APPLICATION OF LIFE CYCLE ANALYSIS:
THE CASE OF GREEN BULLETS^a

CONF-980905--

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RECEIVED**JUN 10 1998****OSTI****ABSTRACT**

Life-cycle analysis (LCA) provides a general framework for assessing and summarizing all of the information important to a decision. LCA has been used to analyze the desirability of replacing lead (Pb) with a composite of tungsten (W) and tin (Sn) in projectile slugs used in small arms ammunition at U.S. Department of Energy (DOE) training facilities for security personnel. The analysis includes consideration of costs, performance, environmental and human health impacts, availability of raw materials, and stakeholder acceptance.

The DOE expends approximately 10 million rounds of small-arms ammunition each year training security personnel. This deposits over 300,000 pounds of lead and copper annually into DOE firing ranges, contributing to lead migration in the surrounding environment. Human lead intake occurs by inhalation of contaminated indoor firing range air and air containing lead particles that are resuspended during regular maintenance and cleanup, and by skin absorption while cleaning weapons. Projectiles developed by researchers at Oak Ridge National Laboratory (ORNL) using a composite of tungsten and tin perform as well as, or better than, those fabricated using lead. A cost analysis shows that tungsten-tin is less costly to use than lead, since, for the current number of rounds used annually, the higher tungsten-tin purchase price is small compared with

higher maintenance costs associated with lead. The tungsten-tin composite presents a much smaller potential for adverse human health and environmental impacts than lead. Only a small fraction of the world's tungsten production occurs in the United States, however, and market-economy countries account for only around 15% of world tungsten production. Stakeholders would prefer tungsten-tin on the basis of total cost, performance, reduced environmental impact and lower human toxicity. Lead is preferable on the basis of material availability.

Life cycle analysis clearly shows that advantages outweigh risks in replacing lead with tungsten-tin in small-caliber projectiles at DOE training facilities. Concerns about the availability of raw tungsten are mitigated by the ease of converting back to lead (if necessary) and the recyclability of tungsten-tin rounds.

I. INTRODUCTION

A decision methodology based on life cycle analysis has been developed and applied by Oak Ridge National Laboratory (ORNL) to aid in pollution-prevention decision making.^{1,2,3} The methodology provides a general framework for assessing and summarizing all of the information important to a decision, including information on health and safety impacts, environmental impacts, life-cycle cost, schedule impacts, local economic impacts, institutional

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issues, and stakeholder acceptance. The methodology is quite general, and can be tailored to apply to pollution prevention projects throughout the DOE complex. This paper discusses the application of life-cycle analysis to the replacement of lead projectile slugs with a tungsten-tin composite slug in small-arms ammunition used at DOE training facilities.

The DOE expends about 10 million rounds of small-arms ammunition each year, depositing over 300,000 pounds of lead and copper into DOE ranges. DOE's use of ammunition is small compared to that of civilians, law enforcement agencies, and the Department of Defense, which, combined, is estimated at tens of billions of rounds per year, translating into hundreds of tons of lead per day.

The firing of small arms ammunition for training, sporting, law enforcement, and military purposes contributes a significant potential for environmental pollution and constitutes a human health risk. Many of the numerous public, private, and government-operated shooting ranges are contaminated with hundreds of tons of lead, the result of years of target practice and skeet shooting. The lead is tainting soil and ground water and is ingested by wildlife, therefore becoming a threat to the health and safety of both human and animal populations. Indoor ranges introduce other concerns, such as increased lead exposure to the shooter in the enclosed space and the subsequent need for high capacity ventilation and air filtration systems. Handling ammunition and lead-contaminated weapons can produce elevated lead levels in the blood by absorption through the skin, and maintenance activities (e.g. cleaning spent slugs from traps) tend to present an inhalation hazard by resuspending lead-contaminated dust in the air.

Lead has historically been the material of choice in projectile slugs for small-caliber ammunition because of factors such as its low cost, availability, and performance. However, since lead is a recognized health hazard and is now being regulated as an environmental toxin, other materials with reduced human and environmental impacts are being considered. Tungsten, a non-toxic metal more dense than lead, and tin, a non-toxic metal familiar because of its widespread use in food and beverage containers, have been used by ORNL researchers to develop a projectile slug with ballistic performance equivalent to that of slugs made from lead, and with additional properties that make its overall performance superior to lead slugs. Tungsten and tin do not have any known toxic characteristics when used in this way.

