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Sustainable Materials Recovery Technologies: A Session from the 2023 Office of the Secretary of Defense (OSD) Strategic Environmental Research and Development Program (SERDP) Symposium, Arlington, Virginia

by Marc Pepi, Warren Assink, Brajendra Mishra, Sean Kelly, Guru Dinda, Jarod Gagnon, Corby Anderson, Patrick Ferrell, and Samantha Snabes

NOTICES

Disclaimers

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14. ABSTRACT
This special report is a compilation of briefs presented at the 2023 Office of the Secretary of Defense Strategic Environmental Research and Development Program Symposium in Arlington, Virginia, within the “Sustainable Materials Recovery Technologies” session. The first five briefs summarized research in mineral extraction from waste streams, while the final brief outlined progress toward 3D printing of waste thermoplastics at the point of need. Presentations were provided by the Government, private industry, and academia with the intent to summarize state-of-the-art research and the art of the possible in this area.

15. SUBJECT TERMS
critical materials, materials recovery, 3D printing, refractory alloys, rare earth elements, Sciences of Extreme Materials

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Contents

List of Tables

1. Introduction

This special report includes the briefs that were presented at the 2023 Office of the Secretary of Defense (OSD) Strategic Environmental Research and Development Program (SERDP) Symposium in Arlington, Virginia, on November 30, 2023. These presentations highlight research in extraction of critical materials from waste streams. The last presentation summarized research in the area of 3D printing from waste polymers at the point of need.

2. Background

The RAND Corporation's National Defense Research Institute 2013 study for the National Intelligence Council, "Critical Materials: Present Danger to US Manufacturing," recommends improving critical material secondary production as part of a long-term strategy for defense supply chain resilience.[1] It is of high importance to the DOD to ensure access to critical raw materials including refractory metals and rare earth elements incorporated into diverse weapons systems and platforms. Increasing domestic supply through advanced recovery methods reduces logistical supply chain risks. This session explored domestic and point-of-need technologies for recovering critical materials, recycling, and re-processing the DOD's own waste materials throughout its life cycle to support a higher level of sustainability. The presenters discussed techniques and technologies for advancing highly productive defense-critical material technological recovery from multiple sources—to include scrap, domestic solid waste stream, polymeric materials recycling, advanced manufacturing processes using secondary resources (i.e., additive manufacturing [AM] and improvements to the critical material life cycle), and applications at the point of need.

3. Session Speakers

The following biographies are for the co-chairs and speakers who presented at this session:

Marc Pepi, ARL (co-chair) – Marc Pepi is a Materials Engineer with the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) and the ARL lead in expeditionary manufacturing using recycled and reclaimed materials. He received a bachelor's degree in Mechanical Engineering, and a master's degree in Engineering Management from Northeastern University. He has worked for the DOD for almost 40 years, in the areas of materials behavior and characterization, failure analysis, inorganic coatings, expeditionary manufacturing, hybrid AM, and cold spray technology. He is a current member of the OSD SERDP/Environmental Security Technology Certification Program (ESTCP) Technical Committee. He has an Army Black Belt in Lean Six-Sigma and is a fellow of the Society for Machinery Failure Prevention Technology.

Warren Assink, AFRL (co-chair) – Warren Assink is a Senior Materials Engineer at the US Air Force Research Laboratory's (AFRL's) Energy Office at Wright-Patterson Air Force Base, Ohio. He has held numerous technical and programmatic engineering and logistical positions within the United States Air Force's (USAF's) Headquarters Materiel Command and multiple center functionals over his 35-year career. Currently, he leads the focus on expeditionary weapons system energy research, development, test, and evaluation efforts supporting the USAF's Advanced Agile Combat Support initiatives. He leads and/or serves as a technical subject-matter expert on numerous USAF or joint service weapons system environmental, safety, and occupational health regulatory life-cycle risk and energy reduction projects and programs. Also, he is currently an SERDP/ESTCP Technical Committee member. He received a bachelor's degree from Michigan State University and a master's degree from University of Dayton.

