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An Analysis of Tinker Air Force Base Thermal Spray Hazardous Waste Stream from 2003-2019 and its Potential Reclamation

Amy E. Silverbush

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THESIS

Amy E. Silverbush, 1st Lieutenant, USAF

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Amy E. Silverbush, BS

1st Lieutenant, USAF

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Amy E. Silverbush, BS

1st Lieutenant, USAF

Committee Membership:

Jeremy M. Slagley, PhD
Chair

Alfred E. Thal, Jr., PhD
Member

Eric G. Mbonimpa, PhD
Member

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Abstract

The disposal of hazardous waste threatens the environment and human health. However, certain hazardous wastes can be recycled or reclaimed to alleviate environmental and financial impacts associated with its disposal and resource demand reduction. A hazardous powder produced by the United States Air Force stems from aircraft maintenance and is composed of metals and ceramics, called thermal spray. This waste can be purchased by an industrial recycler if the waste is composed of valuable metals. Historic data from the depot-level maintenance base Tinker Air Force Base initiated an analysis of annual thermal spray hazardous waste disposal fees, which combined with a sample analysis resulted in an expected value of the waste to a recycler, and potential profits if a contract to recycle the waste was created. Tinker Air Force Base's thermal spray waste stream was valued at $0.16/lb, resulting in an estimated annual profit of $10,856.64 and the saving of an additional $26,463.06 of disposal fees. It is recommended that this research initiates the recycling of thermal spray waste stream throughout the Department of Defense in order to save money and lessen the burden to the environment through disposal and resource extraction reduction.

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Amy E. Silverbush

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I. Introduction

Background

Hazardous material is used and generated in many industrial processes and poses danger to the environment, animals, and human health if not handled properly. When this material is spent it becomes a hazardous waste that must be recovered, treated, or disposed. Prior to 1976, the United States did not carefully manage hazardous material or hazardous waste. The health and safety of workers interacting with hazardous material was covered by consensus standards until the Occupational Safety and Health Act of 1970; however, there was still a significant risk to the health and safety of bystanders affected by the uncontrolled dumping and transport of hazardous waste. These risks as well as the severe environmental effects of unregulated hazardous waste disposal highlighted the United States' need to create legislation protecting people and the environment.

The Resource Conservation and Recovery Act (RCRA) was created to meet this need. RCRA was passed in 1976 with aims to regulate both solid and hazardous waste in the United States. According to RCRA, hazardous waste must be properly tracked and handled throughout its lifecycle, to include hazardous material manufacturing, distribution, use, disposal, and remediation. In November of 1984, Congress passed the Hazardous and Solid Waste Amendments (HSWA) which required the phasing out of land disposal of hazardous waste and the minimization of hazardous waste through source reduction and recycling methods [1]. Furthermore, the Emergency Planning and Community Right-to-Know Act (EPCRA), enacted in 1986, supports community planning for chemical emergencies by requiring reports on the storage, use, and any releases of hazardous materials or wastes to all levels of government [2].

The United States Environmental Protection Agency (EPA) enforces RCRA and EPCRA requirements and RCRA amendments to regulate hazardous waste from “cradle-to-grave.” Companies, federal facilities, and local governments are provided with compliance assistance, and their compliance is verified by the EPA and the particular state through record review and inspections [3]. Hazardous waste generators are responsible for following any additional state regulations set by their state of residence. Although the United States improved its regulation of hazardous waste, it is less successful in the reduction of hazardous waste generation.

In 2015 the United States produced 27.96 million tons of hazardous waste and disposed of 23.8 million tons through deep well or underground injection [4]. When regulated and monitored properly, this method is safe; however, there are historic examples of deep well injection of hazardous waste causing earthquakes, the largest of these a magnitude 5.5 in Denver, Colorado [5]. There is a minor risk of water contamination if the injection site leaks and the hazardous waste migrates vertically. Leaks could be a result of well structural deformation, but any drinking water contamination would be detected through supply monitoring and would mostly be a financial burden rather than a health hazard [6].

Landfilling hazardous waste was the second largest method to dispose of hazardous waste in 2015. Approximately 1.1 million tons of hazardous waste reached landfills or surface impoundments [4]. As with deep-well injection, landfills and surface impoundments must be properly constructed and monitored to ensure public and environmental safety. Water contamination, airborne exposure, and direct exposure are the three biggest risks to improperly managed landfills and surface impoundments. Results regarding the proximity of landfills containing hazardous waste causing any negative health effects to a community are inconclusive, although there were significant increases of self-reporting poor health as a result of a landfill [7].

Not all hazardous material must become hazardous waste and end up in an injection well, landfill, or surface impoundment. There are opportunities to reap benefits from the used or residual hazardous materials from a process. These waste-like hazardous materials are called secondary materials and are classified as either spent materials, byproducts, sludges, commercial chemical products, or scrap metal [8]. Secondary materials do not need to be directly used or reused to be considered recycled. They can also be used in energy recovery through combustion, use constituting disposal, and reclamation [8]. The EPA regulates the recycling of used oil, precious metals, and scrap metal through RCRA; however, levels of regulation stringency in the Code of Federal Regulations (CFR) vary according to how dangerous the material is and how well the material use reflects a typical production process [9].

The Pollution Prevention Act was passed in 1990 in support of the EPA's efforts to reduce pollution through changes in production and material use. This act also emphasized the need for source reduction, or reducing the opportunity for hazardous material to enter the environment prior to any sort of treatment, disposal, or recycling [10]. Based on guidance from RCRA and the Pollution Prevention Act, most hazardous waste management practices have a standard hierarchy of management options. This hierarchy is typically, from top to lowest priority, source reduction, recycling or recovery, treatment, incineration, and finally disposal [11].

Hazardous waste source reduction benefits the environment by reducing the overall demand for a new product, and less resource extraction, which in turn reduces greenhouse gas emissions created during production [12]. Source reduction usually takes place through the development of new technologies and processes, substitution of raw materials, and even some administrative improvements [10]. Increasing resource use efficiency can also act as a source reduction method. The next priority to pollution prevention, recycling and recovery, affects industrial processes in similar ways.

The benefits of recycling hazardous material include more than just the benefits of looser regulations. Many hazardous materials come from non-renewable resources, therefore enabling some of these materials to return to a process eliminates some of the demand to harvest or produce them from new material. In the mining industry, for example, material is becoming more difficult to find, and attempts to extract ores and minerals have experienced decreases in efficiency [13]. Recycling, reusing, or reclaiming hazardous materials like scrap metals and precious metals would alleviate some of this demand. In addition to reducing resource demand, minimizing hazardous waste production will reduce environmental impact, reduce health risks associated with the disposal of hazardous waste, and presents an opportunity for monetary savings for many companies and organizations, including the Department of Defense (DoD).

The DoD is a large generator of hazardous wastes to include contaminated fuel and oil, cyanides, sludges, acids, and solvents [14]. The DoD produces approximately 400,000 to 750,000 tons of hazardous waste per year, primarily from industrial processes involved in maintaining and repairing weapons systems [15], [16]. The DoD spends billions of dollars each year to handle and dispose of hazardous waste [17]. The Air Force alone was responsible for an estimated 96,000 tons of hazardous waste per year [18]. Since the DoD falls under RCRA and Pollution Prevention Act regulations, there have been many efforts to reduce DoD hazardous waste creation.

In the 1980s, Tinker Air Force Base (AFB), Oklahoma, was identified as a large producer of hazardous waste. Tinker AFB is one of the largest industrial installations not only in the United States, but in the world [19]. In 1985, Tinker AFB was scrutinized for its poor practices regarding hazardous waste reduction initiatives. The Government Accounting Office (GAO) reported to the Subcommittee on Environment, Energy, and Natural Resources that Tinker AFB focused on the disposal of its hazardous waste rather than recycling and reuse [19]. The GAO urged Tinker AFB to better separate their hazardous wastes and materials in order to facilitate recycling or reuse. By the time of the 1987 follow-up report on Tinker AFB, the base had initiated hazardous waste reduction methods and had created plans for additional management support [14].

Tinker AFB is still one of the largest industrial bases in the United States and is classified as an organic industrial base (OIB). OIBs are responsible for depot-level maintenance and repair, defined in Section 2460 of Title 10, United States Code, as “material maintenance or repair requiring the overhaul, upgrading, or rebuilding of parts, assemblies, or subassemblies, and the testing and reclamation of equipment as necessary.” Tinker AFB is home to eight DoD, Air Force, and Navy tenants, to include the largest of three depot repair complexes in Air Force Materiel Command [20]. The Air Force Sustainment Center, which directs Air Force operations for air and space weapon system readiness, is a large factor in why Tinker AFB is responsible for its large levels of hazardous waste production [21]. The Air Force Sustainment Center directs an Air Logistics Complex in Oklahoma City, Oklahoma (OC-ALC), which is the largest organization on Tinker AFB.

The OC-ALC is responsible for depot-level maintenance on the C/KC-135, B-1B, B-52, and expanded phase maintenance on the Navy E-6. Additional responsibilities include the maintenance, repair, and overhaul of F100, F101, F108, F110, F118, F119, and TF33 engines [20]. Another important tenant with a large role in the acquisition and disposal of hazardous waste and material at Tinker AFB is the Defense Logistics Agency (DLA) Distribution Oklahoma City. The DLA Distribution Oklahoma City supports the OC-ALC and Tinker AFB’s organizations through providing receipts, storage, issue, inspection, and nearly all activities involved in the shipment of material [20]. The DLA’s function at Tinker AFB is not unique, as the entire United States Air Force (USAF) currently holds a contract with the DLA which gives them the responsibility of the Air Force’s Hazardous Material and Hazardous Waste Management Programs (HMMP and HWMP).

Although the DLA assumes the roles of management and disposal of hazardous waste at Air Force installations, the installation commander is still ultimately responsible for the final disposal of the hazardous waste. However, the DLA is responsible for advising Tinker AFB when a potential market is available for reusing hazardous materials

[20]. In this way, the DLA holds a significant role in Tinker AFB's potential to reduce its hazardous material demand, hazardous waste production, and hazardous waste disposal costs. The DLA, however, is not the only handler of Tinker AFB's thermal spray waste due to its occasional radioactivity.

The Nuclear Regulatory Commission (NRC) regulates radioactive material under the Atomic Energy Act of 1954 but relinquishes its federal authority to NRC approved states [22]. A portion of the drums of thermal spray waste collected by Tinker AFB are radioactive since they exceed the exempt activity limits for natural thorium and natural uranium in accordance with 49 CFR 173.436 [23], [24]. Tinker AFB must document the isotopes on shipping paperwork but is not required to treat the waste stream as a low level mixed waste [23]. The classification of radioactive thermal spray hazardous waste produced by Tinker AFB has been debated between the Air Force Radioactive Recycling and Disposal (AFRRAD), the Air Force Radioisotope Committee (RIC), and the Army's Joint Munitions Command (JMC), who funds the disposal of the Air Force's low level radioactive waste [25]. While the DLA is the lead agent on almost all other government property disposal, the JMC is the lead agent for the disposal of radioactive materials [25].

The radioactive thermal spray waste is typically considered technologically enhanced naturally occurring radioactive material (TENORM). This is because the EPA and some states include naturally occurring radioactive material (NORM) within the TENORM definition if its processing or handling causes an increase in the potential for human exposure relative to its natural state [22]. The accumulation of radiation from the storage of the thermal spray waste powders is enough to increase the potential for human exposure for Tinker AFB. Air Force guidance for the management and use of radioactive materials comes from Air Force Instruction (AFI) 40-201, *Managing Radioactive Materials in the US Air Force*; however, there is not clear criteria for disposal of TENORM in this AFI or in EPA guidance. Therefore it is often disposed of as low level radioactive waste [22], [26]. This is expensive and overly restrictive for low activity TENORM like the thermal spray waste at Tinker AFB [22]. Furthermore, if permitted, disposal and recycling facilities can receive certain activity levels of TENORM [22].

The lack of regulation of TENORM by the federal government and the debate of who will act as the regulatory agency, the US Nuclear Regulatory Commission or the EPA, creates a gray area for the possession and disposal of TENORM of TENORM-like wastes [25]. Additionally, there is lack of TENORM disposal guidance within the DoD. AFRRAD explained that although the thermal spray waste may be radioactive, the DoD lead agent for low level radioactive waste can waiver its radioactivity as outlined within DoD Instruction 4715.27 [25], [27]. An unofficial term, Very Low Level Radioactive Waste (VLLRW), has been adopted to describe the thermal spray waste stream since, although it is by definition TENORM, it produces minimal levels of radiation [25]. AFRRAD calls the situation and process complicated, and notes that many agencies are working toward a viable solution.

Since Tinker AFB is located in Oklahoma, it must comply with regulations set by the Oklahoma Department of Environmental Quality (ODEQ). The ODEQ is comprised of three divisions: Air Quality, Water Quality, and Land Protection [28]. It also hosts a number of councils responsible for setting guidance, such as the Administrative Code. Therefore, in addition to federal compliance, Tinker AFB must follow Title 252 Chapter 205 of Oklahoma's Administrative Code, which was modified in 2019 with an effective date of 15 September 2019 [29], [30]. This chapter includes Oklahoma's Hazardous Waste Management plan and recently adopted modifications.

Hazardous waste generators in Oklahoma must file disposal plans with the ODEQ and must obtain its approval before the waste may be shipped [30]. The plans only need to be approved once, or if they are altered in any way [30]. Hazardous waste transporters in Oklahoma are no longer required to register, but they must ensure the waste is handled in such ways as to avoid leakage, spillage, or dumping, and may not mix hazardous wastes except at approved transfer stations [30]. Title 252 Chapter 205 also requires the owner/operator of a treatment, storage, or disposal facility or off-site recycling facility to have chemical and physical analyses of a hazardous waste with any information needed to properly handle the waste [30]. Radioactive materials must be managed according to the federal Nuclear Regulatory Agency and the ODEQ's Radiation Management rules [30].

Title 252 Chapter 205 of Oklahoma's Administrative Code also contains off-site recycler regulations. It requires recyclers to prove to the ODEQ that the hazardous wastes processed for recycling have a market and are no longer threats to human health or the environment [30]. Other important information in the Hazardous Waste Management plan includes recordkeeping requirements of three years, as well as generator and inspection fees. The ODEQ charges $100 per generator per year for one to two waste streams with additional waste streams at $50 per year each. Generators must also pay $100 per generator per year for inspection and monitoring [30]. Appendix B. of Title 252 Chapter 205 includes a table of applicable submission fees for different hazardous waste treatments.

Since Tinker AFB does depot-level maintenance on many aircraft and engines, it is a major producer of a particular type of hazardous waste: coating powders that resist oxidation, erosion, and extremely high temperatures. Turbine engines are highly susceptible to both oxidation and corrosion due to exposure to hot gases, high pressures, and the overall stresses of the system [31]. As engine demand and performance rose with advances in technology, it became more difficult for the engine parts to maintain their resistance to wear-and-tear. Without the development of the higher-strength, corrosion and heat-proofing coatings, turbine parts would warp, melt, or rust [32].

