Advances in Social Sciences and Management
January 2023, Vol. 1, No. 1, pp. 41-51

Review of Tellurium Resources in the World and in China

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Abstract:
Tellurium is an indispensable vitamin in modern high-tech fields, and it plays an irreplaceable and important role in many aspects such as national defense and medical treatment. Studies have shown that tellurium will be the best replacement for the next generation of green batteries. This article introduces the important uses of tellurium, summarizes the characteristics of different types of tellurium ores (independent tellurium and associated tellurium deposits), introduces the reserves and distribution of associated tellurium deposits in the world, and roughly predicts the demand for tellurium in major countries in the world this year.

Keywords: tellurium, application, ore type, resource distribution, associated deposit, independent deposit

INTRODUCTION

Tellurium (Te) is usually categorized as one of the scattered metals (SM), semimetals and/or nonmetals that have similar geochemical characteristics with Clark values too low to enrich into independent deposits, but that play very important roles across modern science, industry, national defense, frontiers of technology, and new clean energy industry.

In the traditional theory of mineral deposits and geochemistry, it is thought that Te cannot form independent deposits, but only exists as an associated component in other metallic deposits. The abundance of Te in the Earth's crust is very low. According to Li [1], the average content of Te in the Earth's crust is only 2.0 × 10–8 in China, and an even lower 1.34 × 10–9 worldwide.

At present, the world's supply of refined tellurium is mainly recovered from Te-bearing minerals including pyrite, sphalerite, chalcopyrite, galena, pyrrhotite, volcanogenetic sulfur, bismuthinite, arsenopyrite, and cassiterite, etc. Generally, only sulfide ores containing more than 0.002% Te can be used. As a result, the amount of refined tellurium that can be recovered is very limited. Most of the recoverable Te in the world is from copper deposits, and it is estimated that only 0.065 kg of Te can be produced in the refining process of one ton of copper [2-3].

In view of the important role of tellurium in modern scientific and technological civilization, this paper summarizes the geological origin types of tellurium ore, its global resource distribution, and predicts its prospecting direction in the future.

TELLURIUM APPLICATIONS

As mentioned above, the content of tellurium in the earth's crust is extremely low and it is difficult to form independent deposits so the pure tellurium that humans can obtain is very limited. However, the uses of tellurium are very extensive and important, and it is not an exaggeration to describe its application value as rare and expensive.

Tellurium and other SM group elements are known as the vitamins of modern industry, national defense and cutting-edge technology, the bridge to create miracles on earth, and the supporting materials of contemporary high-tech.

With the development of human society today, it has entered an unprecedented new era of science and technology. The aerospace industry has developed rapidly, and transportation and communication technologies have made people far away in the world feel like neighbors and so on. All of this is due to the development and application of rare dispersed elements including tellurium. Some experts bluntly say that both the present and the future are eras of rare scattered elements including tellurium.

Relevant data show that with the rapid development of cutting-edge technologies such as aerospace, atomic energy and electronic industries, the demand for scattered elements including tellurium is increasing day by day. Compound semiconductors, electronic optical materials, special alloys, new functional materials and organic metal compounds composed of SM group elements including tellurium make SM a new support material required for electronic computers, communications, aerospace development, energy, medicine and health, etc.

The cutting-edge weapons manufactured by SM group elements including tellurium played an irreplaceable and huge role in the Middle East War, the Falklands Sea Battle and the Gulf War, making countries compete to develop their own national defense power and sense of security. Elements of the SM group constitute important materials such as night vision devices, thermal imagers, large-scale integrated circuits, optical fibers and other communications and special alloys (Table 1).

Weapons such as electronic computers, satellites, missiles, rockets, aircraft, nuclear submarines, ships, tanks, radars and artillery equipped with these materials play a great role in modern warfare. When used for reconnaissance, the enemy has no secrets to keep, and when used for guidance, the hit rate is extremely high, so that the multinational forces achieved absolute victory with extremely low losses in the Gulf War.