Dr Brajendra Mishra, WPI ("Materials Recovery Technologies for Defense Supply Resiliency") – Dr Brajendra Mishra is the Kenneth G Merriam distinguished professor of Mechanical and Materials Engineering, a Donald M Zwiep distinguished fellow, and director of the Metal Processing Institute at Worcester Polytechnic Institute (WPI). Additionally, Dr Mishra is the director of the National Science Foundation's Industry/University Collaborative Research Center on Resource Recovery and Recycling. Brajendra received his doctorate in Materials Science from the University of Minnesota. Prior to joining WPI, Dr Mishra was a professor of Corrosion and Physico-Chemical Processing in Metallurgical and Materials Engineering at the Colorado School of Mines (CSM) where he now serves as a university emeritus professor.

Dr Mishra has over 35 years of research experience in materials recovery and recycling, molten salt pyrometallurgy, and electrochemistry, as well as many contributions to the application of these technologies to materials development and processing. Dr Mishra has authored over 600 technical publications in refereed journals and conference proceedings. He holds 13 patents and has authored/edited 20 books. He is a fellow of the American Society for Metals (ASM) (2001) and The Minerals, Metals & Materials Society (TMS) (2016). Brajendra served as the 2006 and 2011 TMS president of the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME). Dr Mishra received the Presidential Citation of

AIME in 2015 and the Kenneth Andrew Roe Award from the American Association of Engineering Societies (AAES) in 2016.

Dr Sean Kelly, Solvus Global, LLC ("Technology Enhancements to Ensure Robust Domestic Supply of Secondary Aluminum") – In 2017, Sean Kelly and Aaron Birt co-founded Solvus Global following their doctorate dissertations in materials science at WPI. As Chief Operating Officer, Sean has led the organization from a team of 2 to more than 70 employees. Sean is passionate about leading and interacting with Solvus Global's diverse team of critical thinkers and problem solvers. He strives to create a workplace that professionals want to be a part of to deliver solutions to better this world through sustainable planning and technological advances.

Drawing on his leadership skills, Sean creates a durable, supportive ecosystem within the office and on the manufacturing floor. Sean has grown the footprint of Solvus Global manufacturing from the founding team's kitchens to 48,000 ft^2 of manufacturing space across central Massachusetts. He was named to both the 2021 Worcester Business Journal's "40 Under Forty" and the 2017 Society of Manufacturing Engineers' "30 Under 30" lists.

Acting on his passion for sustainability and renewable resources, Sean secured over $3M through a Small Business Innovation Research grant from the National Science Foundation and a project funded by the REMADE Institute to support the VALIS Insights, Inc's, technology and business enterprise at Solvus Global. Sean is also now board chair for VALIS, as they have transitioned into their own entity raising an oversubscribed seed round investment to deliver AI-powered software tools for metal recycling.

Under Sean's guidance, Solvus Global will continue to recruit, retain, and raise-up an organization and team that will drive economic growth, innovation, and success. When Sean is not in the office, he spends his time figuring out the game of golf—one of his biggest challenges to date.

Dr Guru Dinda, SRNL ("Recycling and Reuse of Tungsten-Rhenium Refractory Alloy Powder for Additive Manufacturing") – Dr Guru Dinda is a Senior Advisory Scientist at Savannah River National Laboratory (SRNL). His research interest is directed toward fundamental understanding of metal AM processes and the accelerated discovery of AM-specific materials. He led the development of various AM processes for manufacturing and remanufacturing of a variety of high-value components made of 4340 steel, aluminum 4047, Inconel 625, Rene 108, Haynes 282, Ti-6Al-4V, and GRCop 84. He earned a doctorate in Materials Science and Engineering from the University of Saarland. Dr Dinda has published 42 journal articles that have been cited more than 3200 times. Dr Dinda is leading the development of a laser-based directed energy deposition system at SRNL for the accelerated discovery of AM-specific materials.

Dr Jarod Gagnon, Johns Hopkins University Applied Physics Laboratory ("Low Temperature Metallurgy and Green Separation Methods for Recycling Rare Earths from End-of-Life Electronics") – Dr Jarod Gagnon is the chief scientist for the multifunctional materials and nanostructures group at the Johns Hopkins University Applied Physics Laboratory. His research focuses on novel materials synthesis, fabrication, and integration. He received his bachelor's of science degree in Ceramic Engineering from Alfred University in 2009 followed by a doctorate in Materials Science and Engineering from Pennsylvania State University in 2014. His research interests include development of methods for AM of single-crystal compound semiconductors, integration of materials into applied systems, synthesis and characterization of thin-film semiconductors, and novel recycling methods for recovery and reuse of critical elements from end-of-life electronic components.