There are three primary coatings types used to prevent corrosion and oxidation, and to resist heat damage on turbine engine parts. The first layer typically applied is a metal-based powder, which can be followed by a bond coat, and finally a ceramic layer [31]. The metal-based coating powders are used for anti-oxidation of turbine parts and primarily composed of nickel or a cobalt-based alloy [31]. They can be used alone for repairs or layered with other ceramic-based thermal barrier coatings (TBCs) which provide additional protection for turbine parts. The TBCs are ceramic and made up of a nickel-alloy bond coat (NiCrAlY) and a layer of yttria stabilized zirconia (YSZ) [33]. The bond coat shares characteristics of both the metal coating and the YSZ ceramic coating [34]. If the materials are applied in separate spray booths with separate ventilation systems, the spent materials can be collected separately. However, if both the metal powders and ceramic powders are either applied in the same booth or collected with the same ventilation system, the waste stream will be a combination of the two. This could affect the waste’s handing and potential for recycling later in its lifecycle by reducing the concentration of valuable metallic materials and reducing the predictability of the characteristics of the waste stream.

In industry practice, turbine parts can be coated using a variety of spraying processes. In general, these methods can be categorized into four groups as flame spray, electric arc spray, plasma overspray, or kinetic spray. The flame spray process can be done with wire or powder as a feedstock which is melted by an oxygen-fuel flame and atomized by compressed air which also directs it toward the part's surface [35], [36]. In electric arc wire spray, an arc is formed by two metallic wires with opposite charges which melts the feedstock wire and is then atomized by the air and shot toward the engine part [35]–[37]. The plasma overspray process involves the ignition of a high frequency arc between an anode and cathode; as gas flows between the electrodes, it is ionized, thereby developing a plasma plume several centimeters in length [35], [36]. The coating powder is injected into the plasma and melted as it is propelled onto the turbine part.

Kinetic spraying techniques of applying protective coatings to different surfaces is not as widely used as those methods previously mentioned since it is the newest development of spray technology [38]. Few companies have the technology to execute coating in this manner; therefore, the market for cold spray has not reached its potential. In cold spray, compressed gases accelerate the coating powder to supersonic speeds as it impacts the surface of the part of interest [36], [38]. Some particles become embedded within the surface of the part, thus creating a gradient between the feedstock material and the part being worked on. The final layers are then heated to form one smooth coat [38].

All three methods vary in the quantity of the coating powder that leaves the nozzle versus how much adheres to the turbine part, but the inefficiencies are always great enough to require powder collection during and post-spray. A range from 50% to 80% of the coating powders ends up on the spray booth floor or in the filters, with the exception of cold spray, which reports closer to a 90% efficiency [38], [39]. The airborne powders are collected through a robust system and put into drums while the settled powders on the floor are collected and added to these drums. The collected spent metal and ceramic powders, which are expensive to handle and dispose of, have the potential to generate profit when reclaimed [40]. The commercial aviation industry's standard practice is to reclaim this collection of powders by selling the drums to a company that is able to separate the valuable materials which in turn are sold to a smelter. In this way, the company not only generates revenue from its spent material, but additionally reduces the need to mine for the metals and minerals that compose the powders.

The thermal spray process also involves a multitude of materials associated with the preparation of a part before and after the thermal spray coatings are applied. The particular surface in need of spray coating must be cleaned and treated either chemically or mechanically and then roughened in order to increase the surface area for material bonding between the thermal spray and the part's surface [35]. The engine part is typically grit-blasted with materials such as chilled iron, steel grit, silicon carbide, or dry corundum, and depending on a company's processes, may be included in the overall waste or recycling stream [35], [41]. Furthermore, the materials associated with the overall process such as rags, tape, filters, and sludge will contain thermal spray or blast media. There is an opportunity to reclaim some of the valuable powders from these items or at a minimum to include them in the recycling stream for ease of the generator.

The spent anti-oxidation and TBC powders are considered hazardous waste due to their explosivity and harmful effect on the environment and human health if disposed of improperly. As aforementioned, hazardous wastes can avoid being classified as such if they can be used as a secondary material instead. When the smelter purchases the powders and can use them as an ingredient toward another product, the powders are no longer considered a waste and no longer fall under the strict RCRA standards as according to 40 CFR 261 [9]. Therefore, commercial aviation maintenance processes promote EPA initiatives to include the Pollution Prevention Act by minimizing hazardous waste production and reducing demand for new mined materials.

Problem Statement

The USAF's depot-level maintenance bases produce hazardous wastes analogous to maintenance plants in the commercial aviation industry. The largest industrial base in the Air Force, Tinker AFB, produces a hazardous waste stream composed of spent thermal spray coating powders. As opposed to its commercial aviation equivalents, Tinker AFB does not partake in the reclamation or recycling of the powder waste. Instead, Tinker AFB must pay disposal fees through the Defense Logistics Agency for each drum of hazardous waste produced. Disposing of the plasma overspray hazardous waste stream in a landfill is expensive and could be avoided. Through its current practices, Tinker AFB is not capitalizing on potential monetary savings. In addition, Tinker AFB may be missing an opportunity to improve their compliance with RCRA and the Pollution Prevention Act through source reduction and the minimization of hazardous waste disposal.

Research Objective

The objective of this research is to analyze Tinker AFB's thermal spray waste stream and current disposal method to determine the feasibility of recycling the waste stream and to quantify any monetary saving or profit potential if the waste was treated differently.

Research Questions

1. How much spent thermal spray material and associated process materials are generated on average by Tinker AFB each year?
2. How much does Tinker AFB spend on its local and DLA contracts to dispose of spent hazardous coating powder waste and associated materials each year?
3. What is the marketability of the spent thermal sprays generated by Tinker AFB and how much money would Tinker AFB save and/or gain from its reclamation?
4. Are there changes to current operations that could positively affect the hazardous waste stream's ability to be reclaimed or the waste stream's value?
5. Has Tinker AFB ever recycled its thermal spray waste, and if so, why were these efforts halted?
6. If, based on current levels of generation rates, the depot-level maintenance bases can save money by reclaiming the coating powders, what is the expected rate per quantity generated?
7. If Tinker AFB can save money by reclaiming thermal spray powders, what actions would be required through the DLA contract and any other agency, in order to implement the reclamation process?

Scope and Limitations

This research will be limited to the spent thermal spray coating material waste generated from calendar year 2003 to September 2019 by Tinker AFB available through an online program used for tracking hazardous waste generation and disposal. Since Tinker AFB uses 26 different spray materials, analyzing the physical and chemical properties and the hazards each material poses and their recyclability is beyond the scope of this thesis. Instead, the thermal spray process at Tinker AFB was scrutinized in order to determine a waste stream most representative of the overall composition of the hazardous thermal spray waste leaving the installation. This resulted in 13 materials that represent the different primary types of coatings as well as the most used materials at Tinker AFB.

Currently, a portion of the thermal spray waste stream must be handled by AFRRAD due to its content of uranium and thorium. At small enough quantities, these waste streams can be sampled; however, accumulation in an entire 55-gallon drum may result in breaching radiation limits under current Air Force and DoD practices. This waste was considered in initial market analysis but otherwise disregarded in this research since the DoD is currently working toward a new classification and handling process of thermal spray waste with very low levels of radiation. Furthermore, the ability to recycle wastes with radiation is limited to a small number of companies that require RCRA permits and advanced training, which would hinder the ability to complete the radioactive materials' recyclability analysis in the timeline of this research.

This research is based on the current practices performed in the year 2019, and addresses rules and regulations published up to 21 October 2019. The market analysis of the waste stream recyclers will be limited to vendors in the United States and based on 2019 pricing and market values. Due to time constraints, only one company was able to sample the thermal spray hazardous waste stream. If the research results in significant findings, this research could be applied to other US Air Force depot-level maintenance bases, Hill AFB, Utah, and Robins AFB, Georgia, in order to determine if reclaiming thermal spray waste in those locations is in their better interest.

II. Literature Review

Chapter Overview

The purpose of this chapter is to gain understanding of thermal spray use in the aviation industry and at Tinker AFB. This literature review also investigates Tinker Air Force Base thermal spray disposal and transportation, thermal spray waste value, recycling opportunities, and the importance and challenges of reusing thermal spray materials.

Available Thermal Spray Technologies

Although there are a multitude of anti-oxidation and thermal resistant coating methods, they are relatively similar in nature. Each method utilizes a feedstock substance and a specific temperature range which is calculated concurrently with material's velocity in order for the material to have the proper characteristics for the surface it is propelled toward. Flame spray, plasma spray, electric arc spray, and cold spray are the four main categories of coating powder applications. The flame spray method can be accomplished through four developed systems: powder flame spray, wire flame spray, detonation gun, and high velocity oxygen fuel (HVOF).

The powder and wire flame spray systems are nearly identical since the difference between them stems only from the form of the feedstock material. These two methods of flame spray were the first thermal spray techniques developed and are still in use today [36]. The flame spray techniques rely on the combustion of fuel gases, typically acetylene and oxygen, to generate the heat required to melt the feedstock material, which is fed into the spray gun [36], [38], [42]. The expanding gas and air jets accelerate the molten material particles toward the surface of the part [36]. The wire flame spray does tend to experience more complete and uniform melting which leads to a denser and smoother coating than powder flame spray [36]. The gas flow rates and fuel-to-oxygen ratio are the controls used to optimize the feedstock particle deposition on the substrate surface. The particles are typically accelerated to speeds of 260 ft/s with jet temperatures of approximately 4700 °F [36].

Powder and wire flame spray are applicable for almost any coating material from polymers to ceramics [36], [42]. These flame spray methods are advantageous for having low capital investments, low operating and maintenance costs, and high deposition rates [42]. Higher deposition rates lead to less wasted feedstock material and less material needing to be disposed of or recycled. Disadvantages include lower bond strengths, higher porosity, and significant heat transfer to the part being sprayed [42]. Tinker AFB operates powder flame spray in one of its booths [43].

The detonation gun flame spray method increases bond strengths and decreases the porosity of the applied coating, but it has a greater problem with heat and momentum transfer from particles to the substrate than the conventional flame spray [36], [42]. The detonation gun also uses acetylene and oxygen for fuel gasses, but they are mixed with a small pulse of feedstock powder and fed into a barrel where it is ignited with a spark plug [42]. The pressure wave from the ignition heats and propels the particles toward the part [36], [42]. Each cycle requires a round of nitrogen to flush the barrel, which limits the spray frequency to a range of 3-6 Hertz and produces enough noise to require sound-proofing of the enclosure [36]. The feedstock particles reach speeds of up to 2,625 ft/s [36].

The detonation gun flame spray technique can be used for any metallic, ceramic, or cermet feedstock material [36], [42]. This method is able to provide a resulting layer with great bond strength, one of the densest and hardest products of thermal spray applications, and is often demanded for commercial aircraft engines [36]. One disadvantage of the detonation gun flame spray is that the particles are deposited at such high speeds that they exhibit residual compressive stress rather than the desired residual tensile stress. This limits how thick the coating can be applied and affects the surface's resistance to wear and tear [42]. Tinker AFB does not utilize the detonation gun, which has a higher efficiency for depositing materials. This is a potentially good investment for Tinker AFB that would reduce waste, but the physical requirements and sensitivity of layering for engine parts would need to be investigated further.

Like the detonation gun method, the final flame spray method, HVOF, uses internal combustion, however, the combustion is continuous. A fuel such as propane, propylene, acetylene, kerosene, or hydrogen is mixed with oxygen and fed into a combustion chamber along with the feedstock powder [36], [42], [44]. As the combusted gas exits the spray nozzle, it can reach speeds of up to 6,000 ft/s [36].

HVOF flame spray methods can apply metallic and cermet materials to a surface but have limitations regarding ceramic materials. Ceramics like zirconia and other carbides require higher temperatures in order to melt; therefore, if HVOF is to be used, acetylene must be the fuel material [42]. Although the HVOF system operates at much lower temperatures than other flame spray techniques, it achieves a very high density from the high velocity of the particles, which makes the HVOF method available to use on airplane turbine blades [36]. Two booths in Tinker AFB's depot-level maintenance center apply thermal spray coatings with HVOF [43].

The electric arc spray method is unique in that it does not require a fuel source to provide heat to melt the feedstock. Instead, two oppositely charged feedstock wires are fed through the spray gun into a compressed air stream; as the wires intersect, a controlled arc is created, which melts the metal wire tips [35], [42]. The compressed air acts as the propellant directing the molten particles toward the part's surface. Approximately 65 standard cubic feet per minute (SCFM) of clean air at up to 100 psi is required for the electric arc spray technique, with arcs operating from 15 to 400A dc or 400 to 1500A dc for high throughput systems [36]. There are many factors that affect the stability of the arc such as wire straightness, the tolerance of the wire guide, the power supply, and ensuring the wire is fed at a constant rate [36].

Since the electric arc spray process relies on ductile and conductive wire feedstock, it is unable to spray pure carbide, nitride, or oxide coatings [42]. Recent electric arc spray developments include the ability to use metal wires with a carbide or oxide core [42]. In relation to other spray techniques, electric arc spray is a low cost operation and transfers less heat to the part's surface, but it often creates a rougher surface [36], [42]. Tinker AFB uses electric arc spray in four booths, three of which also have plasma spraying capabilities [43].

There are two plasma spray methods that can be used for applying coatings to part surfaces, one of which uses atmospheric pressures during application and the other which uses a vacuum environment. The conventional method, atmospheric plasma spray, begins with the creation of plasma as an inert gas, typically argon, nitrogen, hydrogen, or helium, passes between a tungsten cathode and a copper anode [36], [42]. The powered opposite charges create an arc that ionizes the gas, and heats it to such high temperature that when it expands it can create supersonic velocities and high pressure [35], [42]. The feedstock powder is fed into the resulting gas stream, which melts the material and sends it to the substrate's surface, reaching speeds from 1000 to 1800 ft/s [28], [33].

The vacuum plasma spray technique operates identically to the atmospheric plasma spray technique, except the spraying occurs in a low-pressure chamber with a range of 0.1 to 0.5 atm [36]. The low pressure allows the plasma plume to grow in length and width and therefore the gas reaches higher speeds. The higher temperatures and velocity of the gas and particles results in a denser coating with higher bond strength than the atmospheric plasma spray method and most other techniques [36].

Both atmospheric and vacuum plasma spray methods use plasma that reaches temperatures from 11,000 to 27,000 °F, and therefore it can melt and be used to apply any material as a coating [36]. Plasma spray coatings are denser than most other spray coatings, and coat thickness can be controlled to the sensitivity of 0.5 mm, therefore this method is widely used in the aircraft engine industry [42]. It was undisclosed which plasma spray method is currently in use by Tinker AFB in aircraft part repair, but it is most likely atmospheric [43], [45]. The majority of Tinker AFB's coating powders are applied using plasma spray, which takes place in 21 of the 27 booths.