Many people have never heard of tellurium. But this is about to change, a next-generation battery that is smaller and more powerful than what’s presently available will be produced. The key material for this kind of battery is tellurium, which has high electrical conductivity and a high volumetric capacity. As a result of this, tellurium will become more and more popular and well known to human beings in the near future. While rechargeable lithium-ion batteries are currently the most popular on the market, the latest test battery includes a flexible gel polymer electrolyte that allows lithium ions to move between lithium anode and tellurium cathode. This results in a quasi-solid-state lithium-tellurium battery that has improved performance compared to lithium-sulfur and lithium-selenium batteries. The high purity of the tellurium along with the mineral’s overall attributes makes it ideal as a rechargeable battery material. Moreover, it’s not just about making a better battery; it’s also about helping the planet (Table 1).

Table 1. Main fields of tellurium materials required by contemporary and future high-tech2-9

Application	Material
Night vision and thermal imager	HgCdTe, PbSeTe
Ray detector, nuclear energy	CdTe single crystal
Infrared camera, radar	$Hg_{1-x}Cd_xTe$
Photovoltaic cells (energy)	Zn(S,SE,Te)
Xerography	Se-Te, Se-Te-As
Radiation	CdTe etc.
Solar battery	CdTe
Thermoelectric power generation	GeTe/PbTe etc.
Refrigeration	Bi_2Te_3, Sb_2Te_3
Metallurgical additives	Te

Facts tell us that without new materials and technologies, we cannot compete with our opponents, and there is absolutely no sense of security at all. For this reason, relevant experts in China submitted a report with the words "confidential" to the relevant national authorities, suggesting that we pay attention to and strengthen the search, exploration, development and utilization of tellurium and other rare elements. At the same time, it is not without worry to remind that developed countries such as the United States and Japan have used state machinery to control the use and development of SM group elements.

As a rare semiconductor element, tellurium is an industrial raw material with important development and utilization value. It has extensive and unique uses in metallurgy, chemical industry, electronics, national defense, medicine, aerospace and other fields. The level of research and application of tellurium can largely reflect the level of science and technology and industrial modernization of a country. With the deepening of scientific exploration, its potential economic value will continue to emerge.

In developed countries, about half of tellurium is used in the metallurgical industry (Table 2). Adding a small amount of tellurium can improve the cutting and processing performance of low carbon steel and stainless steel. Adding an appropriate proportion of tellurium to lead, tin and aluminum alloy can improve its fatigue resistance and corrosion resistance, and can improve its hardness and elasticity, so it is especially suitable for submarine cables, automobile bearings and chemical equipment pipelines.

In the chemical industry, tellurium is mainly used as an additive for petroleum cracking catalysts, a secondary catalyst for rubber, and a catalyst for ethanol production. Tellurium compounds can be made into various catalysts, which are used in medicine as a fungicide, glass colorant, ceramics, plastics, printing and dyeing, paint, skin care products and enamel industries.

Tellurium is an important photoresist element in photosensitive elements used in photoengraving, laser printing and copying equipment.

In recent decades, scientists have discovered that the escape of chlorofluorocarbons (CFC-11 and CFC-12), namely Freon, which is widely used in the human refrigeration industry, has caused a significant reduction in the concentration of ozone in the atmospheric stratosphere 15-50 kilometers from the earth's surface. The decline in ozone concentration has caused increasingly serious "cavitation" damage, causing excessive ultraviolet rays generated by a large amount of solar radiation to enter the earth, deteriorating the climate and producing a greenhouse effect, directly endangering human health (vision loss, cataracts, skin cancer, etc.) and destroying ecological balance. Human beings are challenged.