Dr Corby Anderson, CSM ("Hydrometallurgical Treatment of Lead and Zinc Materials for Critical Metal Production") – Dr Corby Anderson is a licensed professional chemical engineer with over 40 years of global experience in industrial operations, corporate-level management, engineering, design, consulting, teaching, research, and professional service. He is a native of Butte, America. His career includes positions with Thiokol Chemical Corporation, Key Tronic Corporation, Sunshine Mining and Refining Company, HA Simons Ltd, and the Center for Advanced Materials Processing-Montana Technological University (Montana Tech). He holds a bachelor's of science degree in Chemical Engineering from Montana State University, a master's of science degree from Montana Tech in Metallurgical Engineering, and a doctorate from the University of Idaho in Mining Engineering – Metallurgy. He is a fellow of both the Institution of Chemical Engineers and of the Institute of Materials, Minerals, and Mining. He has directed or co-directed over 40 graduate students. He shares 16 international patents and 4 new patent applications covering several innovative technologies, 6 of which were successfully reduced to industrial practice. He currently directs the Kroll Institute for Extractive Metallurgy and serves at Harrison Western as part of both the Mining Engineering Department and the George S Ansell Department of Metallurgical and Materials Engineering at CSM. He is also the CSM Director for the Center for Resource Recovery and Recycling. In 2009, he was honored by the Society for Mining, Metallurgy, and Exploration with the Milton E Wadsworth Extractive Metallurgy Award for his contributions in hydrometallurgical research. In 2015, he was awarded the International Precious Metals Institute's Tanaka Distinguished Achievement Award. In 2016, he received the Distinguished Member Award from the Society for Mining, Metallurgy, and Exploration, and became a distinguished member of the University of Idaho's Academy of Engineering. In 2017, he received the Engineering Professional Development (EPD) Distinguished Lecturer Award from TMS. In 2019, he was named as a Henry Krumb Distinguished Society for Mining, Metallurgy, and Exploration Lecturer. Also in 2019, he was appointed and serves now as a visiting faculty member within the Minerals Engineering Department of Central South University in China—the largest program of mineral processing and extractive metallurgy in the world. In both 2016 and in 2021 he received an Outstanding Faculty Award from CSM. He was also elected in 2021 to the Sigma Xi Scientific Research Honor Society. In 2022, he received the TMS EPD Distinguished Service Award for his career contributions. Recently, Stanford University listed him in their top 2% of scientists worldwide university ranking. Finally, in 2022 he and his co-authors received the Society for Mining, Metallurgy, and Exploration Taggart Award for a notable contribution to the science of mineral processing.

Patrick Ferrell and Samantha Snabes, re:3D, Inc ("3D-Printing with Reclaimed Thermoplastics") – Patrick Ferrell is a senior engineer at re:3D, with over 20 years of experience in applied physics, engineering, and innovation. He has degrees in Physics and Mechanical Engineering from Texas A&I University (now Texas A&M University–Kingsville) where he was taught that no one has to pay you to be a physicist. Patrick has over 7 years of AM experience and manages several of re:3D's programs focused on recycling plastic waste through AM for the DOD, NASA, and other industry partners. **Samantha Snabes** is an Officer in the USAF Air National Guard and the CEO for re:3D where she facilitates connections to print at the human-scale and/or use recycled materials to access locally driven manufacturing in more than 50 countries. A serial entrepreneur, she volunteers as the global chair of the Institute of Electrical and Electronics Engineers (IEEE) Entrepreneurship Steering Committee. Previously, she served as the Social Entrepreneur in Residence for the NASA Headquarters and Deputy Strategist supporting the NASA Johnson Space Center's Space Life Sciences Directorate after selling a start-up for a Defense Advanced Research Projects Agency (DARPA)-funded, co-patented tissue culture device. Samantha holds bachelor's degrees in Biology, International Relations, and Hispanic Studies; a master's of business administration with concentrations in Supply Chain Management and International Relations; and certifications as a firefighter and Emergency Medical Technician-Basic (EMT-B).