The newest development of spray methods is the cold spray method, which was given its name from utilizing much lower carrier gas temperatures, ranging from 32 to 1290 °F, often lower than the feedstock powder's melting point [42]. To begin, pressurized gas is heated and sent into a converging or diverging nozzle which accelerates the gas to sonic and then supersonic speeds as it expands and cools [36]. The feedstock powder can be introduced in the high-pressure side of the nozzle, or, as some experimental techniques have been successful with, downstream [36]. The gas speed ranges from Mach 2 to Mach 4, and the particles' velocities can reach 3940 ft/s which creates a desired surface on the part of interest through impaction [36], [42].

There are many benefits to the cold spray technique, which continue to grow as it is better developed. Cold spray can be used to apply metals, alloys, composites, and cermet [36], [42]. Since the temperature of the feedstock particles remains relatively low, the material avoids oxidation, evaporation, residual stress, and recrystallization that can be seen in other thermal spray methods [42]. In addition, cold spray has the highest deposition efficiency which can reach over 90%, therefore reducing wasted feedstock powder [38]. Cold spray is also considered better for the environment than other methods because it does not use combustible fuels or gases and as a result of using lower temperatures it requires only a limited amount of energy [38]. This technique is currently used sparingly in the aerospace industry and in some military operations, though not the operations of Tinker AFB [38], [42], [43], [45].

Since cold spray is a newer method, it does have challenges and disadvantages that have yet to be solved. Not many feedstock powders have been created specifically for a cold spray application and therefore cold spray performance is usually not in its optimal state. [38]. Cold spray technology is not readily available in the current market due to lack of exposure, which also contributes to high capital costs [38]. As cold spray technology is developed, it may become a preferred technology by depot-level maintenance bases like Tinker AFB.

Thermal Spray Materials at Tinker AFB

There are a total of 33 feedstock materials in use by Tinker AFB in 2019 for turbine engine part repair, 26 of which were disclosed to the researcher [43]. Each depot-level maintenance activity using these materials corresponds to either corrosion and oxidation prevention or the application of a TBC. The chemical compositions or names of the feedstock materials as given by the thermal spray operations manager at Tinker AFB are listed in a matrix in Figure 1 which includes which booth(s) the material is applied in as well as the total number of booths each material is used in [43]. The X's annotate when a material is in use for each booth. For the majority of the materials, the supplier names and complete chemical compositions of each material were not provided; however, using a major thermal spray supplier's website, this information was discovered and included in a subsequent section.

Booth	NiAl (450NS)	Al2O3	NiCrAl	NiCrAlY	718	Al Polyester	Al Bronze	CuNi	CuNiIn	Fine CrC-NiCr	Coarse CrC-NiCr	H.E. CrC-NiCr	Fine WC-Co	Coarse WC-Co	YSZ TBC	T400	T800	45 VFNS	Wire NiAl	Wire NiCrAl	Wire Moly	HVOF 718	HVOF WC-Co	HVOF NiCrAl	Flame NiAl	Flame Graphite
1	X	X		X					X	X					X											
2	X	X									X															
3	X	X	X		X												X									
4	X	X			X		X																			
5	X		X		X			X		X							X									
6	X		X	X				X		X				X	X	X	X									
7	X		X	X	X	X	X	X		X			X	X	X		X									
8	X							X		X																
9	X	X	X		X					X				X												
10	X	X	X		X									X		X		X								
11	X	X			X											X										
12	X		X	X	X		X	X							X	X			X	X						
13	X	X											X				X									
14																						X	X	X		
15	X			X	X	X						X			X											
16	X				X	X																				
17																						X	X	X		
18																									X	X
19																						X	X	X		
20	X	X					X	X	X	X			X													
21	X						X		X	X			X													
22																			X	X						
23	X							X		X			X			X			X	X	X					
24	X	X																								
25										X									X	X						
26	X			X								X			X											
27	X	X											X													

Figure 1. As-given Tinker AFB Thermal Spray Material and Booth Matrix

Without knowing the precise quantities of each material used in each booth or over any period of time, there are several approaches that could be applied to determine which feedstock materials should be studied and analyzed for this research. There could be an advantage to addressing the material used in the most booths, under the assumption this material would have the highest composition in the waste stream. Another option would be to focus on booths with the fewest materials sprayed in them in order to attempt to more accurately predict the chemical composition of the waste stream. Additionally, exploring a single booth with the most materials sprayed within it could account for the complexity of the waste stream and identify which booth should be sampled to assess the value of the thermal spray waste at Tinker AFB. Finally, analyzing one material of each main coating type (metal, bond coat, TBC), could provide insight into how each affects the value of the waste stream.

The materials used in the most booths is a nickel aluminum compound (NiAl), which is applied in 21 of the 27 total booths. This material is specifically analyzed in a following section. The next highest use material is aluminum oxide (Al_2O_3), which is sprayed in 11 booths, followed by the material labeled 718 and a fine chromium carbon and nickel compound (CrC-NiCr), both which are sprayed in 10 booths. Upon exploration, the material 718 is short for Amdry 718, which is primarily composed of nickel, chromium, and iron, and also contains molybdenum, tantalum, niobium, titanium, and cobalt [46]. These three materials (Al_2O_3, Amdry 718 and fine CrC-NiCr) include metals that have the most value to industrial recyclers and therefore have the largest effect on the thermal spray hazardous waste stream's profitability. Amdry 718, Al_2O_3, and fine CrC-NiCr will be explored further in subsequent sections. These materials have the highest frequency of use, and not necessarily the highest mass in the overall waste stream, but can still provide insight into the waste stream's composition.

The booths with the least material use variation are Booth 18, Booth 22, and Booth 24. Only two powders are sprayed in each of these booths, which makes the waste stream composition from each booth more predictable than the other booths. Booth 18 is the only booth that uses the flame spray method to apply NiAl and graphite. Booth 22 is the only booth that uses only the electric wire arc method and sprays NiAl and a nickel chromium aluminum compound (NiCrAl). Finally, Booth 24 is a brand-new plasma spray booth which is not yet operational but will eventually apply NiAl and Al_2O_3 [43]. The waste streams resulting from these booths would likely have a substantial amount of both nickel and aluminum, which are valuable recyclable materials.

Booth 7, a plasma spray booth, has the largest number of material sprays applied in it with a total of 12 different materials. This booth may have the most representative sample of the overall waste stream and includes NiAl, NiCrAl, NiCrAlY, Amdry 718, Aluminum (Al) polyester, Al bronze, a copper nickel compound (CuNi), fine CrC-NiCr, a fine and coarse tungsten carbide with cobalt compound (WC-Co), YSZ TBC, and T800. Although the feedstocks shared by Tinker AFB in this research are not all listed as their product names, suppliers use a numbered system to log each material. The NiAl is a product called Metco 450NS, the NiCrAl product is labeled as either Metco 443NS or Amdry 960, which share a Safety Data Sheet (SDS) and composition, and the NiCrAlY spray is called Amdry 962. The Al bronze used in this booth is Metco 51NS, and the Al polyester is Metco 601NS. The CuNi alloy is either Metco 57NS, Metco 58NS, Amdry 500C or Amdry 500F, which have nearly identical compositions, and the fine CrC-NiCr compound is from the WOKA 7100 series. WC-Co comes in both fine and course form in the products Metco 5810 and Metco 5812. The researcher was unable to find the product T800 on any supplier website, therefore this powder's chemical composition remained unknown throughout this paper. The product labeled YSZ TBC is an yttria stabilized zirconia ceramic powder, Metco 204NS.

The materials applied in Booth 7 are representative of all three coating types, where the Metco 450NS, Metco 443NS/Amdry 960, Amdry 718, Metco 51NS, Metco 57NS/Metco 58NS/Amdry 500C/Amdry 500F, WOKA 7100, Metco 5810 and Metco 5812 are different metal coats, the Amdry 962 is a bond coat, the Metco 601NS is used as an antioxidation and friction reducing coat, and Metco 204NS is the ceramic TBC. Since the waste stream resulting from operations in Booth 7 is complex and includes all three types of coatings, it presents the best option to analyze as a representation of the entire waste stream. Additionally, the aluminum oxide is not sprayed in Booth 7, but it is the second highest used material at Tinker AFB; therefore, it was also included in the analysis but would not be expected to be in samples from Booth 7. The material analysis will focus on the above thermal spray materials since analyzing all 21 feedstocks exceeds the limitation of the study period.

The thermal spray powder applied in the most booths and in use within plasma spray Booth 7 at Tinker AFB is the metallic powder NiAl, used for oxidation resistance and corrosion protection. The feedstock powder, Metco 450NS, is overwhelmingly nickel with some aluminum and an organic binder. The reported contents for each element are 94% for nickel, 4-5% for aluminum, and 1-2% for the organic binder [47]. Exposure to this material can cause irritation to eyes, the respiratory system, and skin [47]. As previously noted, nickel is a carcinogen to humans; therefore, Metco 450NS exposure can lead to cancer [47]. The powder is not flammable or explosive but poses a large threat to the environment if a spill occurs. The ecological toxicology report for Metco 450NS is based on nickel exposure in the aquatic environment and reports a median lethal dose (LC50) of 96 hours for a freshwater stinging catfish [47]. The LC50 is the concentration of the compound in water that is lethal for 50% of exposed population.

The NiCrAl compound also in use by Tinker AFB in Booth 7 is either Metco 443NS or Amdry 960. This information was not disclosed; however, these two powders have nearly identical compositions. The ingredients of the feedstock are 73% nickel, 18%

chromium, 5% aluminum, and 1% of each manganese, silicon, iron, and an organic binder [48]. The contents of Metco 443NS and Amdry 960 pose an exposure hazard and can result in eye irritation and redness, allergic reactions on skin, respiratory irritation, and could lead to cancer [48]. Like other fine metallic powder, this feedstock powders can be explosive if the dust becomes suspended in the air [48]. Furthermore, NiCrAl powder is harmful to the aquatic environment, and the materials' SDS warn users about the toxicological impacts of water contamination for both manganese and nickel [48].

The feedstock thermal spray material Amdry 718 is used as an anti-oxidation and corrosion resistant layer. It is composed of 53% nickel, 19% chromium, 18% iron, 3% molybdenum, 1-2.5% tantalum, 1-2.5% niobium, 1% titanium, and 1% cobalt [46]. As with Metco 450NS and the Metco 443NS/Amdry 960, Amdry 718 poses the same hazards with nickel and chromium, in addition to cobalt's negative exposure and environmental effects [46]. Cobalt has a high bioaccumulative potential and is known to cause cancer [46].

The Al bronze spray material in use by Tinker AFB is Metco 51NS and is also used in Booth 7. The ingredients to this feedstock are 89% copper, 10% aluminum, and 1% iron; it can irritate eyes and the nose, throat and lungs, but is not known to have significant effects with skin contact or ingestion [49]. Metco 51NS is reactive with oxidizing materials and is subject to explosions if fine dust clouds are created [49]. Furthermore, copper is a contaminant and is dangerous if a spill reaches the aquatic environment [49].

The CuNi compound, which is either Metco 58NS or Amdry 500, serves as an antioxidation thermal spray. The chemical element composition of the spray is 59%

copper, 38% nickel, and 5% indium, which is not flammable but is hazardous since it is a suspected carcinogen [50]. The copper nickel compound can cause allergic skin reactions and damage to organs with repeated exposure and is very toxic to aquatic life. These effects have long lasting impacts [50].

The fine CrC-NiCr is used as a corrosion and wear preventer and is part of the WOKA 7100 series from the supplier. The majority of the WOKA 7100 series has a composition of 80% trichromium dicarbide, 16% nickel, and 4% chromium [51]. As with other thermal spray powders, materials in the WOKA 7100 series are a hazard since they can form combustible dust concentrations in air and are incompatible with oxidizing materials [51]. Additionally, the chromium and nickel content makes the WOKA 7100 series carcinogenic; they can also cause eye irritation, respiratory tract irritation, and skin irritation [51]. The nickel in this compound is also toxic to the environment in an aquatic setting.

The fine and coarse WC-Co compounds Metco 5810 and Metco 5812 share an SDS since their compositions are identical. These products contain 87% tungsten carbide, 12% cobalt, 0.1-1% iron, and 0.1-1% organic binder [52]. As with most metallic powders, exposure to the WC-Co can cause eye and respiratory irritation or a skin reaction; however, ingestion of this product is suspected of damaging fertility [52]. This powder is not flammable in the presence of open flame or sparks; therefore, its largest hazard is as a toxin and carcinogen to people and as a toxin to the rest of the environment, especially the aquatic environment [52].

The bond coat material applied through plasma spray in Booth 7 is composed of primarily metals, labeled by the supplier as Amdry 962, and has an elemental makeup of

67% nickel, 22% chromium, 10% aluminum, and 1% yttrium [53]. The contents of this corrosion prevention and turbine part repair powder are considered a hazardous material due to its negative exposure effects and ignitability. Amdry 962 can cause irritation and organ damage, and it contains material that could cause cancer [53]. When the powder is sprayed, there is a likelihood that it will form hexavalent chromium, a carcinogen which requires strict exposure limits and emission limits as set by the EPA and the Occupational Safety and Health Administration [44], [53]. Additionally, since Amdry 962 and other metal coating powders range in diameter from 10 to 100 µm, any creation of dust composed of this powder is susceptible to combustion and explosion [53], [54].

In addition to dangers during material handling, Amdry 962 and metal powders pose a danger to the environment if spilled or disposed of improperly. Fine nickel and chromium, the two main ingredients in Amdry 962 and a few other thermal sprays addressed in this research, easily infiltrate aquatic environments. The acute nickel lethal concentration (LC50), or concentration of nickel which would kill 50% of tested fish over an exposure period of 96 hours, is only 2.3 ppm [53]. The acute chromium LC50 is 13.9 ppm over an exposure period of 96 hours [53]. It does not take a large concentration of the metals in the aforementioned metallic thermal spray powders to affect the aquatic environment in a negative way.

Another plasma overspray feedstock powder used in Tinker AFB depot-level maintenance operations is an Al polyester. This material, Metco 601NS, acts as an oxidation and corrosion resistant coating that benefits from aluminum’s strength and polyester’s low friction qualities [55]. Metco 601NS is composed of 53% aluminum, 40% poly(oxy-1, 4-phenylenecarbonyl), and 7% silicon [56]. The feedstock powder is hazardous since it is a combustible dust and, if a fine cloud is created, an explosion may occur [56]. It poses a danger to humans since as it is exposed to a flame, carbon monoxide, carbon dioxide, and metal oxides can be produced, and inhalation or exposure can lead to eye and respiratory tract irritation [56]. There is no ecological toxicity information reported by Oerlikon Metco regarding Metco 601NS.

The plasma-sprayed TBC in use in Booth 7 by Tinker AFB is applied to aircraft parts on the same days as the bond coat Amdry 962 [43]. The ceramic TBC powder, Metco 204NS, is composed of 85-91% zirconium dioxide, 7.5-15% yttrium oxide, and 0.1-1.8% hafnium dioxide [57]. Exposure to Metco 204NS and other ceramic powders is less severe in consequence than the metallic powders. Potential health effects include respiratory irritation and eye irritation [57]. The SDS reported by the supplier reports that there is no information regarding the toxicology or ecological information of zirconium dioxide, yttrium oxide, and hafnium dioxide [57]. However, Metco 204NS is considered hazardous due to its reactivity with strong acids and alkalis [57].

