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This document contains brief summaries of the mineral availability, primary metal refinement processes, material costs in raw form and as finished shaped charge liners, relevant material properties, and generalized warhead applications of commonly used, candidate, and hypothetical shaped charge and explosively formed penetrator (EFP) liner materials.

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Liner Materials:

Resources, Processes, Properties, Costs, and Applications

FINAL REPORT

February 1991

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Under:
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INTRODUCTION

This document contains brief summaries of the mineral availability, primary metal refinement processes, material costs, relevant material properties, and generalized warhead applications of commonly used, candidate, and hypothetical shaped charge and explosively formed penetrator (EFP) liner materials. Emphasis is placed on the pure metals, since experience has shown alloys to be lesser performers in shaped charge applications. The exception to this rule may eventually be found in certain candidate EFP liner materials.

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ALUMINUM
26.98

Resources

Aluminum is the most abundant element in the earth's crust after silicon. Bauxite is the principle ore for aluminum. Other ores are Kaolinitic clays, nepheline syenite, anorthosite, and alunite. There are 22 billion tons of known bauxite deposits on the earth. Two thirds are in Guinea, Australia, Brazil, Jamaica, and India. Bauxite reserves in the United States are less than 1% of the world total. Australia, Guinea, Jamaica, Brazil, and the U.S.S.R. account for 70% of the world's bauxite production. 96% of U.S. bauxite requirements have historically been imported.

Annual production of primary aluminum metal in the U.S. is about 4 million tons, and annual demand, including new primary metal and old scrap, is about 9 million tons. The U.S. is, therefore, also a net importer of refined aluminum primary metal. World production is about 21 million tons, with Europe supplying 7.5 and North America 6.7 million tons annually.

Aluminum is critical to national security and the federal government maintains stockpiles of bauxite and aluminum metal.

Processing

Bauxite ore is refined to provide impure hydrated alumina (aluminum oxide), which is then reduced in electrolytic cells to produce the pure metal. This electrolytic process is called the Bayer process, and provides primary metal up to 99.5% purity. Superpurity processing, up to 99.99% pure, is possible using a Hoopes cell. This process involves continuous electrorefining in 3 molten layer, each of greater density. The bottom layer is the anode (molten impure aluminum and copper for greatest density). The middle layer is molten cryolite electrolyte (Na_3AlF_6), and the top layer acts as a cathode to which rises the super pure aluminum.

Cost

99.5% pure aluminum ingots sell for about 90 cents per pound. Aluminum alloy metal stock costs about $4/lb, and aluminum liner forgings cost about $200 each.

Properties

Specific gravity is 2.71; Melting point is 657 deg C; Sound speed is 6.4 km/s; Good shaped charge jet ductility; Heat of combustion 31 MJ/Kg. Corrosion resistance in air: forms very stable oxide from 5 to 10 nm thick. Over 20 year period, in typical non-salt air atmosphere, metal loss is about .08 um/yr.

Applications

Most notably in Maverick warhead; experimental precursors for high jet speed applications; enhanced blast warheads since exothermally reactive.

COPPER
63.55

Resources

Copper is found on every continent as sulfide, oxide, and carbonate compounds. World mine output is about 10 million tons with Chile as the leading producer with 1.8 million tons. The United States is a close second and mines about 1.7 million tons annually. The world refined production of copper is about 12 million tons. The United States is the largest world refiner of primary copper metal, at 2.1 million tons, followed by the U.S.S.R. at 1.5, Chile at 1.2, and Japan at 1.1 million tons. The world consumption of refined copper is about 12 million tons with the three largest consumers being the United States at 2.4, Japan at 1.6, and the U.S.S.R. at 1.4 million tons each. From these statistics is appears that although the United States is a very large miner of copper ore, it must still import ore to meet refiner capacity, and even refined copper to meet domestic demand for the primary metal.

Processing

Copper is refined by smelting the concentrate ore and then by electrolytic processing for greater purity. Electrolytic copper production in the U.S. is about 1.7 million tons. Byproducts of copper production include gold, silver, and molybdenum.

