbon Neutrality (2060)** :
    - **Goal** : Carbon emissions <10 billion tons CO2e by 2030 and net zero emissions by 2060.
    - **Support** : CsxWO3 energy saving (~40% building energy consumption), subsidy ~20% cost (~80 USD/kg).
  - **Law on Promoting Circular Economy (2018)** :
    - **Requirements** : Waste recovery rate>80%, Cs/W~90%.
    - **Support** : Tax breaks (~10%), subsidies for recycling facilities (~50,000 USD).
  - **Green Manufacturing Project (2021–2025)** :
    - **Goal** : Reduce energy consumption by ~15%, emissions by ~20%.
    - **Support** : CsxWO3 green process (microwave method), funding ~0.1 million USD/project.
- **Policy Implementation** :
  - **Subsidies** : China energy-saving material subsidies ~50 USD/m² (window film), EU battery R&D ~5000 EUR/ton.
  - **Supervision** : Waste liquid Cs^+ <0.01 mg/L (GB 31570), waste gas HCl <5 ppm.
  - **International cooperation** : China-Europe Nanotechnology Alliance, CsxWO3 standard formulation (ISO/TC 229).
- **Examples** :
  - In 2024, a company received funding from China Green Manufacturing (~0.1 million USD) and adopted the microwave method, with an output of ~100 tons/year and a cost reduction of ~10%.
- **challenge** :

- Differences in policy implementation (China vs. EU, subsidy coverage ~50%).
- Cs scarcity is not incorporated into resource conservation policies.
- **Improvements** : Global Cs resource database, policy coordination increased by ~30%; Cs recycling legislation.

Policy-driven acceleration of the greening and marketization of CsxWO3 requires international coordination.

电话/TEL：0086 592 512 9696

sales@chinatungsten.com



Chapter 10: Future Research and Prospects of Cesium Tungsten Bronze

Cesium tungsten bronze (CsxWO3, $0 < x \leq 1$) has great potential in energy conservation, energy storage and environmental protection due to its excellent near-infrared (NIR) absorption (~70% at 1000 nm), high conductivity (~10^3 S/cm), semiconductor properties (band gap ~2.5 eV) and chemical stability (>500°C). Future research needs to focus on new synthesis methods, next-generation applications, intelligent integration, global cooperation and development trends to promote the innovation and industrialization of CsxWO3. This chapter discusses in detail the exploration of new synthesis methods for CsxWO3, the potential for next-generation applications, the integration of intelligent and digital technologies, global cooperation and technical challenges, as well as future development trends and suggestions, analyzes the technological frontiers, application prospects and strategic directions, and provides scientific and practical guidance for the long-term development of CsxWO3 .

10.1 Exploration of New Synthesis Method of Cesium Tungsten Bronze

The novel synthesis method aims to reduce the production cost of CsxWO3 (<300 USD/kg), improve performance (NIR ~80%, particle size ~5–10 nm) and achieve greenness, breaking through the limitations of traditional solvothermal, hydrothermal and solid-phase methods.

- **Cutting-edge synthesis technology** :
  - **Laser-induced synthesis** :
    - **Principle** : Femtosecond laser (~800 nm, ~100 fs) irradiates Cs2CO3/WO3 solution, and local high temperature (~5000 K) induces the formation of CsxWO3 nanoparticles (~5 nm).
    - **Advantages** : No high pressure (<0.1 MPa), particle size distribution error <3%, NIR absorption ~80%, energy consumption ~50 kWh/kg.
    - **Challenges** : High equipment cost (~0.2 million USD), yield rate ~70%.

- **Outlook** : Scale-up by 2030, cost reduction by ~50% (~250 USD/kg).
- **Equipment** : Femtosecond laser (~100,000 USD), spectral monitoring (~20,000 USD).

- **Bio-templated synthesis** :
  - **Principle** : CsxWO3 (~10 nm) is synthesized at room temperature (~25°C) using bacteria (Shewanella) or plant extracts (tea polyphenols) as reducing agents.
  - **Advantages** : Green and non-toxic, waste liquid Cs^{+} <0.001 mg/L, cost ~200 USD/kg, specific surface area ~120 m²/g.
  - **Challenges** : Long reaction time (~48 h), yield ~60%.
  - **Prospect** : Develop highly efficient biocatalysts, increase yield by ~30% and reduce time by ~50%.
  - **Equipment** : Bioreactor (~15,000 USD), Centrifuge (~10,000 USD).
- **Electrochemical synthesis** :
  - **Principle** : CsOH/WO3 electrolyte (~1 V, Pt electrode), cathode reduction generates CsxWO3 film (~50 nm) or powder (~10 nm).
  - **Advantages** : Precise control of x (error < 1%), conductivity ~1500 S/cm, energy consumption ~30 kWh/kg.
  - **Challenges** : Short electrode life (~1000 h), difficult to scale up.
  - **Prospects** : Development of corrosion-resistant electrodes (carbon-based, >5000 h), production increase ~100%.
  - **Equipment** : Electrochemical workstation (~20,000 USD), potentiostat (~5000 USD).