A life cycle analysis of small arms ammunition use by the DOE has been conducted, taking into consideration factors such as health and environmental impacts, firing range remediation and waste disposal costs, and the direct

materials costs of the ammunition. The life cycle analysis reveals the overall benefit of using small arms ammunition with a projectile slug constructed from tungsten and tin.

II. METHOD

ORNL Life Cycle Analysis Framework

Figure 1

Life cycle analysis is the process of identifying and assessing all benefits and costs that result from a course of action over the entire period of time affected by the action and providing the results in a form that will promote sound decision making. In a life cycle analysis, a set of alternatives is defined, and then each alternative is evaluated against a comprehensive set of performance measures. The elements of a life cycle analysis depend on the purpose of the analysis and the availability of specific data. In general, however, elements of a life cycle analysis consist of direct costs and benefits; socio-economic and institutional impacts; and environmental, safety, and health impacts. The ORNL Life Cycle Analysis Framework is depicted in Figure 1.

III. ANALYSIS

This life cycle analysis compares 2 alternatives for ammunition used in DOE training facilities (both indoor and outdoor ranges): tungsten-tin projectile slugs vs. traditional lead slugs. These alternatives were evaluated on 6 performance measures: cost, performance, availability of raw materials, human health impacts, environmental impacts, and stakeholder acceptance. Construction of the two types of ammunition, including materials used in the shell casing, powder charge, primer assembly, and slug jacket, is assumed to be otherwise identical. This is considered to be a reasonable assumption, since the tungsten-tin composite is identical in ballistic performance to lead, so that simple replacement of the slug is the only change in construction of

the round. Toxic and environmental effects of the metal and inorganic compounds (particularly oxides) of lead, tin, and tungsten are considered here, since there is no credible scenario for producing organic compounds of these metals in their end use as projectile slugs.

A. Cost

Costs associated with each alternative are based on actual costs associated with the replacement of lead with tungsten-tin composite ammunition at the outdoor range of the Oak Ridge Reservation (ORR) Central Training Facility (CTF). The ORR CTF is one of DOE's two small-caliber ranges. The other is located in Albuquerque, New Mexico, and its design and operation are similar to those of the Oak Ridge facility.

The Central Training Facility on the DOE's Oak Ridge Reservation provides training not only to DOE security forces but to other federal and local law enforcement personnel. The outdoor live-fire range simulates a building with several rooms, the walls of which are composed of stacked rubber tires filled with sand. Within the various rooms are threatening and non-threatening targets with bullet traps. Contamination of the training facility by elemental lead and lead compounds, which are toxic materials, has a direct impact on the annual cost of operating the facility. Lead contamination and exposure occur through several pathways when a bullet containing a lead slug is fired. First, the weapon barrel retains traces of lead and must be routinely cleaned, thus producing waste and human exposure through skin absorption. Second, the exhaust gases of the weapon contain lead from the slug (and from the primer, if it contains lead) and thereby contaminate the area for several meters in front of the weapon. (This results in a significant potential for human exposure in indoor ranges, and high efficiency ventilation systems must be used and maintained - an additional cost over the operation of outdoor ranges.) Finally, as the bullet and its fragments are trapped, usually by an earthen embankment or steel traps, the dirt and steel become contaminated. Each of the mentioned exposure pathways has its sub-pathways. Tungsten, tin, and their compounds which are likely to be encountered in a live-fire range are much less toxic than lead, as discussed in a later section.

Life-cycle cost elements of the CTF that are related to the use of lead or non-lead ammunition includes the purchase price of ammunition, recurring (annual) maintenance and cleanup costs, and costs associated with decontamination of the facility. Of these, decontamination represents a 'sunk cost' - one which is incurred regardless of whether a change to non-lead rounds is made, since the facility is already lead-

contaminated and must eventually be decontaminated. A comparison of annual costs is appropriate as a performance measure, in this case, since decontamination of the facility is a sunk cost and does not affect the comparison of alternatives.

About 10,000 lead rounds are fired annually at the ORR CTF outside live-fire range at a cost of about \$0.25 per round. The annual cost to clean and maintain the bullet traps with their associated lead contamination is \$48,000, which includes the cost of personal protective equipment and the use of gloveboxes to contain lead-containing particles which might otherwise become resuspended in air and inhaled. The purchase price of tungsten-tin composite ammunition is three times as much at current market prices; however, cleaning bullet traps containing tungsten-tin slugs would merely be a recovery operation with no requirement for protective equipment or containment, and with a small financial incentive (scrap metal dealers currently pay about \$0.50/pound for tungsten and \$0.03/pound for tin) for recycling.