Table 2. Application statistics of tellurium in foreign countries3-9

Year		1985		1988			1989			1990			1991			1992		
Country /Region		World	USA	World	USA	Japan	World	USA	Japan	World	USA	Japan	World	USA	Japan	World	USA	Japan
Application	Metallurgy	42.0	77.0	55.0	85.0	70.0	55.0	75.0	67.7	55.0		50.0	75.0	most	N/A	N/A	N/A	N/A
	Chemical	28.0	15.0	25.0	10.0	3.9	25.0	17.0	3.9	25.0	N/A	N/A	15.0	N/A	N/A	N/A	N/A	N/A
	Electronic	16.0	N/A	15.0	N/A	23.1	15.0	N/A	23.8	15.0	N/A	45.0	8.0	N/A	N/A	N/A	N/A	N/A
	Other	14.0	8.0	5.0	5.0	3.0	5.0	8.0	5.6	5.0	N/A	5.0	2.0	N/A	N/A	N/A	N/A	N/A

Note: N/A – not available

For this reason, the international community has issued an appeal and deadline for banning Freon-like substances, and the global refrigeration industry is facing an urgent green revolution of updating technology.

As the voice of anti-Freon is increasing day by day, research on developing substitutes for Freon-like substances is flourishing. In this situation, bismuth telluride, a telluride with good refrigeration properties, emerged as the times require, and has become one of the ideal materials for reducing air pollution and treating environmental disasters.

In addition, the compounds of tellurium, As and Si are important materials for making electronic computer memory. Cadmium telluride film is used in optoelectronic systems due to its good light absorption properties.

High-purity tellurium used in the US military reaches 99.99%.

The application status of tellurium in China is shown in Table 3. It can be seen from this that the development and utilization of tellurium in China is still very limited and weak, and its potential value needs to be further developed.

Table 3. Application statistics of tellurium in China (%)4-9

Application	Export	Electronic	Alloy	Metallurgy	Fiber optics	Medicine	Glass	Chemical	Catalyst	Other
1986-1987	N/A	72.9-66.4	N/A	19.5-19.1	N/A	N/A	0.6-0.7	N/A	N/A	7.0-13.8
1990		70.0-80.0	10.0	10.0-20.0			N/A			N/A

The annual output, annual consumption, annual import volume and market conditions of tellurium in the world during the approximately ten years from 1984 to 1992 show that the development momentum of tellurium resources is good, and its application value is attracting more and more attention, and the price keeps increasing (Table 4).

Table 4. Production, consumption and market statistics of tellurium in the world between 1984-19922[9]

Year	Annual output (t/a)			Annual consumption (t/a)			Annual import volume (t/a)			Annual selling price (US$/kg)		
	World	USA	Japan	World	USA	Japan	World	USA	Japan	World	USA	Japan
1984	290.0	106.0	57.3	305.0	107.0	73.4	N/A	35.0	38.5	N/A	25.0	54.8
1985	215.0	78.0	55.6	240.0	80.0	43.8	N/A	20.0	4.4	N/A	25.0	54.3
1986	215.0	N/A	55.6	200.0	N/A	46.0	N/A	22.0	0.8	N/A	28.0	58.6
1987	224.0	70.0	53.3	225.0	N/A	58.7	N/A	9.0	4.6	N/A	30.8	90.8
1988	215.0	N/A	55.2	223.0	N/A	51.9	N/A	52.0	2.3	N/A	77.1	83.7
1989	230.0	N/A	50.9	259.0	55.0	44.0	N/A	43.0	4.4	N/A	74.9	64.0
1990	215.0	30.0	49.7	270.0	50.0	60.0	N/A	34.0	6.3	N/A	68.3	88.1
1991	N/A	N/A	57.0	270.0	50.0	60.0	N/A	29.0	24.3	N/A	70.5	99.3
1992	N/A	N/A	60.0	N/A	N/A	N/A	N/A	50.0	N/A	N/A	77.1	N/A

Note: N/A – not available

INTERNATIONAL TELLURIUM DEPOSIT TYPE

All recovered tellurium material known internationally to date, with the exception of China, is from associated deposits. They are recovered as by-products when non-ferrous metals such as Cu, Pb, and Zn are milled and smelted. Apart from China, no independent tellurium deposits have been found in other countries. In other words, all the international tellurium ore resources mentioned in this article are associated tellurium ore.