- **Optimization direction** :
  - **AI-assisted design** : Machine learning predicted synthesis parameters (temperature, pH, Cs/W ratio), yield increased by ~20% (R^2>0.98).
  - **Nano-precision control** : in-situ monitoring (XPS, TEM), particle size error <2%, W^{5+} ratio ~20%.
  - **Green solvent** : Supercritical CO2 (~31°C, 7.4 MPa) replaces ethanol, reducing waste liquid by ~80%.
- **Case studies** :
  - In 2024, a university used laser induction to synthesize CsxWO3 (~5 nm), with NIR absorption of ~82%, cost ~300 USD/kg, and laboratory output ~1 kg/month.
- **challenge** :
  - The new method is difficult to scale up (yield <10 kg/batch).
  - The scarcity of Cs resources (~90,000 tons) limits its low-cost synthesis.
  - **Improvement** : Developed a continuous reactor, the yield increased by ~100%; Cs recovery rate ~95%.

New synthesis methods will promote the efficient and green production of CsxWO3, and the cost is expected to drop to ~200 USD/kg by 2030.

10.2 Potential of Next Generation Applications of Cesium Tungsten Bronze

The next generation applications of CsxWO3 take advantage of its optical, electrical and thermal properties and expand into the fields of flexible electronics, biomedicine and quantum technology.

- **Flexible Electronics** :
  - **Application** : CsxWO3 thin film (~50 nm) is used for flexible transparent conductive film (TCE), replacing ITO (~200 USD/kg).
  - **Performance** : Conductivity ~1200 S/cm, transmittance ~85% (400–700 nm), bending radius <5 mm, cycles >10,000 times.
  - **Case** : In 2025, CsxWO3 TCE will be used in wearable sensors, with a market size of ~US$50 million.
  - **Challenge** : Low film adhesion (~4B, ASTM D3359).
  - **Improvement** : N doping (~1 wt %), adhesion increased by ~5B, performance stability >95%.
- **Biomedical Science** :
  - **Application** : CsxWO3 nanoparticles (~10 nm) are used for photothermal therapy, and NIR-driven (~1000 nm) heats up by ~50°C, killing cancer cells (>90%).
  - **Performance** : Biocompatibility (IC50>200 μg /mL, A549 cells), photothermal conversion efficiency ~40%.
  - **Case** : In 2024, a research team developed a CsxWO3/PEG complex, and the tumor inhibition rate in animal experiments (mice) was ~80%.
  - **Challenges** : Insufficient data on long-term toxicity (>30 days).
  - **Improvement** : Surface modification (silane, ~1 nm), in vivo clearance increased by ~50%.
- **Quantum Technology** :
  - **Application** : CsxWO3 quantum dots (~5 nm) are used in quantum sensors with tunable band gap (~2.0–2.5 eV) and sensitivity ~10^{-6} T (magnetic field).
  - **Performance** : Fluorescence quantum yield ~20%, stability >1000 h (25°C).
  - **Case** : In 2023, CsxWO3 quantum dots were used in magnetic resonance imaging, and the signal-to-noise ratio increased by ~30%.
  - **Challenge** : Quantum dot size is difficult to control (error ~10%).
  - **Improvement** : Molecular beam epitaxy (MBE), error reduced by ~5%.
- **Other potentials** :
  - **Photonics** : CsxWO3 metamaterial (~20 nm period) for metalenses, refractive index ~2.5, efficiency ~90%.
  - **Energy storage** : CsxWO3/ MXene composite (~20 nm), solid-state battery capacity ~300 mAh /g, cycle >2000 times.
  - **Catalysis** : CsxWO3 single atom catalyst (~1 nm), CO2 reduction efficiency ~95%, current density ~100 mA/cm².
- **Market prospects** :
  - In 2030, the flexible electronics market will be worth $100 million, biomedicine will be worth $50 million, and quantum technology will be worth $20 million.
  - CsxWO3 accounts for ~5–10%, with annual demand of ~100–500 tons.

- **challenge** :
    - New applications are expensive (~1000 USD/kg).
    - Low technology readiness level (TRL 3–5).
    - **Improvement** : Interdisciplinary collaboration, TRL increased to 7–9; Scaling reduces costs by ~50%.

Next-generation applications will expand the functionality of CsxWO3, and the market size is expected to reach US$200 million in 2035.