4. Meeting Briefings

Six briefings were presented at the Sustainable Materials Recovery Technologies session of the 2023 OSD SERDP Symposium in Arlington, Virginia, on November 30, 2023. Table 1 lists the briefings and presenters.

Table 1 List of presentations/presenters

Section	Title	Presenter
4.1	Session Introduction	Marc Pepi
4.2	Keynote – Materials Recovery Technologies for Defense Supply Resiliency	Dr Brajendra Mishra
4.3	Technology Enhancements to Ensure Robust Domestic Supply of Secondary Aluminum	Dr Sean Kelly
4.4	Recycling and Reuse of Tungsten–Rhenium Refractory Alloy Powder for Additive Manufacturing	Dr Guru Dinda
4.5	Low Temperature Metallurgy and Green Separation Methods for Recycling Rare Earths from End-of-Life Electronics	Dr Jarod Gagnon
4.6	Hydrometallurgical Treatment of Lead and Zinc Materials for Critical Metal Production	Dr Corby Anderson
4.7	3D-Printing with Reclaimed Thermoplastics	Patrick Ferrell and Samantha Snabes

4.1 Session Introduction

Presentation slides from Marc Pepi are provided in this section.

Sustainable Materials Recovery Technologies

Methods to reduce mining, and help the environment:

- *Reuse*: Repurposing items and products for extended use
- *Recycling*: Reprocessing materials to be used elsewhere
- *Recovery*: #1-Disposing of materials while recapturing energy (i.e., heat and power); #2 -Restoration of materials found in waste streams to a beneficial use which were other than their original use

Sustainable Materials Recovery Technologies

The session will feature presentations regarding

- Materials recovery technologies (keynote)
- Technology to ensure a robust domestic supply of secondary aluminum
- Recycling and reuse of refractory alloy powder for AM
- Separation methods for recycling REEs from end-of-life electronics
- Hydrometallurgical treatment of lead and zinc materials
- 3D printing with reclaimed thermoplastics

3

Sustainable Materials Recovery Technologies

What is a critical material[1]?

- It is essential for the functioning of our modern technologies, economies or national security and
- There is a risk that its supply chains could be disrupted

[1]https://www.ga.gov.au/scientific-topics/minerals/critical minerals#:~:text=A%20critical%20mineral%20is%20a,supply%20chains%20could%20be%20disrupted.

2022 final list of critical materials: aluminum, antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, chromium, cobalt, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, germanium, graphite, hafnium, holmium, indium, iridium, lanthanum, lithium, lutetium, magnesium, manganese, neodymium, nickel, niobium, palladium, platinum, praseodymium, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thulium, tin, titanium, tungsten, vanadium, ytterbium, yttrium, zinc, and zirconium

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Sustainable Materials Recovery Technologies

2022 USDLA list also includes another 17 materials not defined as critical minerals. The 17 additional materials are aluminum-lithium alloy, beryllium copper master alloy, boron, cadmium, cadmium zinc telluride, copper, ferrochromium, ferromanganese, lead, mercury, molybdenum, quartz, rhenium, rubber, selenium, silicon carbide, and strontium

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Sustainable Materials Recovery Technologies

Burn pits are large areas where tons of waste products (including trash, plastics, wood, metal, paints, solvents, munitions, and medical and human waste) are burned in the open air. Typically, JP-8 jet fuel, which contains benzene, has been used as an accelerant. Burn pits create large volumes of toxic smoke and other substances. They give off more air pollution than contained burning, because the burning takes place in an open area and at lower temperatures[2].

[2]https://www.cancer.org/cancer/risk-prevention/chemicals/burn-pits.html

https://news.uams.edu/2022/06/07/uams-cavhs-studying-health-effects-of-arkansas-veterans-exposure-to-burn-pits-in-middle-east/

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6

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Sustainable Materials Recovery Technologies

ADMIN

- Total of six presentations with a 20-minute break halfway through
- Each 20-minute presentation will be followed by a 5-minute Q & A
- Let's save our 5-minute "Wrap-Up" for any follow-up questions for the speakers
- Please silence or turn off your cell phones