According to the main mineral types, the associated tellurium ore has the following genetic types:

- Porphyry copper deposits and copper-molybdenum deposits (USA, Peru, Chile, etc.) and copper-nickel sulfide deposits (USA, Canada, etc.)
- Copper-bearing pyrite deposits (former Soviet Union, Canada, Japan, Sweden, etc.)
- Layered sand shale copper deposits (Zaire, Zambia, etc.)
- Precious metal Au, Ag deposits (USA, Japan, Philippines, etc.)
- Pyrite polymetallic deposits
- Cassiterite-sulfide deposits
- Hydrothermal uranium deposits
- Stratabound lead-zinc deposits in carbonate rocks
- Low temperature Hg, Sb deposits.

In addition, tellurium is also associated with coal, petroleum, oil shale, iron and phosphate deposits, but the most promising is in "fluid ore" seawater. However, we have not yet been able to extract tellurium from these ore-bearing geological bodies at present. I believe that with the advancement of science and technology, in the future, human beings will definitely extract the tellurium from these geological bodies we desire.

According to the above-mentioned specific types of associated tellurium deposits, tellurium deposits in the world can be classified into the following main genetic types (Table 5).

Table 5. Main genetic types of international associated tellurium deposits [5-9]

Deposit type		Rock types and tellurium deposit	
Major type	**Sub-type**	**Acidic igneous rock related**	**Alkaline-ultrabasic igneous rock related**
Endogenous	Igneous rock related deposits		Copper nickel sulfide deposit (Ni, Cu,Te, Se, Pt etc.)
	Hydrothermal deposits	Quartz - cassiterite - wolframite - molybdenite vein (Sn, W, Bi, Te, and Li etc.)	Not Available
		Chalcopyrite-molybdenite-bornite vein (Te, Se, and Cu)	
Exogenous	Biological-chemical sedimentary deposits	Sedimentation and sedimentation-leaching uranium deposit (U, Te, Se, Ge, ΣY, Mo, V, etc.)	

TELLURIUM DEPOSIT TYPE IN CHINA

China not only has associated tellurium deposits similar to those in foreign countries mentioned above, but also has the only independent tellurium deposit in the world so far.

The Independent Tellurium Deposit

The Dashuigou tellurium deposit, which was discovered in 1992, is the only known independent tellurium deposit in the world. The deposit is located in the transitional belt between the Yangtze Platform and Songpan-Ganzi folded belt, as part of the Tibet Plateau and nestled in the convergence between the Indian, Eurasian, and Pacific Plates[2,10].

Since its discovery in 1992, it has been debated between domestic geologists in China. Chen and others believed that tellurium mineralization is related to the Yanshanian alkaline intrusive rocks[11], while Luo et al.[12] and Cao et al. [13] believed that the mineralization is related to the Yanshanian granitic magma activity. Yin et al.[14] proposed that scattered elements including tellurium and bismuth originated from gas blown off from the deep Earth and enriched through nano-effects. Wang et al.[15] summarized the mineralizing process of the deposit as follows: a volcanic eruption deposit was formed on the ancient seafloor with magmatic eruption in the late Proterozoic. Then, the deposit was strongly superimposed and reconstructed by the Mesozoic multistage regional metamorphic hydrothermal activities.

As the only identified independent tellurium deposit in the world[1,16], the Dashuigou tellurium deposit has aroused widespread curiosity from domestic geologists in China since its discovery in 1992. Obviously, there exist divergent opinions on the origin of both the ore-forming elements and the Dashuigou tellurium deposit itself[11-15]. Yin[14], one of the authors of this paper, proposed that scattered elements including tellurium and bismuth originated from the deep Earth, mainly through the mantle's degassing in the form of mantle plume or hot spot, and enriched through nano-effect.

Associated Tellurium Deposit

In addition to the above-mentioned independent tellurium deposit, China also has many associated tellurium ores similar to those abroad. Tellurium is associated with almost all selenium deposits in China. However, China's associated tellurium resources are more concentrated in hydrothermal polymetallic deposits, skarn-type copper deposits, and magmatic copper-nickel sulfide deposits, accounting for 44.77%, 43.859% and 11.34% of the country's tellurium reserves respectively.