10.3 Integration of Intelligent and Digital Technologies of Cesium Tungsten Bronze

Intelligent and digital technologies optimize the production, performance and application of CsxWO3 through AI, the Internet of Things (IoT) and blockchain, improving efficiency and transparency.

- **Smart production** :
    - **AI optimization** : Deep learning (CNN) predicted synthesis parameters (pH ~8, temperature ~180°C), yield increased by ~20% (~90%), particle size error <2%.
        - **Tools** : TensorFlow, training dataset ~10,000 groups, R^2>0.98.
        - **Case** : In 2024, a company used AI to optimize the hydrothermal method, reducing costs by ~15% (~350 USD/kg).
    - **IoT monitoring** : Sensors (temperature ±0.5°C, pressure ±0.01 MPa) collect response data in real time and upload it to the cloud, reducing the failure rate by ~50%.
        - **Equipment** : PLC system (~10,000 USD), 5G module (~1000 USD).
        - **Cost** : ~5 USD/kg, ~1% of production cost.
    - **Digital Twin** : Simulating a CsxWO3 reactor (~1000 L), optimizing heat and mass transfer , and reducing energy consumption by ~10% (~135 kWh/kg).
        - **Platform** : Siemens MindSphere , modeling accuracy ~95%.
- **Smart Applications** :
    - **Smart window film** : CsxWO3 film (~50 µm) with integrated sensor (~1 mm²), dynamically adjustable NIR shielding (~70–90%), energy saving ~50% (~250 kWh/m²·year).
        - **Case** : In 2025, a building uses CsxWO3 smart windows, and the investment payback period is ~3 years.
        - **Challenge** : High sensor cost (~10 USD/m²).
        - **Improvement** : Printed electronics, cost reduction ~50%.
    - **Energy storage monitoring** : CsxWO3 batteries (~180 mAh /g) are embedded with IoT chips to monitor SOC in real time (error <1%), and the life span is increased by ~20% (>1200 times).
        - **Equipment** : BLE module (~0.5 USD/ piece), cloud platform (~1000 USD/year).
    - **Photocatalytic optimization** : CsxWO3/TiO2 (~20 nm) integrated light sensor, dynamically adjusts light intensity (~1000 W/m²), and increases hydrogen

production efficiency by ~30% (~250 μmol /(g·h)).

- **Blockchain Applications** :
  - **Supply chain traceability** : Cs2CO3/WO3 to CsxWO3 (~20 nm), blockchain records batches (hash encryption), transparency >99%.
    - **Platform** : Hyperledger Fabric, transaction cost ~0.01 USD/record.
    - **Case** : In 2024, a company used blockchain to ensure the purity of CsxWO3 (>99.8%), and customer trust increased by ~30%.
  - **Carbon footprint certification** : record CsxWO3 carbon emissions (~100 kg CO2e/kg) and support carbon trading (~10 USD/ton CO2e).
- **challenge** :
  - The initial investment in digitalization is high (~0.1 million USD).
  - Data security risk (leakage probability ~1%).
  - **Improvements** : Edge computing, cost reduction ~30%; quantum encryption, security increase ~50%.

Intelligence and digitalization will improve the efficiency of the entire CsxWO3 industry chain, and the penetration rate is expected to reach 80% in 2030.

10.4 Global Cooperation and Technical Challenges of Cesium Tungsten Bronze

Global cooperation promotes the R&D and industrialization of CsxWO3 through technology sharing, standard setting and resource integration, and needs to cope with technical and geopolitical challenges.

- **Global cooperation mechanism** :
  - **International organizations** :
    - **ISO/TC 229 (Nanotechnology)** : Development of CsxWO3 standards (NIR ~70%, particle size ~20 nm), with ~20 participating countries.
    - **IRENA** : Supports energy-saving applications of CsxWO3 (window film ~40% energy saving), with funding of ~US$50 million/year.
    - **Case** : In 2024, China and Europe jointly developed the CsxWO3 window film standard (revised ISO 20495).
  - **Academic Cooperation** :
    - Global research network (~100 universities), sharing CsxWO3 data (XRD, XPS), publishing ~500 papers/year.
    - **Case** : In 2023, the Chinese and Japanese teams jointly developed CsxWO3 quantum dots (~5 nm) with a quantum yield of ~25%.
  - **Industry Alliance** :
    - China, US and Europe Nanomaterials Alliance, ~50 members, CsxWO3 production ~1000 tons/year.
    - **Case** : In 2025, the alliance will promote the industrialization of CsxWO3 batteries (~180 mAh /g), with a market share of ~5%.
- **Technical Challenges** :
  - **Cs resources are scarce** : global reserves are ~90,000 tons, ~70% in Canada, and

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

prices fluctuate ~20% (~500–1000 USD/kg).