The aluminum oxide that is not used in Booth 7 but is applied in the highest number of booths as Tinker AFB is Metco 6103, a material reported as 99.9% Al_2O_3 [58]. If ingested or inhaled, Metco 6103 can cause damage to the lungs, the nervous system, the upper respiratory tract, skin, and eyes [58]. Unlike the majority of the thermal spray materials addressed in this section, Metco 6103 does not have any known significant effects or critical hazards if spilled or released into the environment [58].

Thermal Spray Hazardous Waste from Tinker AFB

The plasma overspray process is used to coat the turbine parts with any of the 13 products. The Metco 450NS, Metco 443NS/Amdry 960, Amdry 718, Metco 51NS, Metco 57NS/Metco 58NS/Amdry 500C/Amdry 500F, WOKA 7100, Metco 5810, Metco 5812, Amdry 962, Metco 601NS, Metco 204NS, and T800 are all sprayed in the same booth; therefore, Tinker AFB collects all unadhered powders through one ventillation system resulting in one collection drum. The composition of this drum will fluctuate depending on what type of aircraft part is being repaired, in addition to the type of repair that is needed. The 12 feedstock powders are not all used simultaneously, instead only one can be applied at a time. The Al_2O_3, Metco 6103, is applied in 11 booths, all of which spray other materials as well. Therefore, any waste streams from these booths will also be mixed with other products. Operations in the booth are not halted to collect each powder stream at the end of a spray of that type. The 55-gallon drum collects the waste streams until it is filled and must be replaced. Without an attempt to keep the leftover coating powders separated, the metals, bonds, and ceramics comingle in the collection barrels.

Through 40 CFR 261.17, the EPA limits the amount of time hazardous waste may accumulate according to whether the producer is a Very Small Quantity Generator, Small Quantity Generator, or a Large Quantity Generator [9]. Since Tinker AFB is a Large Quantity Generator, it is limited to 90 days of accumulation time before the hazardous waste must be removed [59]. The thermal spray hazardous wastes generated by Tinker AFB must be tested periodically in order to determine if the metals content in each drum exceeds the sample reporting limit concentration set by the EPA. Although testing is only required annually, Tinker AFB samples every drum before it leaves the installation. The tests are performed in order to determine whether the waste stream exceeds limits for certain elements. Although the precise quantities of each element were not able to be determined in this research, the following test results can provide some insight into the valuable materials composition of the waste stream.

The Tinker AFB Environmental Laboratory used three to five sampling methods in accordance with EPA standards to detect metals in the thermal spray waste [60]–[62]. One of the most renowned of these testing procedures is the toxicity characteristic leaching procedure (TCLP), which determines how mobile a substance of interest is in its liquid, solid, or multiphase state [63]. The TCLP for the thermal spray coating powders accurately assesses the dangers of a spill or improper disposal. The Tinker Environmental Laboratory Sample Analysis Reports from 2016, 2017, and 2018 show variation in the waste stream metals composition. The metals composition data for each sample in each year are shown in Table 1.

Chromium and nickel are the only two elements with concentrations consistently greater than 20 ppm, which is to be expected since they are ingredients of Amdry 962, Metco 450NS, Metco 443NS/Amdry 960, Amdry 962, WOKA 7100, and Amdry 718 [46]–[48], [51], [53], [53], [60]–[62]. All other metals' concentrations were below detection limits (BDL), with exception of inconsistent concentrations of cobalt (2016-2018), copper (2016-2017), manganese (2016-2017), molybdenum (2016-2017), antimony (2017), and thallium (2016-2017) [60]–[62]. These concentrations can be traced back to individual thermal spray materials, with the exception of antimony and thallium, which may exist in the unexplored material T800 or in an antiquated powder no longer in use for thermal spray by Tinker AFB.

Table 1. Tinker Environmental Laboratory Sample Analysis Reports 2016-2018

		Sample Concentration (ppm)		
Element	Reporting Limit	2016	2017	2018
Silver	0.2 ppm	BDL	BDL	BDL
Arsenic	0.2 ppm	BDL	BDL	BDL
Barium	0.2 ppm	BDL	BDL	BDL
Beryllium	0.2 ppm	BDL	BDL	BDL
Cadmium	0.2 ppm	BDL	BDL	BDL
Cobalt	0.2 ppm	>20	>20	1.06
Chromium	0.2 ppm	>20	>20	>20
Copper	0.2 ppm	12.8	0.23	BDL
Manganese	0.2 ppm	>20	1.41	BDL
Molybdenum	0.2 ppm	4.19	>20	BDL
Nickel	0.2 ppm	>20	>20	>20
Lead	0.2 ppm	BDL	BDL	BDL
Antimony	0.2 ppm	BDL	2.74	BDL
Selenium	0.2 ppm	BDL	BDL	BDL
Thallium	0.2 ppm	0.52	0.9	BDL
Vanadium	0.2 ppm	BDL	BDL	BDL
Zinc	0.2 ppm	-	BDL	BDL
Mercury	5.0 ppb	BDL	BDL	BDL

BDL – Below Detection Limit

Another characteristic of the thermal spray hazardous waste stream from Tinker AFB is that some collection barrels occasionally exceed the limits for natural thorium and natural uranium [23]. In 2017, Tinker AFB reported that its thermal spray waste stream exceeded the exempt activity limits for natural uranium and natural thorium in accordance with 49 CFR 173.436 [23]. To comply with 49 CFR 173.436, Tinker AFB must document the isotopes on shipping paperwork but is not required treat the individual radioactive drums as a low level mixed waste since those levels of radioactivity are higher than the Tinker AFB thermal spray waste's levels [23]. According to regulations, if the contents of the thermal spray waste stream were to ever reach or exceed a combined composition of 0.05% by weight for uranium and thorium, Tinker AFB would need a permit from the RIC to continue their operations [25], [64]. As mentioned in the introduction, Tinker AFB manages the drums with radiation as low level radioactive waste through AFRRAD as a precaution. The closest Tinker AFB came to exceeding the 0.05% by weight was in 2017, where the thermal spray coating wastes reached a maximum of 0.03% by weight for uranium and thorium [23]. The waste stream will continue to need monitoring in order to assure Tinker AFB's compliance. The metals content and radioactivity could affect the waste stream's potential to be considered a secondary material.

Thermal Spray Hazardous Waste Disposal Methods

While the DLA would not disclose the current disposal method and location of the thermal spray hazardous waste, conversations with AFRRAD and Tinker AFB environmental sections led to an unofficial conclusion that the material is buried underground in concrete encasements. If the thermal spray hazardous waste powders were placed directly in a landfill, the site would require a double liner, double leachate collection and removal system, leak detection, runoff, and wind dispersal controls [65]. Since the thermal spray hazardous waste poses a significant threat to the aquatic environment, it would be especially important to monitor and collect leachate, and to ensure there are no leaks. For this reason, hazardous wastes containing metals are often immobilized since other treatment methods do not provide the required removal of the hazard [65].

Thermal Spray Waste Transportation

In order to assess potential disposal or recycling options, it is important to understand transportation regulations set through federal code and any additional requirements from Oklahoma and other pertinent states. The Hazardous Materials Transportation Act of 1975 gave the United States Department of Transportation (DoT) regulatory authority over the transportation of hazardous waste and hazardous material through 49 CFR, Parts 100-185 [24]. The Pipeline and Hazardous Materials Safety Administration (PHMSA), given the responsibility of writing the applicable regulations, has the authority to inspect manufacturing, fabrication, marking, maintenance, reconditioning, repair, testing, and distribution of hazardous materials and shipments [24]. These regulations are applicable to interstate, intrastate, and foreign carriers by rail, aircraft, motor vehicle, or vessel with a hazardous material container.

The general requirements from 49 CFR Parts 100-180 include registration, proper hazardous material classification, packaging, and labeling. Federal agencies like the DoD often make hazardous material shipments through commercial carriers and are fully subject to transportation laws. When the transportation is accomplished with a military vehicle or aircraft, it is not subject to federal jurisdiction, but the state the materials are passing through may require conformation to 49 CFR Parts 100-180 [24]. Additionally, if the military is to sell a product with any hazardous material, it is considered to be engaged in commerce and is required to comply with 49 CFR [24].

A Hazardous Materials Safety Permit is required for transportation of Class 7 materials, which are radioactive materials, and for more than 55 pounds of Division 1.1, 1.2, or 1.3 materials, which are explosive materials [24], [66]. Since the thermal spray waste materials are Division 1 materials, any transportation of the waste material will require a Hazardous Materials Safety Permit by the carrier. Although the very low levels of radioactivity of the thermal spray waste do not require a Class 7 classification, if the waste stream is ever sampled and breaches the uranium or thorium limits aforementioned, it will also require a permit for radioactivity [23], [24].

Shippers are required to identify the hazardous material and to reference 49 CFR 172 for all materials regulated by the DoT. Other responsibilities can include providing warning labels, packaging, markings, employee training, etc. [24]. Often shipper responsibilities overlap those of the carrier in order to provide confirmation of each other's actions. Carriers must maintain responsibility for material compatibility, shipping paper, vehicle marking and placards, blocking, incident reporting, security plans, and training [24].

Certain hazardous materials can be considered consumer commodities if they are intended for retail sale [24]. These commodities, which have many similarities to secondary materials, are called Other Regulated Material – Definitions (ORM-D) and are subject to regulations but present a limited hazard and therefore looser regulations [8], [24]. Therefore, if the thermal spray waste material was sold to a vendor, it would no longer be a hazardous waste according to 40 CFR 261.2 (c)(3) and could be transported as an ORM-D material [9], [24].

Transportation of the thermal spray waste from Tinker AFB to its disposal location requires carriers to comply with the state of Oklahoma's transportation regulations as well as the regulations set by any other state the waste travels through. The DLA representative contacted was unwilling to disclose the current final destination of thermal spray hazardous waste, therefore, with exception of Oklahoma, the specific state requirements were left unexplored. The Oklahoma Corporation Commission Transportation Department requires hazardous material and hazardous waste transporters to apply for an additional permit called the Alliance for Uniform Hazmat Transportation Procedures Permit Alliance Permit (Alliance Permit) which qualifies for transportation within and between Michigan, Nevada, Oklahoma, and West Virginia [67]. If only hazardous material is transported and it remains in Oklahoma or an Alliance Permit state, additional permits are not required.

All shipments in Oklahoma are still required to have a United States DoT number and intrastate license[67]. Interstate commerce requires registration under the Unified Carrier Registration program, and if hazardous waste is transported, the state EPA must issue the carrier a number [67].

Additional Thermal Spray Secondary Material Recycling Opportunities

As previously noted, metal is the most efficient material to recycle, since its properties can be fully restored through recovery efforts [13], [40], [68], [69]. However, the profitability of processing secondary metals depends on the metals concentration in the secondary material it is embedded in [68]. In order to extract the desired metals from a secondary material, it must go through chemical processing in order to strip metal atoms of oxygen or sulfur, or of alloying elements, which can be accomplished by utilizing the different melting points of metals [69], [70]. Thermal spray secondary materials are considered “old scrap metal” since they contain a mixture of metals, alloys, and non-metallics that build up with each recovery cycle [69]. These industrial metal substances are typically treated in a pyrometallurgical process that yields an alloy and an environmentally inert slag [69], [70]. Depending on a company’s specialty, it may focus on optimizing the extraction of one metal over another, but most metal recyclers will emphasize efforts to reclaim aluminum, iron, copper, lead, and zinc [69].

In addition to the aforementioned metals recycling, existing literature conflicts as to whether collected spent ceramic powders can be returned directly back into the feedstock of the thermal spray process. One study claimed that the powders that do not adhere to turbine engine parts are often too deformed from impact with the part’s surface to pass the high standard required by the aviation industry [39]. Another study suggested an intermediate step of making the dust into a slurry and spray drying it was enough to make their ceramic and metallic powders usable as a feedstock [71]. However, this study ran an experiment in a thermal spray shop and did not specify the level of sensitivity the product required in order to meet the adhesion and hardness standards.

Tinker AFB’s use of the ceramic powder Metco 204 presents a capitalization opportunity in the ceramic tile market. Although Tinker AFB would not sell any material directly to a ceramic producer, generating an ingredient in the tile-making process makes its waste stream valuable. The YSZ byproduct of the thermal spray process is valuable as a frit for a ceramic white glaze, which is a high value product [39]. However, Metco 2014 and other stabilized Zirconia powders often contain too much metal pollutant to be used purely without treatment [39]. An additional step of sieving was enough to make the Zirconia pure enough to be combined with quartz and used for glazes, but the color standards were not met with YSZ powders that were too polluted with metal, a consequence of having combined waste streams in a thermal spray booth [39].

Before an engine part is coated using plasma spray, HVOF, flame spray, or electric arc spray, it must be grit blasted and prepped for coating. Grit blasting materials can include glass, sand, steel and other metals, or plastic depending on its purpose of paint, residue, or metal removal [72]–[74]. Many of these materials can be recycled or repurposed. For example, sand and steel blast media can be used as a fine aggregate in asphalt concrete with little to no degradation in strength performance [64]. However, if the steel or metal blasting material exceeds metals regulation limits in a TCLP, the waste must be disposed of as a hazardous waste and can no longer be incorporated into the asphalt concrete [75]. Tinker AFB includes blast media disposal in its agreement with the DLA, and therefore does not recycle or reclaim these materials.

Thermal Spray Waste Value in the Current Market

HVOF, plasma overspray, and cold spray waste and by-products contain components with some value that are desired by certain industries. There are some industrial recyclers willing to pay for coating powder waste since it is an ingredient to their production process. Sending overspray materials to landfills has a negative effect on the environment, and on the generator’s budget. Therefore, a recurring coating powder cost can be turned into a potential profit.

Although overspray materials may be mixed, qualified recyclers can take the entire waste stream and separate it into a product than can be resold to manufacturers [41]. Tinker AFB and other depot-level maintenance bases and commercial aviation equivalents with comingled ceramics and metal waste can still profit from a mixed waste stream. However, the value, and therefore profit margin, can be increased if lower valued materials are separated. Ceramics and aluminum oxide have a much lower value than materials like tungsten, chromium, cobalt, nickel, zinc, and chrome oxide [41]. The cost of separating these materials would have to be compared to the benefits of a higher valued waste stream.

The agglomeration of feedstock chemical compositions shows the potential value in the thermal spray waste stream. nickel, aluminum, chromium, molybdenum, titanium, cobalt, and copper are particularly valued by recyclers. As of 21 November 2019, aluminum was valued at $0.79/lb, copper at $2.65/lb, nickel at $6.57/lb, zinc at $1.07/lb, and cobalt was valued at $16.10/lb [76]. Furthermore, indium is considered one of the most precious metals on Earth, meaning it is rare in existence and difficult to extract [77], [78]. Although the specific prices and values vary day-to-day, the value of metal is predicted to escalate as it becomes more difficult to mine for and process these materials [13]. It is also important to understand that although the prices for pure metallic elements are high, since thermal spray is a mix of ingredients that are difficult to separate and used as alloys, the powder’s value per pound is significantly lower. The collector and/or smelter must account for the effort put forth to extract the valuable materials, while still remaining profitable; therefore, they will offer much less than the market price for the metals [79].