Cost

Electrolytic copper sells for about $1.30 per pound. Precision copper shaped charge liners in low to high rate production sell from $100 to $1000 per liner depending on caliber and degree of complexity.

Properties

Specific gravity is 8.9
Sound speed is 4.7 km/s
Melting point is 1083 deg C
Excellent shaped charge jet ductility
Heat of combustion 2.5 MJ/Kg
Corrosion resistance in air: forms very stable oxide; over 20 year exposure in typical non-salt air atmosphere metal loss is .4um/yr.

Applications

Appears in nearly all chemical energy warhead applications as shaped charge liners and EFPs. Tested alloys include copper/silver, copper/nickel, and others, with results less than for pure oxygen free electrolytic copper.

GOLD
196.97

Resources

Gold occurs mainly as a native metal, alloyed with silver (electrum) and other metals, and as tellurides. Other gold minerals are rare. Gold is commonly associated with sulfide of iron, silver, arsenic, antimony, and copper. Typical ores in South Africa have .20 to .69 ounces of gold per ton of ore. In the U.S., .1 ounce per ton or less is common. Sedimentary rock, sandstones, and igneous rocks are typical formations for gold, with the richest lodes found in fissure veins in quartz rock. Seawater contains an average of .011 parts per billion (ppb) of gold, and ranges from .001 to 44 ppb depending on location. Waters draining from mines in Colorado contain on an average .15 ppb of gold.

World mine production of gold is about 63 million troy ounces (2100 tons) per year. South Africa is the largest producer at 19.5 million troy ounces, followed by the U.S.S.R at 9.6, the U.S. at 7.6, Australia at 5.5, and Canada at 5.1 million troy ounces per year.

Processing

Gold ore content of less than .1 ounce per ton is considered uneconomical to produce. However it is possible to extract from less than .1 ounce per ton using chemical heap leaching. Gold ore is normally concentrated using cyanide leaching and other leaching techniques. Gold bullion is then refined by chlorination in the molten state and then followed by electrolysis.

Cost

.999 fine gold costs about $340 per troy ounce, or about $5000 per pound.

Properties

Specific gravity is 19.3
Sound velocity is 3.2 km/s
Melting point is 1064 deg C
Corrosion resistance in air: does not oxidize at any temperature

Applications

Hypothetical shaped charge liner. High density is a benefit, but equally low sound speed indicates that it may be no better than uranium. An advantage may be found in its ductility, if it leads to greatly improved jet breakup characteristics, compared to its cost.

MOLYBDENUM
95.94

Resources

Nearly all refined molybdenum comes from low-grade deposits of molybdenite (MoS_2). 65 to 70% of U.S. mine output and 45% of world remainder comes from copper porphyry deposits as a byproduct of copper smelting. Primary copper deposits contain .2 to .5% molybdenite, and byproduct copper ores contain .02 to .08% molybdenite.

World mining yields about 260 million pounds (130,000 tons) of molybdenum per year. The United States is the largest producer at 140 million pounds, followed by Chile at 37, Canada at 30, and the U.S.S.R. at 26 million pounds per year.

Processing

Molybdenite is concentrated by grinding and floatation steps to produce lubricant grade MoS_2, which is 99% pure. To produce metallic molybdenum, lubricant grade MoS_2 is converted to MoO_3 (molybdic oxide) by roasting in a furnace at 650 degrees centigrade. This yields 90% pure MoO_3, which can then be reduced with hydrogen to get molybdenum powder. A more refined process is to take the MoO_3 and react it with ammonium hydroxide to get ammonium molybdate, which is then reduced with hydrogen to get 99.95% pure molybdenum powder. Molybdenum powder is then used to form metal stock through powder metallurgy techniques.

Cost

99.95% molybdenum powder is about $17 per pound. Liner forging blanks can cost from $300 to $500 each for small through large caliber designs.

Properties

Specific gravity is 10.2
Melting point is 2610 deg C
Sound velocity is 6.4 km/s
Heat of combustion 7.6 MJ/Kg
Shaped charge jet ductility uncertain
Corrosion resistance in air: suitable for service in oxidizing atmosphere up to 500 deg C without a protective coating.