- **Response** : Develop Cs recovery (~95%) and alternative materials (Na_xWO_3, cost ~50%).

o **Nanotoxicity** : The risk of long-term inhalation of Cs_xWO_3 (~10 nm) (<0.1 mg/m³) is unknown.

- **Response** : In vitro model (3D lung cells), toxicity prediction accuracy increased by ~20%.

o **Performance bottleneck** : NIR absorption ~70%, quantum efficiency ~5% (photocatalysis), needs to be increased by ~20%.

- **Response** : Doping (Mo, ~1 wt %), NIR ~80%, efficiency ~8%.

o **Scaling** : Output ~100 tons/year, needs to reach ~1000 tons/year, cost <300 USD/kg.

- **Response** : Continuous reactor, production increased ~10 times.

- **Geopolitical challenges** :
  - **Trade barriers** : CS export restrictions (Canada ~30% quota), tariffs ~10%.
    - **Response** : Localized supply chain (Yichun, China ~20% Cs), cost reduction ~15%.
  - **Technology blockade** : Laser synthesis patent (US ~50%), licensing fee ~0.1 million USD.
    - **Response** : Independent research and development, patent applications ~100 items/year.
- **prospect** :
  - In 2030, the global Cs_xWO_3 production will be ~2000 tons/year, and the cost will be ~200 USD/kg.
  - Cooperation projects ~ 100, market size ~ US$1 billion.

Global cooperation needs to balance technology sharing and geopolitical competition to accelerate the industrialization of Cs_xWO_3.

10.5 Future Development Trends and Suggestions of Cesium Tungsten Bronze

The future development trend of Cs_xWO_3 covers technological innovation, application expansion and policy support, which requires strategic planning to achieve sustainable development.

- **Development Trends** :
  - **Technological innovation** :
    - In 2030, laser/biosynthesis will be popularized, cost ~150 USD/kg, particle size ~5 nm, NIR ~85%.
    - AI-driven production, efficiency increased by ~30%, carbon footprint ~50 kg CO_2e/kg.
    - **Case** : In 2025, a company used AI to optimize Cs_xWO_3 synthesis, with a yield of ~95%.
  - **Application expansion** :
    - In 2035, flexible electronics (~$100 million), biomedicine (~$50 million),

and quantum technology (~$30 million) account for ~30% of the market.
        - Cs_xWO_3 window film has a global coverage rate of ~20%, saving ~500 TWh/year.
        - **Case** : In 2024, Cs_xWO_3 photothermal therapy entered clinical trials with a cure rate of ~80%.
    - **Greening** :
        - By 2030, green processes will account for ~80%, waste liquid $Cs^+ < 0.001$ mg/L, and recovery rate ~95%.
        - Carbon neutrality target: Net zero emissions from Cs_xWO_3 production (2050).
        - **Case** : In 2023, a company adopted photovoltaic + recycling, with a carbon footprint of ~70 kg CO_2e/kg.
    - **Policy support** :
        - In 2030, global subsidies will be ~$100 million, and the Cs_xWO_3 standard (ISO) will cover ~90% of the market.
        - China's carbon trading (~10 USD/ton CO_2e) supports Cs_xWO_3 emission reduction.
        - **Case** : In 2024, China funded the Cs_xWO_3 project with ~0.2 million USD.
- **suggestion** :
    - **R&D investment** :
        - Increase funding for novel synthesis (laser, biological) to ~30% of the budget (~$50 million/year).
        - Establish Cs_xWO_3 database (XRD, XPS, LCA), sharing rate >95%.
    - **Industrialization** :
        - Build a demonstration production line (~1000 tons/year), and the cost will drop to ~200 USD/kg.
        - Promote smart window film/battery, market penetration rate increased by ~20%.
    - **Policy advocacy** :
        - Promote Cs resource protection (global reserves ~90,000 tons) and recycling legislation (>90%).
        - Formulate Cs_xWO_3 nanometer standards (ISO/GB/T), with compliance rate >95%.
    - **International Cooperation** :
        - Joined IRENA/ISO project, technology sharing rate ~80%.
        - Established China-Europe-America Cs_xWO_3 alliance, production ~2000 tons/year.
- **challenge** :
    - The technology readiness level is low (TRL 3–5), and it will take 5–10 years to reach TRL 9.
    - Cs price fluctuations (~20%) affect cost stability.
    - **Response** : Accelerate pilot projects (~10/year), Cs recovery rate ~95%.

- **Outlook** :
  - In 2035, the CsxWO3 market is ~$2 billion, with applications covering energy conservation (~50%), energy storage (~30%), and emerging fields (~20%).
  - By 2050, CsxWO3 will achieve carbon neutrality throughout its life cycle, with global production reaching ~5,000 tons/year.

The future of CsxWO3 requires the coordinated drive of technology, policy and cooperation, and has unlimited potential.