There are other materials in the thermal spray process that can be valuable to a smelter. Before an engine part is coated using plasma spray, HVOF, flame spray, or electric arc spray, it must be grit blasted and prepped for coating. In standard industry practice, the waste products created with these processes can be included with the plasma overspray waste in order to increase the volume of recycled materials and eliminate any cost associated with their disposal [41]. However, as of 21 October 2019, a change to AFI 32-7042, *Waste Management*, added a section stating that spent blast media will be sampled to make a hazardous waste determination. If the test indicated the spent blast media is hazardous, it cannot be treated as a secondary material under RCRA [80]. Non-hazardous spent blast media may still be recycled. This limits the quantity of blast media that may be recycled at Tinker AFB.

Separating the spray materials to increase their value would involve multiple spray booths in which each material is segregated by booth. Currently, Tinker AFB sprays up to 12 powders in one booth and alternates the days each type of spray is used. For example, Tinker AFB personnel may repair one part beginning with the spraying of Amdry 962 and Metco 204NS and the next day change operations to the spraying of 450NS and 601 NS [43]. Capping and removing drums between days the materials are changed and further separating materials to segregate the four individually would require additional manpower, time, and likely additional booths. The separation of thermal spray would be even more complex in booths with more sprays in use. Tinker AFB's current plasma overspray booths, as a turnkey operation, are approximately $1M each. The benefit to cost analysis of additional operating systems aimed to minimize material comingling was not performed in this thesis but is a consideration for additional research.

Thermal Spray Secondary Material Transportation

Since the thermal spray hazardous waste materials become a sellable product, they can be handled as secondary materials and a commercial commodity. As aforementioned, secondary materials and commercial commodities are susceptible to less stringent regulations [8], [24]. This means that during shipping of the plasma overspray secondary material to the purchaser, the drums no longer need to be classified as a hazardous waste [41]. The shipment must still comply with federal and state regulations of the locations of the purchaser and producer. For shipments of secondary material leaving Tinker AFB, Oklahoma used to require transporter registration, but now simply requires the assurance of safe transport without spills, leaks, dumping, or hazardous waste mixing [30]. Any additional state requirements from the location of the recycler would need to be complied with, however the recycler will often provide the necessary details [41].

The cost to ship the secondary materials will depend on recycler location, agreements, and material amounts. The distance between Tinker AFB and the recycling vendor will have an impact on the shipment cost. The cost per mile to transfer a secondary material should be calculated in order to compare costs and benefits of possible recycling vendors. Additionally, a recycling vendor may charge to pick up a shipment of secondary material if agreed upon by the material generator. In other words, Tinker AFB could come to an agreement regarding who will have responsibility for transporting the thermal spray spent materials. According to industry practice, Tinker AFB could pay to transport the waste through the DLA, or the fees to transport the material could be deducted from the purchase of the secondary material [40], [41], [81], [82].

Since hazardous waste can only be stored by large quantity generators for 90 days, shipments of the thermal spray hazardous waste material must occur every three months at a minimum [59]. However, since secondary materials are not considered hazardous wastes, they can be stored indefinitely. This implies that Tinker AFB could change the frequency at which the thermal spray spent materials are shipped to a recycler if it was more manageable or profitable. This would need to be done with caution since the materials do not change hazardous properties and are still dangers to human health and the environment.

Importance and Challenges of Recycling and Reusing Thermal Spray Materials

The recycling or reuse of spent thermal spray coating powders is beneficial to the economy and the environment when considering both metals and ceramics. The United Nations Environmental Program released a report in 2013 about the importance of metals recycling, stating that the growing world population cannot continue its current rate of metals consumption without surpassing sustainable resource use [13]. Metals can be recycled almost indefinitely, and use of metal secondary materials would decrease mining and toxic waste impacts to the environment, as well as decrease energy use [13], [68], [69]. Additionally, the cost of mining raw ceramic materials is high economically and environmentally [39].

The World Business Council for Sustainable Development recognizes the need for businesses to be accountable for a portion of the human contribution to climate change [83]. These increasing pressures can be alleviated by the sustainability concepts brought forth by the concept of a circular economy. A circular economy aims to achieve a closed cycle of material flows, which counters traditional practices of creating products without consideration of their end states [84]. The main purpose of a circular economy is to cultivate business practices that implement the concepts of sustainable development [85], [86]. To some businesses, this goal is too vague; however, the idea to evolve into an economy that produces zero-waste would mean economic savings in the long run, as well as lessen negative human environmental impact which should propel greener business practices [87], [88].

As a result of diverging definitions of a circular economy, there are a multitude of principles the thermal spray industry could adopt or reengineer businesses to in order to partake in circular economy efforts. However, most of these principles are easiest to implement with a new business model that requires a reevaluation of supply-chain relationships [84]. Additionally, partnerships with other industries, resource extractors, and companies with similar materials or byproducts are a necessity, as is changing the relationship with consumers [89]. For Tinker AFB thermal spray operations to move toward a circular economy, the installation should work with its thermal spray feedstock supplier, the DLA, and AFRRAD to minimize resource extraction and waste, look for recycling or reuse opportunities, and determine what changes in the current processes are necessary to adopt, while maintaining the thermal spray process specifics for the required aircraft repair standards.

The challenges surrounding recycling and reusing thermal spray materials overlap with those of general sustainable development. The social, environmental, and economic dimensions of sustainable development must all transform to make source reduction more viable, recycling more incentivized, and lifecycle thinking more prevalent [13]. Overcoming the mindset that resources are infinite will challenge the current structure of civilized society, with an emphasis on the industrial sector [90]. To make the shift toward sustainable thinking, long-term economic goals must bypass the sole consideration of monetary savings and focus on conserving resources whether or not it is profitable [13], [90]. Furthermore, complex products like thermal spray or cold spray coating powders may require multi-stage recycling steps as a result of containing multiple compounds and alloys [13]. This added step of difficulty can deter profit-seekers. Furthermore, technology must improve in order to recover as much material from both simple and complex products as possible [13], [68], [69], [90].

Summary

There are many thermal spray methods used to repair aircraft engine parts, all of which result in the collection of unadhered thermal spray powders. These powders are composed of primarily metals and ceramics and are hazardous due to their explosivity from fine particle size, negative health effects, and ability to contaminate the aquatic environment. Tinker AFB uses 33 different thermal spray powders, and as a Large Quantity Generator, can only store thermal spray hazardous wastes for 90 days. The current disposal practices through the DLA were not disclosed, although through interviews with subject matter experts, it was discovered that the waste is likely contained in concrete and buried. Transportation of the waste must meet required federal and state regulations.

The value of thermal spray waste depends on its metal content, although other materials in the thermal spray process can be included in a sale to a recycler for ease of the producer of such wastes. The storage and transportation of thermal spray would be subject to fewer regulations if recycled since it would be considered a secondary material. Recycling thermal spray is an important step to reducing resource demand and environmental impacts from mining as well as waste disposal. As resources become more limited and their extraction less efficient, it is important for many industrial processes to work toward becoming a circular economy.

III. Methodology

Chapter Overview

The purpose of this chapter is to outline the acquisition of data for this research and how it was processed. This chapter also explains the selection of potential recycling vendors and the process to collect a sample of Tinker AFB's thermal spray waste.

Data Sources

The Air Force Civil Engineer Center (AFCEC) can amass all USAF data inputted through a computerized database, the Enterprise Environmental, Safety, and Occupational Health Management Information System (EESOH-MIS). Additionally, EESOH-MIS stores data from previously utilized computer databases that held the same purpose. Currently, EESOH-MIS is used to manage exposure risk for chemicals and hazardous working conditions at each installation. A few examples of the multitude of hazardous waste information tracked and recorded in EESOH-MIS include source location, waste stream characterization, quantity, and important tracking dates. Compiled records generated by AFCEC were requested for the depot-level maintenance bases of Tinker AFB, Hill AFB, and Robins AFB with all hazardous waste stream data for 2016, 2017, 2018, and the beginning of 2019. The data was received as a spreadsheet with tabs of information regarding the waste profile, chemical profile, and waste disposal. After initial data analysis, it was determined to focus solely on Tinker AFB's hazardous waste streams, and therefore all waste stream data for Tinker AFB was requested. The final hazardous waste stream spreadsheet from Tinker AFB included all waste disposal data from the years 2002 to 2019. In order to obtain a better perspective about Tinker AFB operations and waste practices, different subject matter experts and units working at or with Tinker AFB were contacted.

Tinker AFB’s waste practices are overseen by the 72nd Civil Engineering Directorate, Environmental Management Branch. The Environmental Management Branch works with regulatory agencies to develop and implement policy and pollution prevention investments on base. The branch provided additional data regarding the thermal spraying material acquisition, composition, and initial SDSs, and was available to answer additional research questions about collection and disposal practices for the hazardous waste. The Environmental Management Branch at Tinker AFB also guided the collection of the hazardous thermal spray waste stream samples, provided contacts for different thermal spray operations, and worked as Tinker AFB’s liaison between the installation, the DLA, and the thermal spray recycling contractor.

The 72nd Aerospace Medicine Squadron Bioenvironmental Engineering Flight at Tinker AFB is responsible for minimizing job risk for base personnel, in addition to hazardous material emergency management responses. The Bioenvironmental Engineering Flight provided information regarding the health and safety measures surrounding the thermal spray waste stream. This information included the thermal spray hazardous waste’s radioactivity analysis and memorandums regarding the handling of the thermal spray hazardous waste. They also provided AFRRAD contacts and explained its applicability to thermal spray recycling decision-making. Furthermore, the Bioenvironmental Engineering Flight answered additional research questions about plasma overspray hazardous waste characteristics and labeling. They also discussed the debate regarding the refinement of TENORM and NORM waste classifications in order to properly handle and treat the waste stream.

A thermal spray operation manager working in Tinker AFB's thermal spray shop was contacted in order to confirm how Tinker AFB applies the coating powders, what the powders are, if they are sprayed in the same booth, and the schematics and price of the current spray booths. The operation manager provided a table of the number of booths, what thermal sprays are applied in each, what type of spray was used, and how many parts the booth repaired per week, as well as the total numbers of thermal spray powders in use and how frequently the collection drums must be changed.

The AFRRAD team at Wright-Patterson AFB, who helps manage the thermal spray disposal of any radioactive collection drums, were interviewed in order to explore the possibilities of recycling radioactive thermal spray waste. They provided background information on their roles, the history of thermal spray's radioactivity and classification, applicable standards and regulations, and information about what steps would be necessary in order to recycle the radioactive thermal spray. Finally, the team clarified that not all the thermal spray waste must be handled or coordinated through AFRRAD; only some of the drums leaving Tinker AFB reached radioactivity limits requiring AFRRAD to dispose of them. The rest of the hazardous waste drums are still managed and disposed of by the DLA.

Additionally, a representative working for the DLA was contacted in order to get insight into the DLA's processes and its history at Tinker AFB. The DLA member oversees the disposal section of the DLA at Tinker AFB and manages disposal contracts. When given a list of questions such as the current waste stream disposal method and disposal location, the cost of disposal, and what happened leading to the transition from recycling the thermal spray hazardous waste stream to disposing of it, the DLA disposal representative at Tinker AFB responded that he was unable to answer any questions. He said he would send the questions to DLA Public Relations and DLA Headquarters, who would contact the researcher with replies, but these DLA sections were not heard from throughout the duration of this research. With pressure from Tinker AFB's environmental management team, the DLA disposal representative was able to share the DLA's previous contract documents with a vendor that purchased Tinker AFB's thermal spray waste in May of 2016. The contract information included quantities and total purchase price for the thermal spray waste for that year. This vendor was contacted and used as another data source as discussed in a subsequent section.

Data Processing

A process was developed in order to determine the hazardous waste streams of interest and the associated generation information. The compiled EESOH-MIS spreadsheet's first tab titled Waste Profile includes the installation name, Waste Profile Number, waste description, year, number of containers, and total weight of the hazardous waste for that year. This tab of the spreadsheet will be searched for any waste description that could result from the flame spray, electric arc spray, plasma spray, HVOF, or cold spray processes. Since blast media, filters, and other miscellaneous items like tape involved in the thermal spray process can still contain valuable materials or benefit from being included in the recycled material, they were considered in spreadsheet searches. Furthermore, with guidance from AFRRAD and a thermal spray recycler, thermal spray sludge was included as well. The chosen phrases used to evaluate the entries on the spreadsheet include “plasma,” “spray,” “metal,” “TBC,” “thermal,” “coat,” “powder,” “dust,” “HVOF,” “oxygen fuel,” “flame,” “arc,” “chrom-,” “nickel,” “grinding,” “blast,” “ceramic,” “sludge,” and “alum.” Any data entry with one of these key words was recorded in a table on a new spreadsheet.

The Waste Profile Number of the recorded entries was applied as a data filter in the next tab of the EESOH-MIS spreadsheet in order to produce a list of chemical descriptions for each waste stream. The chemical profile information includes the Waste Profile Number, waste description, chemical, case number, the chemical’s concentration range, and its flash point. The chemical profile information was compiled for each Waste Profile Number of interest and recorded in a new tab on the spreadsheet. The same Waste Profile Numbers were used to compile data from the final section of the EESOH-MIS spreadsheet.

The final tab on the EESOH-MIS data spreadsheet is titled Waste Disposed, and includes data columns of installation name, Delivery Order Line Number, Generator Number, Current Site, Stream Number, Stream Name, Waste Stream Description, Waste Profile Number, Version, Waste Description, Label, Disposal Method, Contract Line Number (CLIN) cost, unit of measure and description, EPA listed hazard number, and finally Container Number and Weight. The waste Disposal Method details whether the disposal method was local or through the DLA, the waste determination (hazardous or nonhazardous), and whether the material was recycled or disposed. Each waste disposal is tracked under its DLA or local CLIN and differs for each waste stream and installation.

In order to assess the hazardous waste streams for each depot-level maintenance base, the new spreadsheet was sorted according to installation and saved as individual spreadsheets. The entries produced from the key word search were scrutinized in order to determine if the entry was involved in the thermal spray process by thoroughly analyzing its description and chemical properties. The hazardous waste stream entries deemed unassociated with the thermal spray process were removed, and the remaining entries were added to a final spreadsheet.

The aforementioned process was applied to the originally compiled EESOH-MIS data for all three depot-level maintenance bases received from AFCEC. Tinker AFB disposal records produced 62 Waste Profiles associated with the thermal spray process. There were 24 Waste Profiles used for thermal spray waste powders, to include Metal Treatment Rework, Plasma Spray/Grinding, and Wire Spray with Nickel and Chrome. The other 38 profiles included thermal spray filters, rags and tape, sludge, blast media, and blast media filters.