Applications

Experimental shaped charge liners for high speed jet applications.

SILVER
107.87

Resources

Two thirds of the world's silver resources are found in copper, lead, and zinc deposits. Silver with gold accounts for the other one third. U.S. resources are about 6 billion troy ounces (200,000 tons) and the world total is estimated to be about 25 billion troy ounces. Silver minerals in the United States are Ag, Ag_2S, AgCl, $Ag_{16}Sb_2S_{11}$, Ag_3AsS_3, Ag_2SbS_3, Ag_3SbS_4, and $Cu(Sb,As)S_3$).

World mine production is about 16000 tons annually, with Mexico as the largest producer, mining 2500 tons, and the U.S. second at 2100 tons annually. U.S. refining of .999 fine silver bullion is approximately 3800 tons annually. The difference between U.S. mining and refining is accounted for through recycling of products containing silver, most notably in the film industry, and through imports of silver bearing ores.

World consumption is about 14,800 tons, and U.S. industry consumes about 4100 tons of this annually. The United States is a net importer of silver bullion.

Costs

.999 fine silver sells for about \$4 per troy ounce, or \$58 per pound.

Properties

Specific gravity is 10.5
Melting point is 961 deg C
Sound velocity is 3.6 km/s
Heat of combustion 140 KJ/Kg
Corrosion resistance in air: oxide is marginally stable at room temperature and unstable at elevated temperatures.

Applications

Hypothetical. Low sound speed and proportionally low density makes its use questionable. Price is not necessarily prohibitive. It may have potential if its ductility translates into better breakup times for shaped charge jets.

TANTALUM
180.95

Resources

Tantalum raw materials have not been produced in the U.S. since 1959 because domestic deposits are so low in grade. The principle source for tantalum is the isomorphous series of minerals containing tantalum and columbium, iron, and manganese oxides. Columbium and tantalum are found together in most rocks and minerals. The U.S. imports tantalum containing concentrates and tin slags for primary supply.

Tantalum concentrates come from Canada, Brazil, Australia, and Thailand. Tin slags come from Thailand and Malaysia. Synthetic concentrates made by upgrading tin slags come from Germany. The United States does not have the industrial capability to upgrade tin slags. Thailand tin slags account for 20% of the world tantalum production.

World production of tantalum is about 1900 thousand pounds (less than 1000 tons) annually (see gold). Thailand is the largest producer at 687 thousand pounds, followed by the U.S.S.R. at 330, Brazil at 174, Australia at 166, and Malaysia at 161 thousand pounds annually. The U.S. government maintains a strategic stockpile of tantalum and concentrates of about 1650 thousand pounds of tantalum content.

Processing

Beginning with tantalum concentrates or tin slags, a digestion method is used in which hydroflouric acid followed by liquid-liquid extraction with methyl isobutyl ketone results in a floutantalic acid solution, from which is precipitated either potassium tantalum flouride (K-salt) or potassium tantalum chloride, by addition of potassium flouride or chloride, or tantalum pentoxide, by addition of ammonia. Normally, for the production of pure metal tantalum, K-salt is then reduced by sodium at 800 degrees centigrade in metal retorts to get a tantalum powder. The powder is then pressed, vacuum sintered, and melted to consolidate the metal.

Cost

Tantalum concentrates cost about $30/lb of tantalum content. Tantalum metal stock prices fluctuate rapidly because of supply variability, but average about $170/lb. Actual liner costs, based solely on metal content, can cost upwards of $1000 for large caliber liners, and finished low rate production liners can cost between $1500 and $2000 each.

Properties

Specific gravity is 16.6; Melting point is 2996 deg C; Sound velocity is 4.0-4.5 km/s (estimate); Good jet ductility; Heat of combustion 5.7 MJ/Kg
Corrosion resistance in air: oxidizes at about 300 deg C

Applications

Candidate shaped charge liners for missiles and torpedoes; EFP liner for SADARM

TUNGSTEN
183.85

Resources

Tungsten is found primarily in quartz veins and contact-metamorphic sheelite and wolframite deposits. Tungsten is found and produced on nearly all continents and occurs as WO_3, $CaWO_4$, $FeWO_4$, and $MnWO_4$. Granite contains the highest concentrations, although metamorphic rocks are a principle source. In many deposits it is found with copper, tin, bismuth, antimony, or molybdenum minerals. In a few deposits it is a coproduct or minor biproduct of the other commodities. Tungsten becomes concentrated in the residual fluid of crystallizing magmas as the tungstate ion, tungstic acid, or sodium tungstate.