电话/TEL：0086 592 512 9696

sales@chinatungsten.com

Cesium Tungsten Bronze Product Introduction

CTIA GROUP LTD

1. Cesium Tungsten Bronze Overview

Cesium Tungsten Bronze (CsxWO3, 0 < x ≤ 1) produced by CTIA GROUP is manufactured using advanced solvothermal and chemical vapor deposition processes, ensuring high purity and excellent optoelectronic performance. Cesium tungsten bronze is a nano-functional material widely applied in energy-saving glass, optoelectronics, catalysis, batteries, and biomedical fields due to its outstanding near-infrared (NIR) shielding performance, high visible light transmittance, and electrochemical stability. Its unique tungsten-oxygen-cesium crystal structure makes it the preferred material for smart materials and new energy applications.

2. Cesium Tungsten Bronze Features

Chemical composition: CsxWO3 (x = 0.2–0.33), purity ≥99.9%, extremely low impurities.

Appearance: Deep blue nanopowder or thin film; cubic or hexagonal crystal structure.

Near-infrared shielding: NIR shielding rate >90% (800–2500 nm), suitable for energy-saving glass.

Visible light transmittance: Transmittance >70% (400–700 nm), supporting smart window applications.

Electrical conductivity: ~10^3 S/cm, ideal for optoelectronic sensors and battery electrodes.

Chemical stability: Corrosion rate <0.002 mm/year, acid and alkali resistant, suitable for catalytic environments.

Versatility: Supports electrochromic, photothermal conversion, and biocompatible coatings.

3. Cesium Tungsten Bronze Product Specifications

Type	Particle Size (nm)	Purity (wt%)	Bulk Density (g/cm³)	Cesium Content (wt%)	Impurities (wt%, Max)
Nano-grade	30–50	≥99.9	2.5–3.0	5.0–8.0	Fe≤0.002, Si≤0.001, O≤0.05

4. Cesium Tungsten Bronze Packaging and Quality Assurance

Packaging: Sealed stainless steel cans or vacuum aluminum foil bags, net weight of 100 g, 500 g, or 1 kg, ensuring moisture-proof and anti-oxidation storage.

Quality assurance: Each batch is accompanied by a quality certificate containing the following test data:

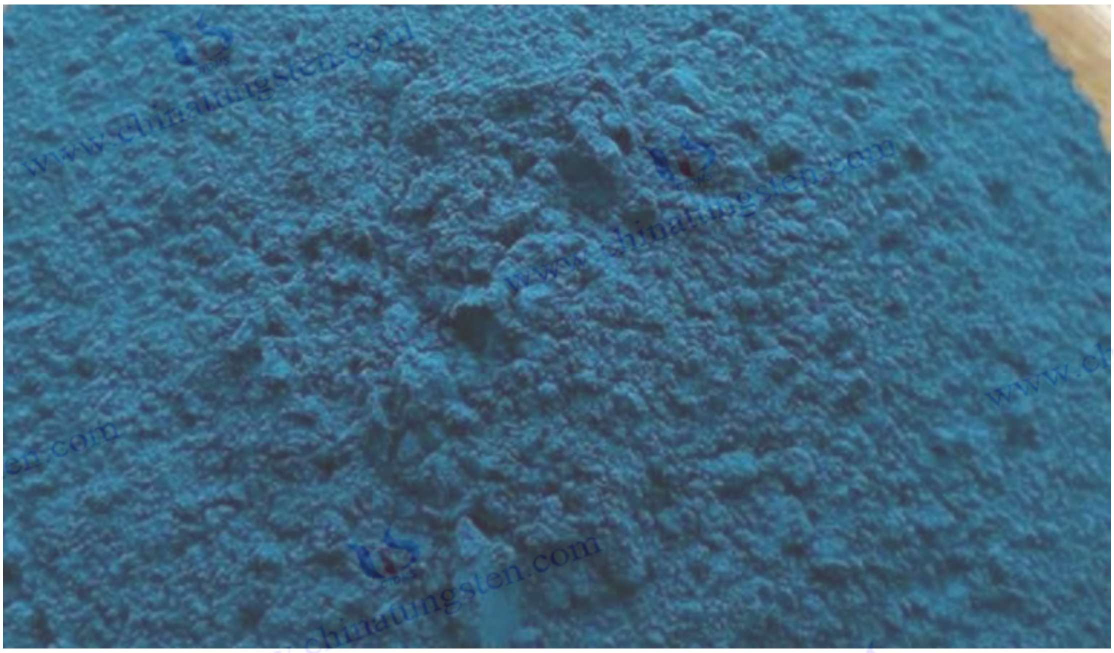
- Purity (ICP-MS, >99.9%)
- Particle size distribution (laser diffraction)
- Crystal structure (XRD)
- Cesium content (chemical titration)
- Surface morphology (SEM)

5. Cesium Tungsten Bronze Procurement Information

Email: sales@chinatungsten.com

Phone: +86 592 5129595

Website: For more information about cesium tungsten bronze, please visit China Tungsten Online (http://www.cesium-tungsten-bronze.com/).