The search through the Robins AFB and Hill AFB Waste Profile Numbers and waste descriptions produced less straight-forward results that would need to be verified in future research if the results of this thesis are conclusive. The Waste Profile Numbers found included entries related to thermal spray operations and disposal but were not as populous as Tinker AFB. The management of hazardous waste programs varies between Tinker AFB, Hill AFB, and Robins AFB. This is attributed to differing state regulations, differing industrial processes, and the autonomy of each base leading the installation's individual control of its own program. Further analysis for turbine engine part coatings hazardous waste streams were focused on Tinker AFB, since they are the largest industrial base in the United States and the largest producers of coating powder waste between the three depot-level bases. Additionally, Tinker AFB was able to confirm the Waste Profile Numbers for its use of thermal spray materials and had executed a recycling contract for thermal spray waste in the past, although the program has since dissolved [45].

This led to a request for any Tinker AFB hazardous waste disposal data in EESOH-MIS in order to provide a more in-depth analysis of Tinker AFB's use and disposal of the thermal spray hazardous wastes. AFCEC then compiled EESOH-MIS waste disposal data for Tinker AFB from 2002-2019, and the previously stated search process was repeated.

In order to determine the quantity of thermal spray hazardous waste produced by Tinker AFB per year, the Waste Disposed tab's column titled Container Weight was summed for each identified year of disposal. The total disposal cost per year was found in a similar manner by multiplying the cost per unit measure by the number of units. For some entries the unit of measure was one container, so the cost of disposal for that item was simply the cost per unit. The other entries' unit of measure was per pound, so the disposal cost for that item was the cost per pound multiplied by the container weight.

The disposal costs were evaluated in several ways. Costs were initially separated and summed by the type of item disposed such as filters, sludge, rags, blast media, or spray material waste. This separation was a result of the original key word search and relied on the researcher's discretion. Using this method, the thermal spray waste data was more comprehensive than what was identified by Tinker AFB. These results were considered independently after the profiles identified by Tinker AFB were analyzed.

Tinker AFB provided two profile numbers of thermal spray waste used during the timeframe of the recorded data. These profile numbers were used to separate the thermal spray material information from the rest of the entries and compared to the values tracked by Tinker AFB in order to ensure the calculations were focused on the right set of hazardous wastes. The thermal spray disposal costs and quantity generated per line item were plotted in order to determine if they resembled a common distribution. The disposal costs were further broken down according to the year the disposal was approved. Annual total costs of disposal including all material types were also found to determine the total disposal cost associated with thermal spray operations and total potential savings if all materials were included in the reclamation process.

The quantity of thermal spray operations waste was also considered in data analysis in order to predict future years' quantities generated by Tinker AFB. The quantities of each type of item disposed were summed, in pounds, and separated by year of approved disposal. Unlike the cost of disposal, the quantities of thermal spray hazardous waste were left separated by both item type and year. This is due to the fact that the value of the waste stream will rely only on the reclaimable materials such as thermal powders and metal blast media, whereas other materials like rags and filters can be included in the recycling process for ease of the waste generator but do not add value to the material for purchase.

A statistical analysis was performed for the total cost of disposal of thermal spray operations per year and for the type of thermal spray operation hazardous material per year with and without outliers. The same analysis was performed for the quantity of waste thermal spray powder generated per year with and without outliers. Additionally, the thermal spray powder material was analyzed in terms of cost per pound per year in order to account for severe fluctuations of quantity disposed each year. The mean, variance, standard deviation, median, and a 90% confidence interval were calculated for the above identified thermal spray operations data. The amount generated, costs per year, and cost per pound were plotted and included in the results section to scrutinize the data for any trends or anomalies. The quantities for each type of waste were also analyzed, however large variances and uncertain nomenclature led to convoluted results that would need additional refinement, which is outside of the scope of this research.

Market Analysis

To determine if the thermal spray hazardous waste streams produced by Tinker AFB are marketable, potential industrial waste recyclers were sought out. This process began with the identification and contact of commercial aviation companies that work on engine parts in the same manner as depot-level maintenance bases like Tinker AFB. General Electric Aviation was one of these companies willing to work with the Air Force Institute of Technology. General Electric Aviation allowed the researcher to tour two of its Ohio plants in April 2019, during which the plant members shared their best practices for reclaiming the waste from their coating process. Additionally, the Ohio plants' General Electric Aviation environmental lead shared the names of General Electric Aviation's industrial recycler partners and what qualifies a good industry partner.

Many industrial recyclers advertise their ability to analyze a waste's composition through shipments of one-pound samples, or by assessing the quantities and composition of the waste stream. Therefore, the goal was to identify industrial recyclers willing to accept thermal spray wastes in the United States and contact each recycler in order to either perform a sample test or send relevant hazardous waste stream data. Potential recyclers were found through Google searches using the phrases “plasma spray recyclers,” “industrial spray recyclers,” “thermal spray recyclers,” and “coating powder recyclers.” From the results of these searches, the company website was explored to determine whether the company recycled materials comparable to the Tinker AFB hazardous waste stream. Many companies were eliminated as options during this evaluation.

The websites of the remaining recycling companies were then searched for contact information and information regarding the evaluation and acceptance of difference waste streams. Attempts to contact each potential recycler included emails and telephone calls, and furthermore narrowed the list of potential thermal spray recyclers. The most common reasons for a company’s removal from the list of potential recyclers included lack of successful contact, inability to accept the thermal spray drums because of its hazardous qualities, and inability to accept the thermal spray because of its radioactivity. For this reason, only the thermal spray under radiation limits was used to advertise to vendors. Additionally, a few recycling vendors were skeptical as to the value of the plasma overspray due to the potentially high content of the ceramic TBCs. Only companies willing to test samples of the actual thermal spray hazardous waste within the timeframe of this research were considered in order to determine the stream’s actual value and marketability.

Tinker AFB’s Environmental Branch and Bioenvironmental Flight were unable to provide and ship samples to any company; therefore, the few companies still in communications were asked to travel to Tinker AFB to collect the samples they would then test. Only one company, Ardleigh Minerals, Inc. (Ardleigh), the same company who had a contract to recycle Tinker AFB thermal spray waste in 2016, was responsive and willing to collect and test the hazardous waste samples. Furthermore, Ardleigh was able to provide some of the previous contract documents between themselves and the DLA from agreements for a one-time pickup dated May 2016 as a supplement to the documents provided by the DLA. These documents included information about contract price, quantity of thermal spray collected in May 2016, and how much the DLA made by selling the materials. The relevant contract document information is reported in the results and discussion section and was compared to 2019 marketability data collected by Ardleigh as described below.

A total of four samples were obtained from Tinker AFB thermal spray waste drums on November 18, 2019, and tested by Ardleigh at its facility in Euclid, Ohio the following week for current market value [91]. Three of the samples were pure thermal spray spent powders, and one included other materials such as tape and filters [91]. The exact value per sample as well as the concentration of the metals in each sample was not disclosed. However, Ardleigh did suggest a full sample analysis, that would likely result in increased market value estimation, if any movement was made toward reinstituting the previous contract [91]. Based on the estimation of cost per pound, pounds per year, and thermal spray waste stream value per pound, a comparison was done in order to estimate the amount of money Tinker AFB could save each year and make each year, in addition to the total difference in monetary spending.

Summary

Data for this research was provided by AFCEC, who was able to provide EESOH-MIS data for Tinker AFB from 2003 through September 2019. This data set was evaluated in order to separate relevant thermal spray data and estimate the quantity produced each year as well as annual disposal costs. This data was supplemented by different entities involved in Tinker AFB’s thermal spray processes. In order to determine the value of the thermal spray waste stream, a vendor visited Tinker AFB and took four samples, which were analyzed by a laboratory. The vendor did not share the laboratory results but did provide an estimate for the thermal spray waste’s value per pound.

IV. Results and Discussion

Chapter Overview

The purpose of this chapter is to communicate the results of the methods taken in Chapter III, to include the results of the EESOH-MIS data analysis and the waste stream valuation. Additionally, this chapter will examine the outcomes and provide insight regarding the thesis research.

Spreadsheet Analysis

As received, the AFCEC-compiled EESOH-MIS spreadsheet for Tinker AFB from 2002 to 2019 contained 375,386 waste disposal entries. Of these entries, 16,495 entries (4.4% of the total) did not contain disposal approval dates, either from error or lack of waste stream in that year, and were therefore excluded in the analysis. From the remaining 358,891 waste disposal entries, the data evaluation and key word search produced 57,495 relevant entries for Tinker AFB thermal spray disposal operations and included data from 2003 to September 2019. After the data was sorted by material, there were 11,521 thermal spray powder entries, 6,377 rags and tape entries, 7,183 thermal spray filter entries, 221 sludge entries, 32,114 blast media entries, and 79 blast media filter entries.

For the initial analysis, all years of data except 2019 are included, since at the time of research and spreadsheet compilation, three months of disposal costs and quantities had not been recorded. The data received from the year 2019 was only included in data analysis involving the cost per pound of thermal spray disposal fees, which relied on the assumption that the cost of disposal per pound will remain constant for the remainder of the 2019 calendar year.

Although the key word search produced more than two Waste Profile numbers associated with thermal spray materials, in order to compare the recycling potential with historic data and conform to current Tinker AFB thermal spray waste collection operations, the same profile numbers from the 2016 recycling contract were used. These Waste Profile numbers are 20020 and the 2002C-H series. The set of calculations done hereafter for thermal spray powder waste are only for those two profiles; however, there are other thermal spray powder materials disposed of, such as containers of unused feedstock, that should be included in future disposal opportunities considered.

The line item disposal costs were compiled into a histogram, Figure 2, in order to determine if they fit any distribution. The distribution is somewhat lognormal, however there is a large spike at the $256 - $272 bin, which is due a large portion of the thermal spray waste having a flat rate disposal cost per drum at $262.26. The mean of the line item disposal cost is $95.80 with a standard deviation of $78.10.

The line item disposal quantities, in pounds, were also compiled into a histogram. As displayed in Figure 3, the quantities disposal of per barrel most nearly resemble a lognormal distribution. As with the cost per line item, values below zero cannot be obtained, and the data is skewed right. The mean of the disposal quantity per line item is 245 lbs with a standard deviation of 147 lbs.

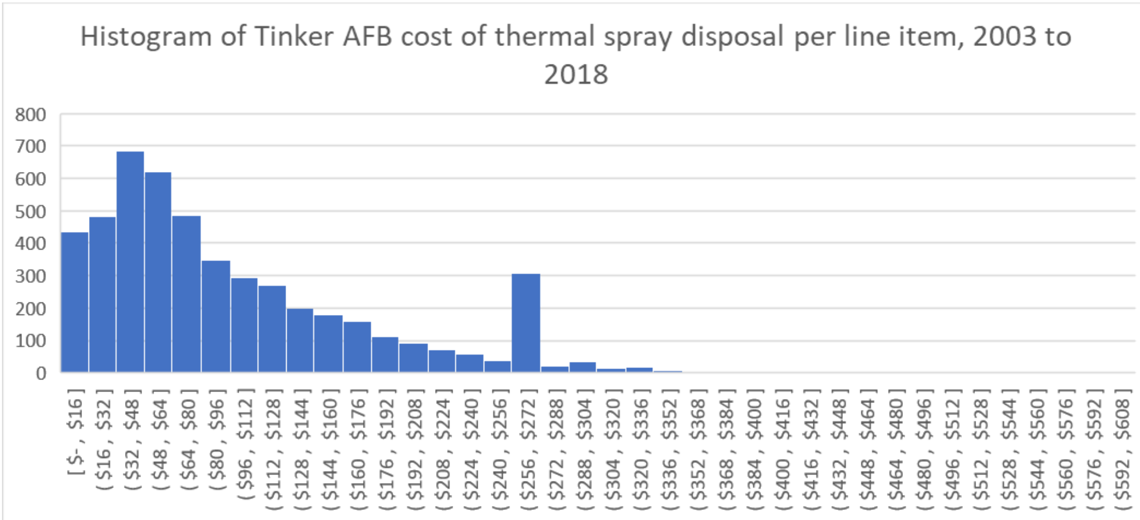

Figure 2. Histogram of Tinker AFB disposal cost line items from 2003 to 2018

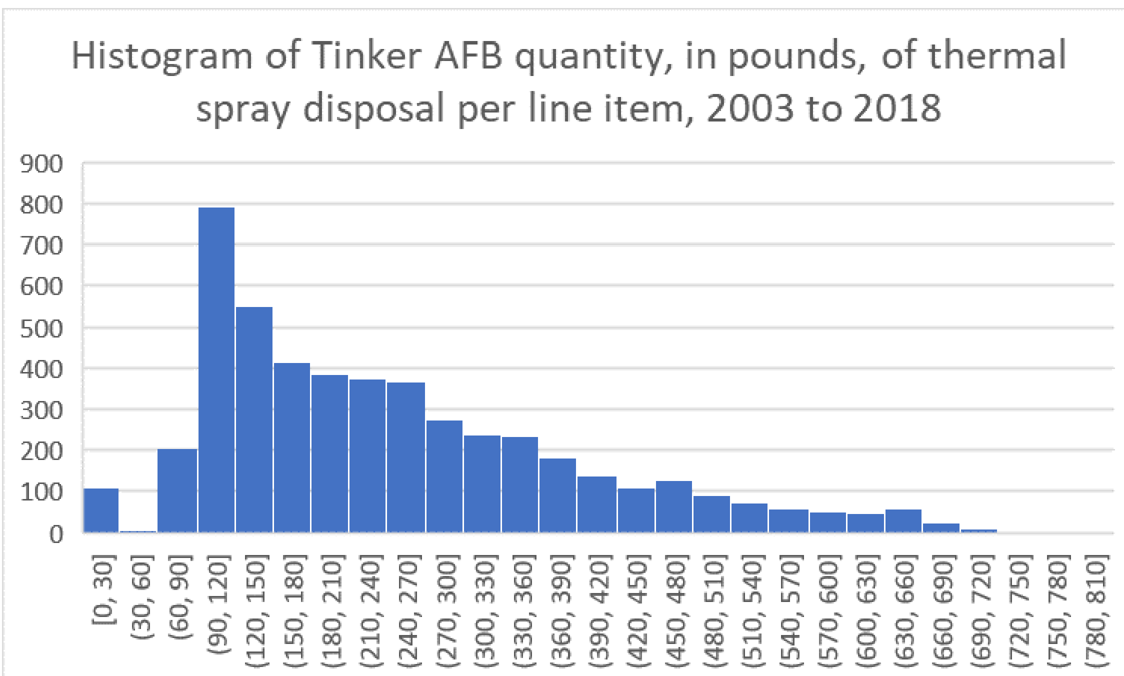

Figure 3. Histogram of Tinker AFB line item disposal quantities, in pounds, for 2003 to 2018

The following results for mean disposal cost and quantity generated for each material type containing a complete dataset is included at the end of the Spreadsheet

Analysis section in Table 2. The mean disposal cost of thermal spray powder materials per year is $29,486.62 with a standard deviation of $18,594.78. Many confidence intervals calculated in this research included negative dollar values or quantities produced, which does not have a logical interpretation in these circumstances. The confidence intervals that drop below zero will be reported in this section with lower bounds of zero. A 90% confidence interval for the disposal cost of thermal spray materials has a lower bound of $0.00 and an upper bound of $60,168.00. The thermal spray powder disposal costs for year 2012 was nearly an outlier at $66,351, likely resulting from the data points labeled as a cleanup effort from a spill. The disposal costs for 2015 are also relatively small in comparison to the years 2010 through 2018, at $22,295.52. Although this is not an outlier, it can be explained by the recyclable materials removed from the disposal lists that year. This highlights a discrepancy between the previous recycling contract, with a material pickup date of May 2016, and the spreadsheet. The collection of the hazardous waste sold to the vendor could have taken place partially in 2015, but the previous recycling contract is not reflected in the 2016 EESOH-MIS data. Furthermore, not all the thermal spray waste powders from 2015 or 2016 were recycled, however when the contract dissolved over dispute it was likely before the end of the 2016 calendar year.