World tungsten concentrate production based on tungsten content is about 43,000 tons annually. China is the largest producer at 15,000 tons, followed by the U.S.S.R. at 9200 tons, and the U.S. at 780 tons.

Processing

Tungsten ore concentration is by gravity and flotation methods. Concentrations are then processed chemically to produce ammonium paratungstate (APT) from which tungsten powder is eventually made. APT is calcined in a rotary air furnace which drives off the ammonia and converts the APT to tungsten oxide. The tungsten oxide is then place in iron or nickel boats and pushed through heated tubes counter to a flow of hydrogen. Grain size of the powder is based on the original oxide size and the time and temperature of the reduction process. For example, all else constant, at 800 degrees centigrade a particle size of 0.5 um results, and at 1200 degrees centigrade a 10 um size results.

Cost

Tungsten powder costs about $22/lb. Forged tungsten billets cost an average of $50/lb, and experimental large caliber liner forgings average over $3,000 per forging. Finished machined low rate production liners can cost up to $3500.

Properties

Specific gravity is 19.25
Melting point is 3410 deg C
Sound velocity is 5.2 km/s
Heat of combustion 4.6 MJ/Kg
Although very brittle at ambient conditions, shows good ductility during shaped charge jetting.

Applications

Candidate shaped charge liner material; attractive because of high density and high sound speed.

URANIUM
238.03

Resources

Uranium oxide (U_3O_8) is found naturally in the earth's crust and provides the raw material for producing enriched uranium (U235), which can undergo continuous fission and is, therefore, used in atomic reactions, and its byproduct depleted uranium (U238), from which plutonium is produced. The demand for plutonium, is significantly less than the plentiful supply of byproduct U238, and as a result is made available by the U.S. government for heavy metal product application. World uranium oxide production is about 44.7 thousand tons annually. Canada is the worlds largest producer at 14,000 tons, followed by the United States at 7000 tons.

Processing

Uranium oxide ore is heap leached to form a concentrate, which is then chemically processed into uranium hexaflouride (UF_6) gas for the enrichment process. The lighter and more rare uranium isotope U235 is extracted by centrifugal means, leaving depleted UF_6, which is furnished to manufacturers of depleted uranium metal. UF_6 is reduced to UF_4 (greensalt) in a chemical reactor, and then reduced to metallic uranium in a reduction furnace. This operation involves blending magnesium chips with the UF_4 and placing the mixture in a steel vessel. The charged vessel is placed in an electrically heated furnace and brought up to the reaction-ignition temperature (normally 1080 degrees F). The spontaneous exothermic reaction is sufficient to reduce UF_4 and form uranium metal (a derby) and magnesium flouride slag.

Cost

Uranium oxide costs about $17/lb. The uranium content in UF_6 costs about $47/lb. Depleted uranium plate stock is produced for about $29/lb, and large caliber liners in medium rate production cost about $2500.

Properties

Specific gravity is 19.05
Melting point is 1133 deg C
Sound velocity is 2.5-3.0 km/s (estimate)
Heat of combustion 4.6 MJ/Kg
Corrosion resistance in air: Oxidizes slowly in air and is marginally stable; is coated for long shelf life.
Pyrophoric; heat of combustion:
Excellent jet ductility

Applications

Candidate shaped charge liner for missile systems; experimental EFP liner; alloyed with Niobium (Columbium) for experimental EFP liner.

ZIRCONIUM
91.22

Resources

Zircon is the only zirconium mineral of commercial significance and is recovered only as a coproduct or biproduct of titanium minerals processing from sand deposits. United States production of zirconium containing concentrate is about 115,000 tons annually. This level of production is number three in the world.