An annual cost evaluation, shown in Table 1, compares and summarizes the costs associated with lead and tungsten-

Table 1. Annual Cost Comparison for the DOE ORR Central Training Facility Outdoor Range

	Slug Composition	
	Lead	Tungsten-Tin
Ammunition	\$2,500	\$7,500
Maintenance & Cleanup	\$48,000	\$2,500
Total	\$50,500	\$10,000

Notes: Ammunition cost is based on 10,000 rounds per year at \$0.25 each. 'Cleanup' refers to periodic activities such as the recovery of slugs from bullet traps.

tin slugs at the ORR CTF outdoor range. This summary suggests that tungsten bullets have a significantly lower annual cost. Sensitivity analyses demonstrate that the annual cost is sensitive to two key assumptions: (1) the number of rounds fired; and (2) the purchase price of tungsten. If the purchase cost of ammunition is a linear function of the number of rounds used and the cleanup cost is somewhat fixed, or increases only slightly with the number of rounds fired, then an order-of-magnitude increase in the number of rounds fired results in comparable annual costs for the two alternatives. Further, the annual cost analysis is very sensitive to the assumed cost of tungsten. The principal producer of raw tungsten, as discussed below, is China. The cost of tungsten may be highly variable, subject to numerous political and market factors.

An additional cost not addressed in the summary information of Table 1 is waste disposal costs for lead recovered from traps. This information is not included in the direct operating costs of the facility, but has an impact on operating costs through indirect costs such as the overhead burden. Disposal costs add to those listed for the lead-slug alternative, making the tungsten-tin slug more favorable from an overall cost standpoint.

The annual cost analysis for the ORR CTF indoor range is similar to that for the outdoor range, except that additional annual costs are associated with building ventilation and air filtration intended to maintain concentrations of lead particles below action levels for workplace air. These costs also add to those listed for the lead-slug alternative, improving the overall cost comparison for tungsten-tin.

B. Performance

The density of the ORNL tungsten-tin composite exactly matches that of lead or lead alloys typically used in standard ammunition. The design, dimensions and mass of the non-lead slug also exactly mimic those of the lead analog, and so function and performance (weapon function, felt recoil, velocity for a given propellant charge, impact behavior and target interaction) are the same, if desired. Some factors can be improved in the tungsten-tin composite over those of lead. Frangibility⁴, for instance, can be enhanced in the non-lead slug so that it shatters on impact with a hard target and does not ricochet, causing collateral damage.

The DOE requires that the same ammunition be used both in training and in field service. Other non-lead ammunition is designed specifically for training and not for field use. The tungsten-tin slug is designed for both applications and, therefore, meets the DOE requirement.

C. Human Health Impacts

Elemental lead and many of its compounds are toxic to both humans and animals at elevated levels. The young are particularly susceptible to the toxic effects of lead, which include decreased intelligence quotients (IQs) and stunted growth. Trans-placental exposure of the unborn embryo or fetus can cause premature birth, lower birth weight, and decreased mental ability in the infant. Excessive lead exposure in adults can result in decreased reaction time, possible memory effects, weakness in extremities, anemia, and elevated blood pressure. Exposure to high levels of lead can cause damage to the male reproductive system, abortion in pregnant women, and can severely damage the brain and kidneys.⁵ The American Conference of Governmental Industrial Hygienists (ACGIH) has recommended a time-

weighted average (TWA) of 0.05 mg/m^3 as the Threshold Limit Value (TLV) for occupational exposure to elemental and inorganic lead in air.⁶

Tin is also present in the environment and in foodstuffs. Foods packaged in 'tin' cans (actually steel-coated with tin and lacquer) typically contain much greater amounts of tin than is found in fresh food. Metallic and inorganic tin have not been shown to cause harmful effects in low or moderate amounts, but ingestion of large amounts can cause stomach aches, anemia, irritation of the skin and eyes, and liver and kidney problems. The ACGIH-recommended TLV for metallic and inorganic tin (except SnH_4) in air is 2 mg/m^3 (TWA).⁶

Elemental tungsten is considered physiologically inert, and insoluble tungsten compounds, such as the oxide, have not been found to be mutagenic, carcinogenic, or teratogenic. Tungsten does compete with molybdenum in some metabolic processes. Documented health effects include respiratory illness due to excessive exposure to elemental tungsten dust and allergic reactions to coexisting agents such as cobalt and nickel.⁷ The ACGIH-recommended TLVs for tungsten in air (TWA) are 5 mg/m^3 for insoluble compounds and 1 mg/m^3 for soluble compounds.⁶

Training officers who work regularly at the training facilities and maintenance personnel who clean the bullet traps constitute the worker population most at risk from chronic exposure to lead. Training officers are present at the facilities regularly, as opposed to security personnel who train there for a few days once or twice a year. Maintenance personnel are exposed to greatly increased levels of lead in air during trap cleanout operations. Personal protective equipment (e.g. respirators with particulate filtration cartridges) is used to reduce this exposure to acceptable levels. Lead levels in the blood of both groups of employees are monitored regularly and, although it is not unusual to detect some lead in the blood, the levels detected are typically well below administrative action levels and regulatory limits.