The mean quantity of thermal spray powder materials disposed each year is 75,295 lbs with a standard deviation of 38,138 lbs. The 90% confidence interval for thermal spray powder quantity has a lower bound of 12,367 lbs and an upper bound of 138,224 lbs. However, the thermal spray powder quantity disposed in 2012 was identified as an outlier at 186,914 lbs, likely resulting from spill cleanup as identified in the waste descriptions for that year. The initial results of the thermal spray powder disposal costs per year and quantity disposed of per year from 2003 to 2018 are displayed in Figure 4.

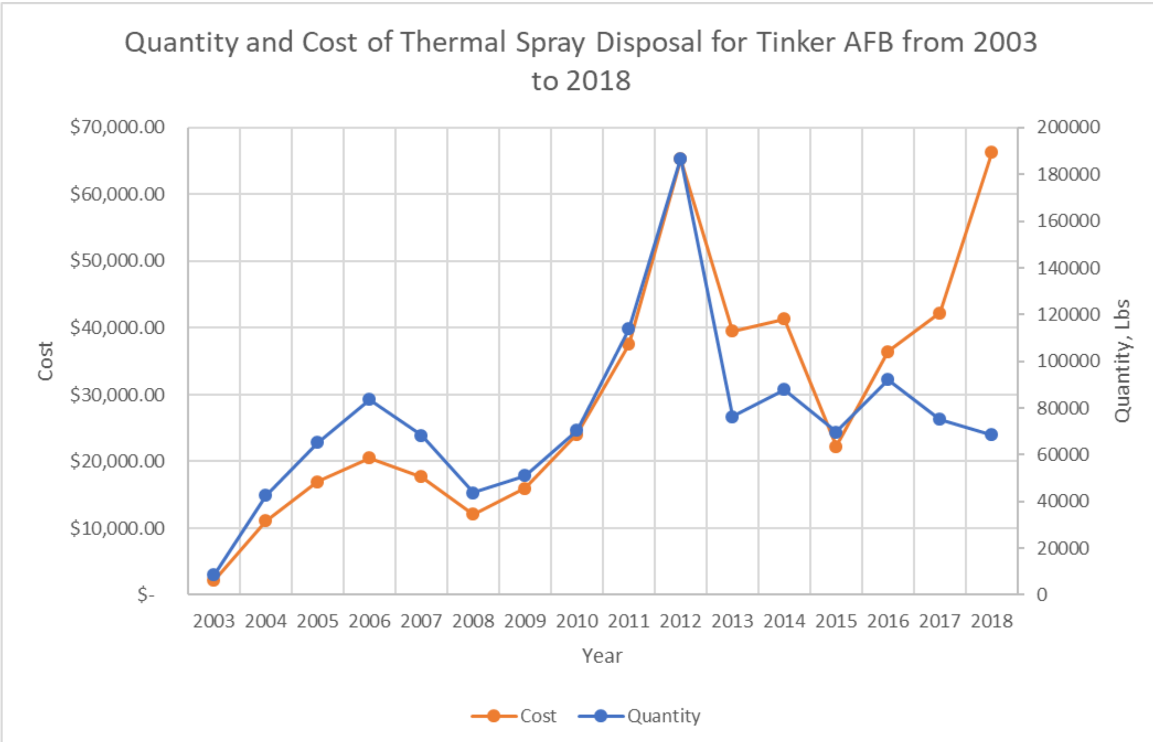

Figure 4. Quantity and Cost of Thermal Spray Powder Hazardous Waste Disposal per Year at Tinker AFB from 2003 to 2018

Since 2012 was identified as a thermal spray powder waste quantity per year outlier, for the next data analysis, 2012 was omitted and the descriptive statistics for costs and quantities were recalculated. After removing the 2012 anomaly, the mean disposal cost of thermal spray powder materials is $27,097.94 with a standard deviation of $16,512.11 and a 90% confidence interval with a lower bound of $0.00 and upper bound of $54,342.92. For the thermal spray powder waste disposal quantities, the mean disposal amount was 67,854 lbs with a standard deviation of 24,682 lbs and a 90% confidence interval of 27,129 to 108,579 lbs. These ranges are large since there is a lot of variability in the disposal quantities and cost for thermal spray materials. This could be a result of variability in product types, part types, booth additions, and operations tempo each year. Furthermore, the number of booths operating at Tinker AFB has steadily increased over time, likely resulting in increased thermal spray use and therefore waste.

The thermal spray powder hazardous waste disposal costs per pound of thermal spray for the years 2003 through 2019 provide another metric useful in the prediction of future disposal costs based on the amount disposed. The average disposal fee for Tinker AFB's thermal spray powder hazardous waste is $0.42/lb with a standard deviation of $0.24/lb. A 90% confidence interval resulted in the range of $0.03/lb to $0.81/lb for thermal spray powder disposal. In this method of analysis, the year 2012 was no longer an outlier, since the quantity and cost escalation were directly related. However, the disposal fee per pound for the year 2019 was an outlier at $1.02/lb. The increased costs could result from a change in materials, an emphasis on a less efficient thermal spray method, a change in the DLA contract, etc. that needs to be further investigated. As with previous efforts, the outlier was removed and descriptive statistics recalculated. After removing 2019, the mean cost of thermal spray powder hazardous waste disposal per pound was $0.39/lb with a standard deviation of $0.19/lb and a 90% confidence interval from $0.07/lb to $0.70/lb. However, a graphic representation of the cost per pound each year shows an upward trend; therefore, 2019 may not be an invalid data point.

Including all years from 2003 to 2019, the thermal spray cost per pound each year was plotted along with a line of best fit for both a linear and exponential increase, and since the exponential equation had the higher R^2, it was used in a predictive model to determine the cost per pound in future years. The cost per pound data and trendline, as well as its R^2 value are displayed in Figure 5, where "x" is equal to the year of interest minus 2002. If the cost per pound each year is assumed to increase exponentially from 2003, the cost per pound of disposing thermal spray hazardous waste through the DLA will reach $1.08/lb by 2025.

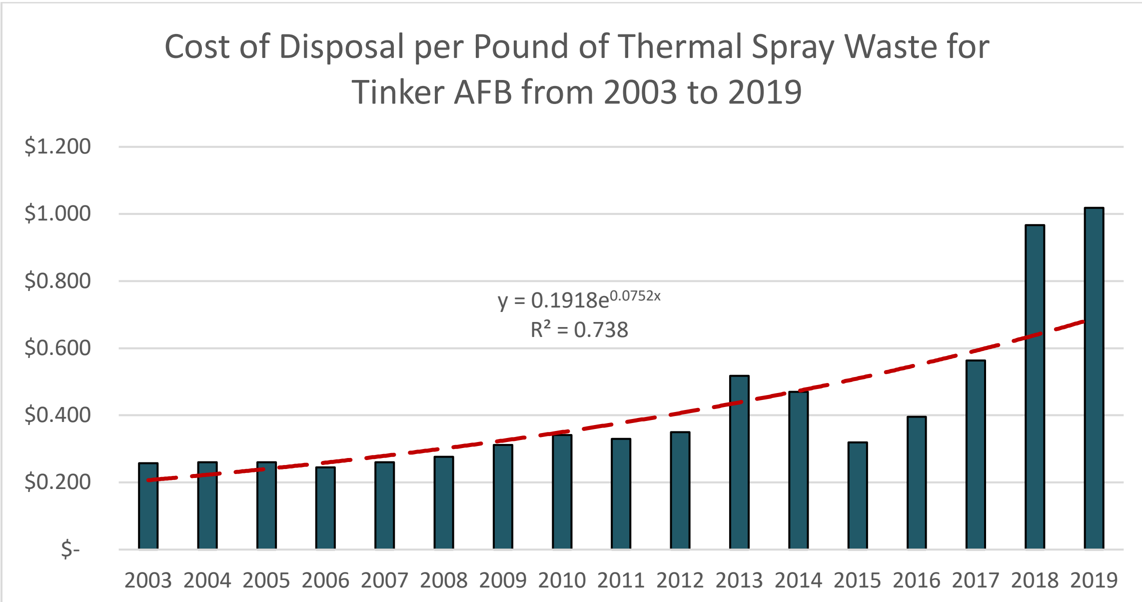

Figure 5. Annual Cost of Thermal Spray Hazardous Waste Disposal in Dollars per Pound per Year at Tinker AFB from 2003 to 2019

Using the $0.39/lb average disposal cost per pound of hazardous waste along with the average quantity of thermal spray waste generated from 2003 to 2018 excluding 2012, 67,854 lbs, the expected disposal fee per year is $26,463.06. Using the exponential model created for cost per pound that resulted in $1.08/lb expected cost in 2025 and the average quantity of thermal spray waste generated from 2003 to 2018 excluding 2012, the thermal spray powder hazardous waste disposal fees per year are expected to be $73,282.32 by 2025.

Descriptive statistics were found for all the remaining materials' cost and quantities each year. These values varied greatly from year to year and therefore the prediction for costs and quantities are not as useful. This is most likely due to name change, a few items labeled as spills, and holes in the data from changing electronic recording systems. Sludge data was absent from years 2015 to 2019, and blast media filter data was absent in 2010 and 2013 to 2019; therefore, sludge and blast media filters were not included in data analysis.

The blast media data had the highest variation but also included years in which some types of media were recycled and years with cleanup data. The average annual cost to dispose of blast media from 2003 to 2018 was $283,625.96 with a standard deviation of $ $774,507.80. The year 2012 and 2013 were outliers with blast media disposal fees of $499,858.47 and $3,153,167.67. With 2012 and 2013 removed from consideration, the mean blast media hazardous waste disposal cost per year was $63,213.52 with a standard deviation of $53,180.23. The average quantity generated was 366,901 lbs with a standard deviation of 263,212 lbs. With all years from 2003 to 2019 included, the average cost per pound of blast media was $0.37/lb. At this price per pound, the expected annual cost to dispose of hazardous blast media is $135,753.42.

Thermal spray rags and tape had an annual average disposal cost from 2003-2018 at $10,411.05 with a standard deviation of $7,402.18. The 90% confidence interval for thermal spray rags and tape had a lower bound of $0.00 and an upper bound of $22,624.64. The quantity for this material had a mean value of 28,451 lbs with a standard deviation of 20,082 lbs which created a 90% confidence interval from 0 lbs to 61,586 lbs.

The average cost per pound was $0.44/lb with a standard deviation of $0.27/lb and a 90% confidence interval from $0.00/lb to $0.89/lb.

The average annual cost to dispose of thermal spray filters from 2004-2018 (there is no filter data for 2003) was $19,186.01 but since the year to year data fluctuated greatly, the standard deviation was $19,167.40 and the 90% confidence interval ranged from $0.00 to $50,812.22. The average annual quantity was 32,502 lbs with a standard deviation of 24,634 lbs and a 90% confidence interval from 0 lbs to 73,148 lbs. The cost per pound had an average of $0.53/lb with a standard deviation of $0.23/lb and a 90% confidence interval from $0.15/lb to $0.91/lb.

The total cost of thermal spray hazardous waste disposal each year, excluding sludge and blast media filters, was estimated solely for exploration due to its high variability, inclusion of outliers, and inconsistencies. The mean disposal cost per year from 2003 to 2018 was $346,056.83 with a standard deviation of $775,121.90 and a 90% confidence interval with a lower bound of $0.00 and an upper bound of $1,625,008. The mean quantity generated per year from 2003 to 2018 was 913,121 lbs, with a standard deviation of 1,347,006 lbs and a 90% confidence interval from 0 lbs to 3,135,681 lbs.

Table 2. Summary of Thermal Spray Operations Materials Analysis

Thermal Spray Operations Waste Analysis

Material		Disposal Cost	Quantity Generated	Cost per Pound
Thermal Spray Powder	Annual Mean	$ 27,097.94	67,854 lbs	$0.39/lb
	Std. Dev.	$ 16,512.11	24,682 lbs	$0.19/lb
	90% C.I.	($0.00, $4,342.92)	(27,129 lbs, 108,579 lbs)	($.07/lb, $.70/lb)
Blast Media	Annual Mean	$ 63,213.52	366901 lbs	
	Std. Dev.	$ 53,180.23	263212 lbs	
	90% C.I.	($0.00, $150,960.90)	(0 lbs, 801,201 lbs)	
Rags and Tape	Annual Mean	$ 10,411.05	28,451 lbs	
	Std. Dev.	$ 7,402.18	20,082 lbs	
	90% C.I.	($0.00, $22,624.64)	(0 lbs, 61,586 lbs)	
Thermal Spray Filters	Annual Mean	$ 19,186.01	32,502 lbs	
	Std. Dev.	$ 19,167.40	24,634 lbs	
	90% C.I.	($0.00, $50,812.22)	(0 lbs, 73,148 lbs)	
Total Operations	Annual Mean	$ 345,056.83	913,121 lbs	
	Std. Dev.	$ 775,121.90	1,247,006 lbs	
	90% C.I.	($0.00, $1,625,008)	(27,129 lbs, 3,135,681 lbs)	

Market Analysis

The DLA and Ardleigh provided documents from a May 2016 bill of sale that showed the quantity and value of the thermal spray powder secondary material sold to Ardleigh. These documents reflect that 19,333 lbs of thermal spray powders were sold to Ardleigh with a unit cost of $0.16/lb for an agreed total price of $3,093.28. The period of time the thermal spray powders accumulated before shipment from Tinker AFB was not shared, therefore the comparison of this data to the EESOH-MIS data is not reasonable. Based on the yearly average of 67,854 lbs, the predicted time period of the gathering of the spent materials is approximately 3 months, which aligns with the current frequency of thermal spray hazardous waste shipments from Tinker AFB.

Ardleigh's 18 November 2019 thermal spray hazardous waste sampling valued the waste stream yet again at $0.16/lb, with a caveat that the waste could have more value, but a more in-depth analysis was needed. Using the average quantity of thermal spray hazardous waste produced each year, this means the expected profit from the sale of Tinker AFB's thermal spray waste is $10,856.64. Using the expected annual disposal cost of $26,463.06, the total monetary difference between disposal and recycling thermal spray powders is estimated to be $37,319.70. With the exponential cost per pound model, the total monetary difference between disposal and recycling thermal spray powders is projected to $84,138.96 for the year 2025.