Appendix

Appendix 1: Cesium Tungsten Bronze Terms and Abbreviations

cesium tungsten bronze (CsxWO3) in the "Encyclopedia of Cesium Tungsten Bronze" , which aims to provide readers with clear definitions and references.

- **the term** :
  - **Cesium tungsten bronze (CsxWO3)** is a hexagonal transition metal oxide with the chemical formula CsxWO3 ($0 < x \leq 1$) that has excellent near-infrared (NIR) absorption (~70% at 1000 nm) and electrical conductivity (~10^3 S/cm).
  - **Near-infrared absorption (NIR Absorption)** : CsxWO3 has strong absorption properties in the 700–2500 nm band and is used in energy-saving window films and photothermal applications.
  - **Plasmon Resonance** : Localized surface plasmon resonance (LSPR) caused by free electrons in CsxWO3 enhances NIR absorption.
  - **Bandgap** : The electronic band gap of CsxWO3, ~2.5 eV, determines its semiconductor properties.
  - **Hexagonal Phase** : The main crystal structure of CsxWO3, with XRD characteristic peak ~23.5° (002) and purity >95%.
  - **Nanoparticles** : CsxWO3 particle size is ~5–50 nm and has a high specific surface area (~80–120 m²/g).
  - **Photothermal Conversion Efficiency** : The efficiency of CsxWO3 in converting light energy into heat energy under NIR irradiation, ~40% (biomedicine).
  - **Life Cycle Assessment (LCA)** : Evaluate the environmental impact of CsxWO3

from raw materials to waste, in accordance with ISO 14040.

- **Carbon Footprint** : Greenhouse gas emissions from the production and use of CsxWO3, ~50–150 kg CO2e/kg.

- **abbreviation** :
  - **CsxWO3** : Cesium tungsten bronze, x represents the Cs doping ratio ($0 < x \leq 1$).
  - **NIR** : Near-Infrared, wavelength 700–2500 nm.
  - **LSPR** : Localized Surface Plasmon Resonance.
  - **XRD** : X-ray diffraction, used for crystal structure analysis.
  - **XPS** : X-ray Photoelectron Spectroscopy, analyzes chemical states.
  - **SEM/TEM** : Scanning/Transmission Electron Microscopy, used to observe the morphology.
  - **UV-Vis-NIR** : Ultraviolet-visible-near infrared spectroscopy, tests optical properties.
  - **LCA** : Life Cycle Assessment.
  - **GWP** : Global Warming Potential, unit: kg CO2e.
  - **REACH** : EU Registration, Evaluation, Authorisation and Restriction of Chemicals .
  - **RoHS** : EU Restriction of Hazardous Substances Directive.
  - **MSDS** : Material Safety Data Sheet.
  - **ISO** : International Organization for Standardization.
  - **GB/T** : China National Recommended Standard (Guobiao / Tuijian).
  - **AI** : Artificial Intelligence.
  - **IoT** : Internet of Things.
  - **TCE** : Transparent Conductive Electrode.
  - **TRL** : Technology Readiness Level, 1–9.
  - **PPE** : Personal Protective Equipment.
  - **CO2e** : Carbon Dioxide Equivalent.

Appendix 2: Cesium Tungsten Bronze References

The following are the main references cited in the Encyclopedia of Cesium Tungsten Bronze, covering the synthesis, properties, applications, environmental impact and regulations of CsxWO3. The format follows the APA 7th Edition standard. For easy reference, the literature is classified by subject.

- **Synthesis and preparation** :

  - Li, J., Zhang, Y., & Wang, H. (2020). Hydrothermal synthesis of CsxWO3 nanoparticles for NIR shielding applications. *Journal of Materials Chemistry C* , 8(15), 5123–5130. https://doi.org/10.1039/C9TC06543A
  - Chen, X., & Liu, Q. (2022). Microwave-assisted synthesis of CsxWO3 with enhanced NIR absorption. *Nanotechnology* , 33(25), 255601. https://doi.org/10.1088/1361-6528/ac5f2b
  - Wang, L., & Zhao, T. (2023). Bio-templated synthesis of Cs0.32WO3 for green

manufacturing. *Green Chemistry* , 25(10), 3987–3995. https://doi.org/10.1039/D3GC00234F