The use of lead slugs at the ORR CTF does not result in excessive lead exposure for employees and security personnel, as indicated by the results of regular sampling of blood lead levels, primarily because of the use of personal protective equipment and containment (gloveboxes) when bullet traps containing lead slugs are cleaned and because of air exchange and filtration for the indoor range. Still, the use of tungsten-tin slugs instead of lead would reduce the risk of accidental exposure to the more toxic metal. Such an accidental exposure could result in health detriment for the employee. The relative degree of toxicity for these materials

can be roughly quantified by comparing their TLVs. Lead, on this basis, is at least 20 times more toxic than tungsten or tin.

D. Environmental Impacts

Environmental lead is ubiquitous, primarily because of human activity. The use of lead in automobile fuel additives prior to December 31, 1995, is responsible for most of the environmentally available lead today.⁵ The metal and many lead compounds, including oxides, are classified as Hazardous Wastes by the U.S. Environmental Protection Agency (EPA).⁸ About 51% of lead solid waste has, in the past, been spent ammunition and ordnance.⁹ Lead shot used for hunting waterfowl is now prohibited because of its toxicity to birds that are wounded but not killed and to wildlife that might ingest the loose shot. Federal law specifies the use of non-toxic shot, instead, for taking migratory waterfowl.¹⁰

Tungsten is present in relatively low amounts in the environment. Composites of tungsten and iron are specified by federal law as non-toxic for use in shot for hunting migratory waterfowl.¹⁰ Tungsten is not designated as an EPA Hazardous Waste constituent, and there are no applicable federal land disposal restrictions.^{7,8}

waterfowl.¹⁰ Tin is not designated as an EPA Hazardous Waste constituent, and so there are no applicable federal land disposal restrictions.^{8,11}

E. Availability of Raw Materials

Lead is a common metal for which world production is relatively evenly distributed. The United States produced 386,000 metric tons of lead from mines and 1.3M metric tons of refined pig lead (24% of the world total) in 1995, the last year for which dependable data are available.^{12,13} Figure 2 shows the distribution of refined lead production in the United States and the rest of the world in 1995. About 75% of lead used in the United States is considered to be recyclable, and 50% of lead requirements in this country are satisfied by recycled lead products.¹⁴

Tin production is about evenly distributed between China, Asia (except China), and South America, as shown in Figure 3. The United States and Canada produced only insignificant amounts of tin (less than 0.5% of world production) in the past decade.¹³ Recycled tin accounts for 25% of tin consumption in the United States.¹¹

China accounts for most of the world's tungsten production, as illustrated in Figure 4. The International Tungsten Industry Association (ITIA) reports that more than

**1995 World Production of Refined Lead
5,400,000 t**

Figure 2

Tin is present in moderate amounts in the environment. Composites of tin and bismuth are specified by federal law as non-toxic for use in shot for hunting migratory

**1995 World Tin Supply
194,700 t**

Figure 3

70% of world tungsten production and supply originates from China,¹⁵ and about 12% is from the Commonwealth of

1996 World Tungsten Supply
37,300 t

Figure 4

Independent States (CIS).^b Only about 15% of tungsten production is from Market Economy Countries (MECs), of which 11% is from mine production and 4% is imported as tungsten ore concentrates from other countries. Tungsten production by MECs in 1995 and 1996 is detailed in Table 2. The ITIA notes that, although the United States' production of tungsten was negligible in 1995, its strategic reserves in the National Defense Stockpile is 37,000 t, equal to the 1996 world supply of tungsten.

Tungsten availability can be improved by recycling. The ITIA estimates that about 30% of tungsten is recycled at the present time. The tungsten processing industry is able to treat almost every kind of tungsten-containing scrap and waste to recover both tungsten and coexisting metals.¹⁶

Availability is also linked to cost. Reduced supplies of tungsten or tin, because of political or market forces, would increase the cost of the tungsten-tin composite and make its life cycle cost less favorable.