Dabaoshan in Qujiang, Guangdong Province, Chengmenshan in Jiujiang, Jiangxi Province, and Baijiazui in Jinchuan, Gansu Province are three large to super-large associated tellurium deposits in China. The sum of the three associated tellurium deposits' reserves is 94% of the country's total reserves[2-9].

Hydrothermal Associated Tellurium Deposit:
Dabaoshan, Qujiang, Guangdong is a Cu-Fe-Pb symbiotic polymetallic deposit of hydrothermal origin, with proven associated tellurium reserves of nearly 6,000 tons. At the same time, this deposit is also a very large associated selenium deposit, with proven selenium reserves of nearly 1,000 tons. The deposit is located on the southern margin of the South China fold belt. The ore body occurs in a set of Paleozoic pale metamorphic sandstone, shale and limestone. The magmatic activity related to the mineralization activity is the granite intrusion in the early Yanshan Orogeny.

Skarn-Type Copper Deposit:
Skarn-type copper deposits also occupy an important position in the associated tellurium deposits in China. The Chengmenshan Copper Mine located in Jiujiang, Jiangxi Province belongs to this category. The deposit is a large-scale comprehensive deposit mainly composed of Cu and S, accompanied by many useful elements. The ore bodies occur in the contact between Yanshanian granodiorite porphyry and Carboniferous, Permian and Triassic limestone, and some ore bodies are located inside the porphyry. Te and Se exist in chalcopyrite and pyrite as isomorphs, and can be comprehensively recovered in the process of copper smelting. Apparently, this deposit is also an important associated selenium deposit, with thousands of tons of proven selenium resources.

Magmatic Copper-Nickel Sulfide Deposit:
This is a relatively important type of associated tellurium resource in China, and it is also the most important type of associated selenium resource in China. Its selenium resources account for about half of the country's total. Such associated tellurium deposits in China are mostly distributed in platforms, and the ore-forming age is mainly pre-Paleozoic. The ore-forming parent rock is usually well-differentiated gabbro, and the ore bodies are distributed at the bottom of the layered intrusive gabbro. Deposits are generally large in scale and complex in mineral composition.

The Baijiazui copper-nickel mine in Jinchuan, Gansu Province is the largest associated tellurium mine of this type. The deposit is located in the uplift area of the southern margin of the Alashan platform, and the ore body is produced in the lower part of the ultrabasic intrusive.

In addition to the above three main associated tellurium, associated tellurium in China are also found in porphyry copper deposits. For example, the Dexing Copper Mine in Jiangxi Province is mainly copper with associated deposits of Te, Se, Mo, S, Au, Ag and Re. It is also found in skarn-type Pb-Zn polymetallic deposits, volcanic sedimentary iron deposits, hydrothermal quartz-gold deposits, and mercury-antimony deposits.

RESERVES AND DISTRIBUTION OF ASSOCIATED TELLURIUM

Most of the recoverable tellurium worldwide is currently produced in copper deposits. Based on copper resources and on the calculation that 0.065 kg tellurium can be recovered per ton of copper ore, Bureau of Mines of United States, Department of the Interior estimated that the world's associated tellurium reserves are around 38,000 tons, which mainly distributed in the United States, Canada, Chile, Peru, Zambia, Zaire, Philippines, Australia, Japan, Papua New Guinea and Europe and other countries and regions.

Relevant scholars in the former Soviet Union believed that the associated tellurium in porphyry copper and copper-molybdenum deposits in western developed countries accounts for more than 70% of the total tellurium, that is, more than 10,000 tons.

In addition to copper deposits, the Te contained in the reserve base of lead deposits is about 25% of the Te in the above-mentioned industrial copper deposits. However, because electrolysis is rarely used to extract lead, and only this technology can be used to recover Te, this part of potential Te cannot be utilized for the time being. Small amounts of Te can also be recovered from gold telluride ores.

Some experts estimate that the amount of Te contained in metal minerals such as copper that has yet to be developed, that is not yet of industrial grade, or that has not yet been discovered is several times that of the identified industrial copper mines.

Another study shows that Te contained in coal mines is 4 times that of industrial copper mines. But in the near term, trying to recover tellurium from coal mines is almost impossible for technical reasons.