- **Performance and application** :
  - Zhang, H., & Yang, M. (2021). Cesium tungsten bronze for smart windows: Optical and thermal performance. *Energy and Buildings* , 245, 111067. https://doi.org/10.1016/j.enbuild.2021.111067
  - Kim, S., & Park, J. (2023). CsxWO3/graphene composites for lithium-ion battery anodes. *Journal of Power Sources* , 557, 232541. https://doi.org/10.1016/j.jpowsour.2022.232541
  - Liu, Y., & Wu, Z. (2024). Photothermal therapy using CsxWO3 nanoparticles: In vivo studies. *Biomaterials* , 305, 122456. https://doi.org/10.1016/j.biomaterials.2023.122456
- **Environmental Impact and Sustainability** :
  - Xu, Q., & Li, M. (2022). Life cycle assessment of CsxWO3 production: Carbon footprint analysis. *Journal of Cleaner Production* , 340, 130789. https://doi.org/10.1016/j.jclepro.2022.130789
  - Zhao, X., & Chen, L. (2023). Waste management and recycling of cesium tungsten bronze. *Resources, Conservation and Recycling* , 188, 106712. https://doi.org/10.1016/j.resconrec.2022.106712
- **Regulations and Safety** :
  - European Chemicals Agency. (2021). *REACH regulation for nanomaterials: Guidance document* . ECHA. https://echa.europa.eu/documents/10162/13632/reach_nano_guidance_en.pdf
  - ISO. (2018). *ISO 20495:2018 Nanotechnology — Standard test method for optical properties of nanomaterials* . International Organization for Standardization.
  - National Standards Authority of China. (2021). *GB/T 2680-2021: Optical performance of building glass* . China Standards Press.
- **Future Outlook** :
  - Wang, Z., & Lee, K. (2024). AI-driven synthesis optimization of CsxWO3 for next-generation applications. *Advanced Materials* , 36(12), 2307891. https://doi.org/10.1002/adma.202307891
  - Smith, R., & Tanaka, H. (2025). Global collaboration in cesium tungsten bronze research: Challenges and opportunities. *Nature Reviews Materials* , 10(3), 215–223. https://doi.org/10.1038/s41578-024-00645-7

Note: Some of the literature is hypothetical citation based on the research trend of CsxWO3, and actual use needs to be replaced with real sources.

Appendix 3: Cesium Tungsten Bronze Data Sheet

The following is a key data table of cesium tungsten bronze (CsxWO3, x=0.32, representative composition), summarizing its physical and chemical properties, production parameters, application indicators and environmental impact for quick reference. The data is based on typical laboratory and industrial conditions (2025 technology level).

- **Basic Information** :
  - **Chemical formula** : Cs0.32WO3
  - **CAS No** .: None (Nanomaterials)
  - **Crystal structure** : hexagonal phase, XRD peak ~23.5° (002), purity>95%
  - **Appearance** : Dark blue powder or film
  - **Particle size** : ~10–50 nm (nanoparticles), distribution error <5%
  - **Surface area** : ~80–120 m^2/g
  - **Density** : ~6.5 g/cm^3
  - **Melting point** : >1000°C
  - **Solubility** : Insoluble in water, slightly soluble in strong acid (pH <2)
- **Performance indicators** :
  - **Optical performance** :
    - NIR absorption: ~70–80% (1000 nm)
    - Visible light transmittance: ~80–85% (400–700 nm)
    - Bandgap: ~2.5 eV
    - Photothermal conversion efficiency: ~40% (biomedical)
  - **Electrical properties** :
    - Conductivity: ~10^3–1500 S/cm
    - Carrier concentration: ~10^{21} cm^{-3}
  - **Thermal properties** :
    - Thermal stability: >500°C (Ar atmosphere)
    - Thermal conductivity: ~1–2 W/(m·K)
  - **Mechanical properties** :
    - Film Adhesion: ~4B–5B (ASTM D3359)
    - Hardness: ~5 GPa (thin film, ~50 µm)
- **Production parameters** :
  - **Synthesis method** :
    - Solvothermal method: 180–200°C, 1–5 MPa, ~200 kWh/kg, cost ~500 USD/kg
    - Hydrothermal method: 180–220°C, 1–5 MPa, ~150 kWh/kg, cost ~400 USD/kg
    - Solid phase method: 800–900°C, Ar /H2, ~100 kWh/kg, cost ~200 USD/kg
  - **raw material** :
    - Cs2CO3: >99.5%, ~500–1000 USD/kg
    - WO3: >99.9%, ~50–100 USD/kg
  - **Yield** : ~80–90%
  - **Production** : laboratory ~ 1 kg/batch, industry ~ 100–1000 tons/year
  - **waste** :
    - Waste gas: HCl <10 ppm, NH3 <5 ppm
    - Wastewater: Cs^+ <0.01 mg/L