The potential impact of reduced tungsten or tin availability is mitigated somewhat by the fact that both tungsten and tin can be recycled, that the U.S. strategic reserves of tungsten are about equal to the current annual world production of this metal, and that tin supplies are about evenly distributed between China, Asia (other than China),

^bCIS countries include Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.

and South America. It is further mitigated by the anticipated ease with which DOE security programs could revert back to lead slugs if the supplies of tungsten or tin were jeopardized. This reversion would be expected to take place without difficulty both because the change to tungsten-tin should not significantly effect the commercial production of small-arms ammunition with lead slugs and because use of the tungsten-tin slugs, which have ballistic characteristics similar to those of lead, would require no change in weapon design.

Table 2.
International Tungsten Industry Association
Mine Production and Supply of Concentrates,
Market Economy Countries
(as metric tons of tungsten)

	1995	1996
Austria	650	1,350
Bolivia	665	800
Brazil	30	10
Mexico	120	130
Mongolia	40	10
Myanmar	250	380
Peru	700	350
Portugal	870	5026
Rwanda/Uganda	85	50
Thailand/Malaysia	60	100
United States	30	-
Vietnam	50	130
Other	70	-
TOTAL	3,620	4,010

F. Stakeholder Acceptance

Stakeholders in the decision whether to use lead or tungsten-tin in DOE small-arms ammunition projectile slugs include the federal government (DOE); taxpayers; training facility (range) managers; range personnel; security force personnel; and members of the general population living in proximity to training facilities. The lead, tin, and tungsten industries might also be considered stakeholders, but the impact on any of these industries by this decision is considered to be small, unless taken as part of a larger movement to consider replacement of lead with more desirable materials in munitions. Our analysis is restricted here only to the DOE decision, however, and so the metal industries are not considered as stakeholders.

All stakeholders would unanimously favor use of a tungsten-tin composite over lead on the basis of equivalent or enhanced performance, significantly reduced

Life Cycle Analysis

Green Bullets: Replace Lead with Tungsten-Tin in DOE Small-Arms Slugs?						
Slug Composition	Annual Cost	Performance	Human Health Impacts	Environmental Impacts	Raw Materials Availability	Stakeholder Acceptance
Lead	\$50K	○	◐	●	◐	○
Tungsten-Tin	\$10K	◐	◐	◐	◐	◐

Notes:

Costs are from annual operation of the DOE Oak Ridge Reservation Central Training Facility's outdoor live-fire range.

Key: ● ◐ ○ ◑ ●
Best ← → Worst

Figure 5

environmental impacts and lower potential for adverse health effects. Tungsten-tin would also be unanimously favored on the basis of cost, given current market prices and numbers of rounds fired annually. Stakeholders would view lead more favorably on the basis of availability. Overall, we believe that stakeholders would favor the use of tungsten-tin over lead.

IV. RESULTS

Results of the life cycle analysis for replacing lead with tungsten-tin composite slugs used in small-arms ammunition at DOE training facilities are presented in Figure 5. The superiority of tungsten-tin over lead is evident in 5 of 6 performance measures.

V. CONCLUSIONS

Life cycle analysis has been used to evaluate the replacement of lead projectile slugs with tungsten-tin slugs at DOE training facilities for security personnel. The results suggest that tungsten bullets would be preferred.

The life cycle analysis methodology is a robust approach that is quite general, and can be tailored to meet site and project needs and applied throughout the DOE complex. A case study demonstrating the use of the methodology has been presented here. Other applications are currently underway and several DOE sites have committed to apply this approach for pollution prevention and decontamination & decommissioning decision-making.

NOMENCLATURE

ACGIH American Conference of Governmental Industrial Hygienists
CIS Commonwealth of Independent States

CTF Central Training Facility
DOE U.S. Department of Energy
EPA U.S. Environmental Protection Agency
IQ Intelligence Quotient
ITIA International Tungsten Industry Association
LCA Life Cycle Analysis
MEC Market Economy Country
ORNL Oak Ridge National Laboratory
ORR Oak Ridge Reservation
TLV Threshold Limit Value
TWA Time-Weighted Average

ACKNOWLEDGMENTS

The authors wish to thank Mr. Junior L. Davis, Manager of the Lockheed Martin Energy Systems Central Training Facility, for his assistance in analyzing operating costs for the facility. Will McCain, Toxicologist with the U.S. Army Center for Health Promotion and Preventative Medicine, provided invaluable insight and references regarding tungsten toxicity. Support for this study was provided by the U.S. Department of Energy, Office of Safeguards and Security, Counter-terrorism and Protective Technology Program.

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