Discussion

The large variation in both the cost of disposal and the quantities of thermal spray materials disposed of each year by Tinker AFB are likely a result of change in aircraft, increase in thermal spray services and booths, variation in the amount and type of materials sprayed, and possible spills. The thermal spray operations manager at Tinker AFB was unaware of any major spills or variations in output but was aware of a few minor spills over the last decade, and shared that six booths had been added since 2012 [43]. The additional booths may account for some variation in spray materials, but overall the data are inconsistent. Although the variation in the data led to some of the confidence intervals produced in the statistical analysis to include negative numbers for both costs and quantities of thermal spray associated operations' waste, in reality it is impossible to obtain negative values of either metric, and therefore the lower bounds were reported as zero. It is therefore safe to assume Tinker AFB will only experience positive monetary benefits from a thermal spray recycling contract. Furthermore, thermal spraying will likely remain the top method for engine repairs at depot-level maintenance bases in the USAF. Although technological advancements will increase application efficiency and minimize waste, there will always be some amount of valuable thermal spray powder material leftover to reclaim.

In addition, the Tinker AFB Waste Profile numbers 20020 and the 2002 series may not be the only recyclable thermal spray powder material waste produced by Tinker AFB from 2003 to 2019. There were other line items recorded from the key word search of the EESOH-MIS spreadsheet such as containers of unused thermal sprays that could be included in a recycling contract that would increase the value of the waste stream. Waste materials that do not increase the value of the thermal spray waste stream should also be included in the recycling contract. Although they will not increase the value per pound of the materials shipped from Tinker AFB, it will remove their disposal costs and provide a time relief as well as facilitate an easier process for Tinker AFB laborers, who will be able to dispose of all thermal-spray-related waste together. Since there was a large variation in total thermal spray operations waste materials disposal fees and quantities, the researcher cannot confidently report the savings that could stem from their inclusion in a recycling contract, but it would be a savings, nonetheless.

The estimations of $10,856.64 per year of profit from a recycling contract with Ardleigh, and removal of an average of $26,463.06 per year in disposal fees should propel Tinker AFB and the DLA to move forward in recycling contract efforts. The profit generated by Tinker AFB will vary with the quantities of thermal spray wastes generated and the potential annual assessment of the thermal spray waste's value per pound. The payments made by Ardleigh or any other future recycling contractor will go to the DLA at Tinker AFB.

The sample value of $0.16/lb produced by Ardleigh in November 2019 did not align with the researcher's expectations. It is unlikely that the four samples taken by Ardleigh had the exact composition of the wastes that were sampled in 2015 to estimate the purchase price in the previous contract. Additionally, the initial 2019 sampling request was to take at least one sample from each drum that was not classified as TENORM. The three samples of thermal spray powder hazardous waste and one sample of peripheral waste materials by Ardleigh is not enough to be able to produce a confident marketability estimate. However, Ardleigh has the advantage of being the only thermal spray recycler currently interested in doing business with Tinker AFB, and this lack of competition means they can set almost any price. Tinker AFB will still save money from no longer paying to dispose of the thermal spray waste, and make money from a recycling contract, but the calculated overall economic change is likely underestimated since the waste's market value is probably higher.

The researcher does acknowledge and understand that the Ardleigh estimate is based on many uncertainties and is therefore likely to be a considerable underestimation of the thermal spray's value. Ardleigh must advertise a price that is low enough to account for variation in the waste stream's valuable materials, the effort required to separate and treat materials, transportation costs, and must include a profit margin. Furthermore, this particular industry is known to underestimate thermal spray values to the DoD and government agencies. It would be wise for Tinker AFB to advertise to other companies before confirming another contract with Ardleigh. It is the opinion of the researcher that Tinker AFB needs to better advertise to companies across the United States or in Canada, since they may be able to offer a better deal or more efficiently utilize thermal spray materials. If the TENORM classification of a portion of the thermal spray powder wastes changes, the advertising strategy should change to include recycling vendors that have permits and the technology to recycle waste with radiation.

Ardleigh had a contract in dated May of 2016 to recycle Tinker AFB's thermal spray hazardous wastes through the DLA. Due to miscommunications, the contract dissolved, and Ardleigh was placed on a list of contractors that are no longer allowed to bid on Tinker AFB contracts. However, as aforementioned, Ardleigh is one of the few companies able to recycle thermal spray wastes, and as of 2019 is the only company interested in partnering with Tinker AFB once again [79]. The feasibility of Tinker AFB recycling its spent thermal spray powders heavily relies on the ability of Ardleigh to do business with the installation, and since the conflict occurred as a result of an error in payment with the DLA, all three entities should come to an agreement and resolve any remaining issues. Contacting the representatives from these groups during the research period for this thesis acted as a catalyst to the consideration of another contract.

During the 18 November 2019 site visit, the DLA, a member of the Tinker AFB Environmental Branch, and an Ardleigh representative met to discuss previous contract issues and ways to move forward on a new recycling contract. Although the researcher suggested an Indefinite Delivery/Indefinite Quantity (IDIQ) contract, it is likely any resulting contracts between these entities will need to be renewed annually, or per pickup.

During the discussion of contract type, Ardleigh did state they could update the value of the thermal spray waste each year, which Tinker AFB should enforce should there be a significant increase in the waste's marketability.

This research only considered thermal spray hazardous waste managed by the DLA at Tinker AFB, and therefore did not consider TENORM thermal spray waste managed by the JMC. The radiation that can accumulate in the thermal spray waste drums results in its classification as TENORM, although its levels hardly concern AFRRAD since they are on the extremely low end of the spectrum. AFRRAD has approached the RIC numerous times since some of the thermal wastes were considered TENORM proposing exceptions or a reclassification of the thermal spray waste. The RIC is finally considering the proposal and is discussing the issue with the JMC, which could result in a new classification for thermal spray wastes that allow them to be included in recycling processes. According to DoD Instruction 4715.27, *DoD Low-Level Radioactive Waste (LLRW) Program*, the Secretary of the Army can waive a specific LLRW activity case-by-case in order for the producer to handle the waste in the manner they see fit [27]. Tinker AFB has not submitted a waiver for thermal spray waste handling. If waived, reclassified, or if regulations change, the supplementation of the current viable thermal spray hazardous waste with TENORM thermal spray waste will at the very least increase the quantity of thermal spray materials recycled. This would also result in a likely increase of profitability in a Tinker AFB thermal spray contract.

Although recycling thermal spray materials produced by Tinker AFB is beneficial in all aspects, the results of data analyses are only as accurate as the data inputted to EESOH-MIS and there is no way to estimate the accuracy of the system's data. The compiled data was composed of EESOH-MIS and previously used databases; therefore, the naming conventions and the types of information recorded are not standardized. Blank entries could have been a result in the change of type of data recorded between the different databases. There is also no way to track possible human errors or to know the care at which the hazardous waste data is entered or checked. The best solution for this moving forward is to ensure those using and entering information into EESOH-MIS are properly trained, audited for accuracy, and know of the system's importance.

Investigative Questions Answered

1. On average, Tinker AFB produces 67,854 pounds of thermal spray powder waste per year. An average of 366,901 lbs of blast media, 28,540 lbs of thermal spray rags and tape, and 32,502 lbs of thermal spray filters are disposed of each year.
2. The spent thermal spray powders cost Tinker AFB an average of $27,097.94 per year, and when consider on a per pound basis, this amounts to $0.39/lb. Blast media disposal costs an average of $63,213.52 per year, thermal spray rags and tape disposal costs an average of $10,411.05 per year, and thermal spray filter disposal costs average $19,186.01 per year.
3. The thermal spray waste stream generated by Tinker AFB was valued by Ardleigh at $0.16/lb. Using the thermals spray average quantity and disposal cost per pound as well as the waste valuation, the expected profit from recycling thermal spray at Tinker AFB is $10,856.64, and expected savings are $26,463.06 per year. With the exponential cost per pound model, the total monetary difference between disposal and recycling thermal spray powders is $84,138.96 for the year 2025.

4. Thermal Spray waste streams can increase in value with increased metal concentration or better separation of materials before they reach the recycler. While the concentration of metals cannot be altered by Tinker AFB while still performing the required level of aircraft maintenance, it may be possible to separate the types of thermal sprays being collected. This suggestion must be met with scrutiny, since it would require an increase in time and manpower for the thermal spray waste collection process. Thermal spray waste's ability to be reclaimed is affected by certain levels of radioactivity, which is under discussion within the DoD.
5. Tinker AFB recycled its thermal spray waste with Ardleigh during a one-time pickup in May of 2016. The contract dissolved during miscommunications with the DLA and Ardleigh. Steps are being taken to resolve these issues as a result of this thesis research in order to create a new contract.
6. If other depot-level maintenance bases have waste streams with similar characteristics to Tinker AFB, they can expect to save \$0.39/lb in thermal spray waste disposal fees.
7. In order to reclaim Tinker AFB's thermal spray waste powders, the DLA at Tinker AFB should advertise a contract with an industrial recycler. Since Ardleigh is the only vendor interested at the current time, they should be contacted, and a contract negotiated. The Tinker AFB environmental and bioenvironmental flights should remain involved in the discussions to ensure the proper steps are taken to protect the environment from spills, and to ensure the

safety of Tinker AFB workers. If the radioactive thermal spray wastes are ever reclassified, they should be included in the recycling process.

Summary

Tinker AFB EESOH-MIS data analysis resulted in an average of $26,463.06 in thermal spray powder disposal fees per year and an average of 67,854 lb thermal spray powder generated per year. The data contained a lot of variation likely caused by inconsistent data entry, change in databases, changes in nomenclature, spills, and changes in operations. The thermal spray powder waste samples Ardleigh evaluated were valued conservatively at $0.16/lb, resulting in an estimated annual profit of $10,856.64. Since the cost per pound model was best modeled exponentially, the expected cost per pound for Tinker AFB in 2025 is $1.08/lb for a total expected disposal cost of $73,282.32.

If Tinker AFB pursued a new contract with Ardleigh, the company would do a more in-depth analysis of the thermal spray waste stream in order to increase the valuation accuracy. However, since Ardleigh is the only company in the area vocal about doing business with Tinker AFB, they have the advantage of setting a low valuation. Ardleigh had a contract with the Tinker AFB DLA in 2016 which dissolved through miscommunications. The research in this thesis sparked discussions between the two entities in order to remove Ardleigh from their current Tinker AFB bid ban. Tinker AFB should capitalize on the opportunity to reduce disposal costs, make a profit, and alleviate liability that stem from disposing of hazardous waste.

V. Conclusions and Recommendations

Chapter Overview

The purpose of this chapter is to summarize the thermal spray disposal and recycling research, reinforce the significance of recycling hazardous materials for Tinker AFB and the DoD, and recommend actions for Tinker AFB, the DLA, and the DoD.

Conclusions of Research

The thermal spray waste produced by Tinker AFB depot-level maintenance operations has an estimated value of $0.16/lb, resulting in approximately $10,856.64 per year of profit based on historical data. Switching from disposal to recycling of thermal spray waste would furthermore alleviate an estimated $26,463.06 in annual disposal fees. These estimates do not consider the potential to include other thermal spray operation materials such as blast media, filters, and sludge, in the waste stream, which would alleviate additional disposal fees. Although current profitability estimates are an underestimate due to the risk taken by the contractor and lack of comprehensive sampling of the waste's marketability, as a contract with a recycler moves forward, the value per pound of the thermal spray waste will likely become more accurate. It is important that Tinker AFB asks for revaluation of the thermal spray materials at least annually. Furthermore, expansions within the thermal spray recycling industry would result in more competition within the market which could also increase the profitability of the waste stream.

Since the thermal spray waste becomes a secondary material when it is recycled, the negative environmental impact of the waste's disposal is reduced. Depleting resources will eventually put a financial and physical strain on acquiring new materials and will emphasize efficiently using and reusing materials. The industry should make efforts to become more circular, even if it means reengineering the current processes. For Tinker AFB thermal spray operations to move toward a circular economy, the installation should work with its thermal spray feedstock supplier, the DLA, and AFRRAD to minimize resource extraction, waste, look for additional recycling or reuse opportunities, and determine what changes in the current processes are necessary to adopt.

Significance of Research

Based on the results of this research, Tinker AFB is spending unnecessary money on the disposal of thermal spray powder hazardous waste. This disposal is associated with liability if the hazardous waste is disposed of improperly or spilled. By recycling thermal spray powders, some of this liability is removed since the waste is never buried. Additionally, as resource strains increase, the ability to reduce resource demand in the metals market should be capitalized. This research demonstrates the need for increased efficiency in thermal spray methods to work toward a demand solution. The DoD relies on the DLA to research in these markets in order to find resource reduction opportunities. At some locations it may be important to investigate whether this market research is happening and what steps it would take to implement new waste handling methods.

Recommendations for Action

The author recommends that Tinker AFB, Ardleigh, and the DLA enter into a contract in order for Ardleigh to purchase Tinker AFB’s thermals spray operations hazardous waste. This contract should renew annually with adjustment according to the valuation of the thermal spray powders. Furthermore, the DoD should apply the findings of this research to all military branches. The maintenance done at Tinker AFB and other depot-level maintenance bases is not unique to the USAF. Any military installation performing aircraft engine repair will have a waste resembling the thermal spray wastes at Tinker AFB. These installations should also work with the DLA to test the worth of the materials and advertise their thermal spray wastes to industrial recyclers.

Recommendations for Future Research

There is not much peer-reviewed literature on the subject of recycling thermal sprays. Although the concept is executed in the commercial aviation sector, it seems to be a common practice that relies on the industrial recycler to provide estimates on price and ability to recycle. There another gap in knowledge regarding thermal spray direct recycling into other processes, as well as possible collaboration with similar waste streams such as 3D printing waste. Some completed research of ceramics recycling is only useful for pure ceramic materials, and not a mixture of ceramics and metals. These identified topics should be investigated in the future.

Summary

Tinker AFB and the DoD could save, and make, money by recycling thermal spray hazardous wastes, and reduce the waste's impacts on the environment. The DoD should use the findings of this research and apply them to any military installation that generated thermal spray waste.

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14. ABSTRACT The disposal of hazardous waste threatens the environment and human health. However, certain hazardous wastes can be recycled or reclaimed to alleviate environmental and financial impacts associated with its disposal and resource demand reduction. A hazardous powder produced by the United States Air Force stems from aircraft maintenance and is composed of metals and ceramics, called thermal spray. This waste can be purchased by an industrial recycler if the waste is composed of valuable metals. Historic data from the depot-level maintenance base Tinker Air Force Base initiated an analysis of annual thermal spray hazardous waste disposal fees, which combined with a sample analysis resulted in an expected value of the waste to a recycler, and potential profits if a contract to recycle the waste was created. Tinker Air Force Base's thermal spray waste stream was valued at $0.16/lb, resulting in an estimated annual profit of $10,856.64 and the saving of an additional $26,463.06 of disposal fees. It is recommended that this research initiates the recycling of thermal spray waste stream throughout the Department of Defense in order to save money and lessen the burden to the environment through disposal and resource extraction reduction.						
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