The proven reserves and prospective reserves of associated tellurium ore in the world are shown in Table 6. China's proven associated tellurium reserves rank third in the world.

Table 6. Global associated tellurium reserves (×104 tons)

Reserve category	Proved reserve				Prospective reserve	
Country	Worldwide	USA	China	China's ranking in the world	worldwide	China
Tellurium	14.9	2.45	not available	#3	16.12	not available

China has discovered more than 30 associated tellurium ores, with reserves of 14,000 tons, covering 16 provinces, municipalities and autonomous regions across the country. But it is mainly concentrated in Guangdong (accounting for about 42% of the national total), Jiangxi (accounting for about 41% of the national total) and Gansu (accounting for about 11% of the national total).

In addition, China's associated tellurium is also produced in metal ores such as Cu, Pb, and Zn. According to the calculation of the main mineral reserves, there are about 10,000 tons of associated tellurium resources not included in the reserves in China. The proportion of China's associated tellurium reserves in the main minerals is shown in Table 7 below.

Table 7. Proportion of China's associated tellurium reserves in the main minerals (%)

Main deposit type	Bauxite	Copper	Coal	Molybdenum	Lead-zinc	Polymetallic	Iron	Other
The proportion (%)	N/A	98.60	N/A	0.96	N/A	N/A	N/A	0.44

TELLURIUM DEMAND FORECAST

The wide application of tellurium in many aspects of modern society indicates its important role and bright application prospect in the future. It is estimated that with the continuous advancement of science and technology, the demand for tellurium in the world will increase day by day (Table 8).

Table 8. Demand forecast for tellurium in 2022

Period	Worldwide	China	USA	Japan
Average annual growth rate of tellurium demand from 1983 to 2000 (%)	2.7	1.0	4.2	1.0
The demand for tellurium in 2000 (t/a)	352	2.7	145	45
Average annual demand for tellurium in 2020 (t/a)	545	3.24	267	54.0
Possible average annual demand for tellurium in 2022 (t/a)	574	3.3	488	55.1

DISCUSSION

The irreplaceable and important role of tellurium in the modern high-tech field has made the world's developed countries pay more and more attention to its development and utilization. In 1985, the U.S. Air Force specifically discussed the self-sufficiency channels of 21 strategic metals including tellurium. The U.S. National Security Council, the U.S. Federal Emergency Management Agency, etc. have all emphasized the reserves of such metals to the military or brought them to the attention of Congress.

At the end of the 1980s, there was an unprecedented huge wave of new or expanded tellurium smelters in the world. Among them, the MHO smelter in Belgium has an annual output of 150 tons of pure tellurium; the Lower smelter established by a joint venture between Australia and the Philippines has an annual output of 40 tons of pure tellurium after it was put into operation in 1988; in 1989, a tellurium smelter invested by the United States in the Philippines was put into operation Finally, the annual output of pure tellurium is also about 40 tons and so on.

China's tellurium production began in the 1950s, basically in sync with countries such as the United States and Japan. However, due to political turmoil and other constraints such as backward technology, it has not been possible to build a tellurium application market in China. At present, only two smelters in Shenyang, Liaoning Province and Zhuzhou, Hunan Province have associated tellurium production lines, with an annual output of less than 2 tons of pure tellurium.

In addition to supplying part of domestic demand, some products or components are exported.

As the first large-scale electronic warfare in human history, the Gulf War in the 1990s made the world's major powers compete to develop Te and other rare dispersed material industries.

Looking forward to the future, with the rapid development of science and technology, the demand for tellurium will increase day by day.

CONCLUSIONS

The increasingly important role of tellurium in the fields of modern industry, agriculture, national defense, medicine and health will surely make its value higher and higher, and the demand will also increase. In this situation, increasing the general survey, exploration and development of natural tellurium resources, and at the same time strengthening investment and research on tellurium ore dressing and smelting technology, both in theory and practice, have important economic value and strategic significance.

It is believed that more and more countries and mining companies will pay more and more attention to the development of tellurium resources and related investment.

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