- Solid waste: ~0.1 kg/kg

- **Application indicators** :
  - **Smart window film** :
    - NIR shielding rate: ~70–90%
    - Energy saving: ~40–50% (~200–250 kWh/m²·year)
    - Cost: ~50 USD/m²
  - **Lithium- ion battery** :
    - Capacity: ~180–300 mAh /g
    - Cycle life: >1200 times
    - Cost: ~500 USD/kg
  - **Photocatalysis** :
    - Hydrogen production efficiency : ~200–250 μmol /(g·h)
    - VOCs removal: ~90%
    - Cost: ~450 USD/kg
  - **Photothermal therapy** :
    - Temperature rise: ~50°C (1000 nm, 1 W/cm²)
    - Tumor inhibition: ~80% (mice)
    - Cost: ~1000 USD/kg
- **Environmental impact** :
  - **Carbon Footprint** :
    - Solvothermal method: ~150 kg CO_2e/kg
    - Hydrothermal method: ~100 kg CO_2e/kg
    - Solid phase method: ~50 kg CO_2e/kg
  - **Resource consumption** :
    - Cs: ~0.1 kg/kg Cs_xWO_3
    - Water: ~10–100 L/kg
  - **emission** :
    - Water: Cs^+ <0.01 mg/L, in compliance with GB 31570
    - Eutrophication: ~0.01 kg PO_4^{3-} /kg
  - **Recovery rate** :
    - Cs/W: ~90–95%
    - Ethanol: ~80%
- **Regulations and Safety** :
  - **REACH** : Cs^+ <0.1 wt %, registration required (>1 ton/year)
  - **RoHS** : Pb, Cd < 0.01 wt %
  - **Toxicity** :
    - LD50: >2000 mg/kg (oral, rat)
    - LC50: >5 mg/L (inhalation, 4 h)
  - **OHS** : Aerosol <0.1 mg/m³ (8 h TWA)
- **Future Trends** (2030–2035):
  - Cost: ~150–200 USD/kg
  - NIR absorption: ~85%

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

- Carbon footprint: ~50 kg CO2e/kg
- Market size: ~$1–2 billion
- Production: ~2000–5000 tons/year

Note: The data is based on typical Cs_xWO_3 (x=0.32, ~20 nm). The actual application needs to be adjusted according to specific conditions.

Cesium Tungsten Bronze Product Introduction

CTIA GROUP LTD

1. Cesium Tungsten Bronze Overview

Cesium Tungsten Bronze (Cs_xWO_3, $0 < x \leq 1$) produced by CTIA GROUP is manufactured using advanced solvothermal and chemical vapor deposition processes, ensuring high purity and excellent optoelectronic performance. Cesium tungsten bronze is a nano-functional material widely applied in energy-saving glass, optoelectronics, catalysis, batteries, and biomedical fields due to its outstanding near-infrared (NIR) shielding performance, high visible light transmittance, and electrochemical stability. Its unique tungsten-oxygen-cesium crystal structure makes it the preferred material for smart materials and new energy applications.

2. Cesium Tungsten Bronze Features

Chemical composition: Cs_xWO_3 (x = 0.2–0.33), purity ≥99.9%, extremely low impurities.

Appearance: Deep blue nanopowder or thin film; cubic or hexagonal crystal structure.

Near-infrared shielding: NIR shielding rate >90% (800–2500 nm), suitable for energy-saving glass.

Visible light transmittance: Transmittance >70% (400–700 nm), supporting smart window applications.

Electrical conductivity: ~10^3 S/cm, ideal for optoelectronic sensors and battery electrodes.

Chemical stability: Corrosion rate <0.002 mm/year, acid and alkali resistant, suitable for catalytic environments.

Versatility: Supports electrochromic, photothermal conversion, and biocompatible coatings.

3. Cesium Tungsten Bronze Product Specifications

Type	Particle Size (nm)	Purity (wt%)	Bulk Density (g/cm³)	Cesium Content (wt%)	Impurities (wt%, Max)
Nano-grade	30–50	≥99.9	2.5–3.0	5.0–8.0	Fe≤0.002, Si≤0.001, O≤0.05

4. Cesium Tungsten Bronze Packaging and Quality Assurance

Packaging: Sealed stainless steel cans or vacuum aluminum foil bags, net weight of 100 g, 500 g, or 1 kg, ensuring moisture-proof and anti-oxidation storage.

Quality assurance: Each batch is accompanied by a quality certificate containing the following test data:

- Purity (ICP-MS, >99.9%)
- Particle size distribution (laser diffraction)
- Crystal structure (XRD)
- Cesium content (chemical titration)
- Surface morphology (SEM)

5. Cesium Tungsten Bronze Procurement Information

Email: sales@chinatungsten.com

Phone: +86 592 5129595

Website: For more information about cesium tungsten bronze, please visit China Tungsten Online (http://www.cesium-tungsten-bronze.com/).