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7

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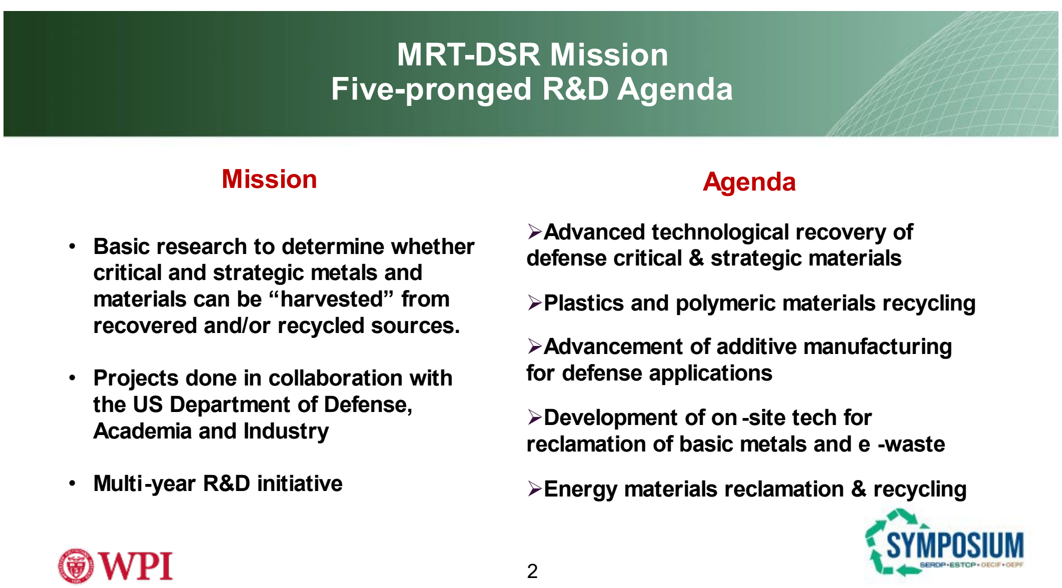
4.2 Materials Recovery Technologies for Defense Supply Resiliency

Presentation slides from Dr Brajendra Mishra are provided in this section.



University Industry Collaborative

Industry & University Partners
13 Projects

- Applied Materials
- Gas Technology Institute
- Indium Corp.
- GDB Intl.
- Grensol
- Terves
- ErCo
- Univ. of Toronto
- Purdue University
- Univ. of Maryland
- Univ. of Minnesota
- KU Leuven, Belgium
- Univ. of Queensland

WPI Research Investigators
17 Projects: 11 Co-PIs

- Brajendra Mishra
- Jianyu Liang
- Adam Powell
- Robert Hyers
- Danielle Cote
- Yan Wang
- Yu Zhong
- Nima Rahbar
- Michael Timko
- Thomas Christiansen
- Elke Rundensteiner

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MRT-DSR Year 2024 Projects
New People, New Projects

Recovery of Rhenium from Superalloy Swarf, Grindings, and Scrap – Robert Hyers

Robust Strategies for Handling Mixed Plastic Waste Streams for Military Applications – Michael Timko

Recycling Metal Feedstock Powder After Cold Spray Processing – Danielle Cote

Microstructure Optimization of Additively Manufactured High Carbon Steels Fabricated from Powders of Recycled Steel – Thomas Christiansen

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MRT-DSR Projects at WPI

Metal Powder Production with Electrolysis – Yan Wang

Environmentally Friendly Recovery of Valuable Materials from E -Wastes – Jianyu Liang

Multiple Effect Distillation for Magnesium Alloy Recycling – Adam Powell

On-Demand Rapid Fabrication of Components Using Forward Operating Base Aluminum Waste – Jianyu Liang

Recycling Rare-Earths for the US Military Applications – Adam Powell

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5

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MRT-DSR Projects at WPI

Optimization of Sorting and Separation Techniques for Recycling and Reclaiming Scrap from ARL Organizations – Brajendra Mishra

Recycling of Non-metallic components in Automotive Lithium-ion Batteries – Yan Wang

End-to-end Recycling and Components Recovery and Reuse in a Lead Acid Battery – Brajendra Mishra

Processing of Robust Multifunctional Structures from High Entropy Alloys Powder – Nima Rahbar