Processing

Titanium bearing sand is dredged and treated by wet-gravity methods, using spirals, cones, sluices, or jigs to produce a bulk, mixed, heavy-mineral concentrate containing zircon, titanium minerals rutile and ilmenite, and other marketable minerals like monazite. Zircon and monazite are non-conductive and can be separated by electrostatic methods. Monazite is slightly magnetic and can be separated by electromagnets. Quartz and kyanite are then separated by gravity concentration. The concentrate is then dried, and then high-tension separators and induced roll magnetic separators remove residual conductive and magnetic minerals. 99% pure zircon results.

Metallic zirconium is made by the Kroll process, in which zirconium tetrachloride is reduced with molten magnesium in an inert atmosphere. The zirconium tetrachloride is made by mixing zircon and carbon in an arc furnace, and then chlorinating. Zircon sand can also be directly chlorinated in a fluidized bed of carbon to produce the zirconium tetrachloride.

Cost

Metallic zirconium costs about $15/lb.

Properties

Specific gravity is 6.49
Melting point is 1852 deg C
Sound velocity is 4.62 km/s
Pyrophoric; Heat of combustion: 12 MJ/Kg Zr
Corrosion resistance in air: forms a visible oxide at about 200 deg C.

Applications

Used as shaped charge liner for enhanced behind armor effects.

Material Properties Summary Table

Material	Group	Mol. Wt. gm/mole	Spec. Grav.	Vs Km/s	Heat of Com. MJ/Kg	Pyrophoric	Melt Pt deg C
Aluminum	III	26.98	2.71	6.4	31	yes	657
Copper	I	63.55	8.9	4.7	2.5	no	1083
Gold	I	196.97	19.3	3.2	---	no	1064
Molybdenum	VI	95.94	10.2	6.4	7.6	no	2610
Silver	I	107.87	10.5	3.6	0.14	no	961
Tantalum	V	180.95	16.6	4-4.5	5.7	no	2996
Tungsten	VI	183.85	19.25	5.2	4.6	no	3410
Uranium	III	238.03	19.05	2.5-3	4.6	yes	1133
Zirconium	IV	91.22	6.49	4.62	12	yes	1852

Material Supply and Cost Table

Material	World Production tons/yr	Major Countries	Source Characteristics	Costs metal stock	Costs finished liners
Aluminum	21 million	Europe, North Am.	ore main product	$0.90/lb	$600/lb (est)
Copper	12 million	U.S., USSR, Chile	ore main product	$1.30/lb	$600/lb (est)
Gold	2100	S. Afr.,USSR, U.S., Australia, Can.	ore main product; copper biproduct	$5000/lb	n.a.
Molybdenum	130,000	U.S.,Chile,Can., USSR	ore main product; copper biproduct	$17/lb	$600/lb (est)
Silver	16,000	Mexico, U.S.	coproduct with Cu, Pb, Zn, Au	$58/lb	n.a.
Tantalum	< 1000	USSR, Thai., Braz.	tin byproduct	$170/lb	$1000/lb (est)
Tungsten	43,000	China, USSR, U.S.	ore main product Cu, Mo coproduct	$50/lb	$1500/lb (est)
Uranium	44,000	Canada, U.S.	ore main product	$29/lb	$1000/lb (est)
Zirconium	500,000 (est)	Others, U.S.	Ti co/biproduct	$15/lb	n.a.

Material Applications and Contractor Table

Material: <u>Contractor</u>	Al	Cu	Au	Mo	Ag	Ta	W	U	Zr
Alliant	-----	Main Chg	—	------	—	—	-----	—	—
Aerojet	-----	Main Chg EFP	—	Main Chg Prim. Chg	—	EFP	Main Chg	Main Chg	—
CRT	Prim. Chg	—	—	—	—	—	Main Chg	—	—
Phys. Int.	-----	Main Chg Prim. Chg EFP	—	------	—	Main Chg	Main Chg	—	Main Chg
NMI	Prim. Chg	—	—	—	—	—	—	Main Chg Prim. Chg	—

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