Recovery of Terbian and Europium from Spent CFL Lights – Brajendra Mishra

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MRT-DSR Projects at WPI

Value-added Products Recovery from Bauxite Residue Waste – Brajendra Mishra

Smart AI-Driven Materials Science Analytics for the U.S. Army – Elke Rundensteiner

In-situ Smelting of Discarded Urban Scrap into Aluminum Alloys – Jianyu Liang

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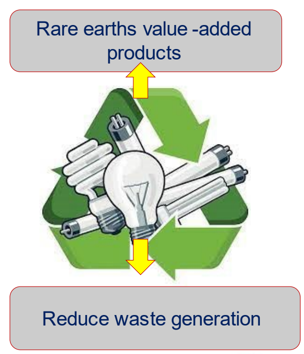
Recovery of Terbium and Europium from Spent CFL Lights

OBJECTIVES

- Develop optimized conditions for the separation and recovery of mainly Eu and Tb along with other rare REs (La, Ce and Y) as value-added products

HIGHLIGHTS

- In addition to providing an alternative source for the critical metals (Y, Eu, La, Ce and Tb) from domestic scraps, the complete utilization of fluorescent lamps will help reduce waste generation.



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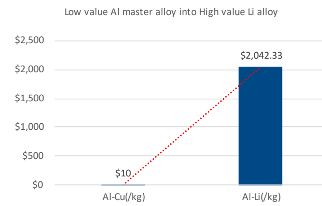
In-situ Smelting of Discarded Urban Scrap into Aluminum Alloys

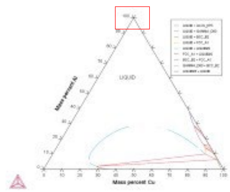
OBJECTIVES

- Transfer waste streams into product streams
- Design and fabricate a "Test Work Furnace"
- Design a new Al -Cu-Li alloys
- Investigate structure and mechanical properties of new alloys



HIGHLIGHTS

- Methodology for synthesizing Al -Cu-Li by using discarded Li-Cu film
  - Securing critical materials
  - Waste to Product
- Mechanical properties of new Al -Cu-Li alloy



Al-Cu-Li (1000K, 726.85°C)

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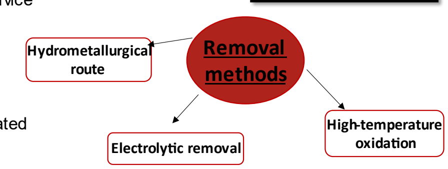
Residual Nb Removal from 440C Tool Steel

PROBLEM

- Nb is deposited on a 440C tool steel substrate for an additive manufacturing (AM) application
- After removing the deposited AM product, a thin layer of Nb stays adherent to the steel substrate. It specifically stays stuck to the tight corners of the steel substrate.
- Opportunity: Development of a non -destructive method to remove Nb from the tool steel substrate to increase the tool steel's service life

OBJECTIVES

- Maximum removal of Nb
- Minimal or negligible damage to steel substrate
- Maintaining mechanical integrity and performance of post -treated steel
- Potential recovery of Nb for full -cycle recycling
- Economic and technical comparison of proposed methods



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Recycling Rare Earths for the U.S. Military Applications

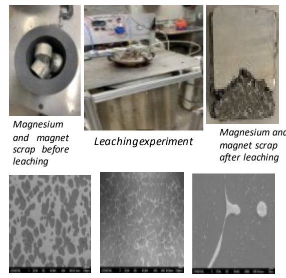
OBJECTIVES

- Assess rare earth needs across the U.S. Department of Defense building on existing work at DOD, ARL and CMI.
- Conduct techno-economic analysis of existing and proposed rare earth recycling processes using a common framework.
- Identify new methods for rare earth recycling
- Conduct validated modeling, demonstration and plan scale-up of key process technologies.

HIGHLIGHTS

- Effect of nickel coated NdFeB magnet on leaching.
- Leaching composition of rare earth elements after stirring.
- A continuous gravity-driven multiple effect thermal system for distilling of magnesium from magnesium-neodymium alloy.

Leaching temp: 900C



Magnesium and magnet scrap before leaching — *Leaching experiment* — *Magnesium and magnet scrap after leaching*

SEM Image of bottom section — SEM Image of middle section — SEM Image of top section

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11

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Multiple Effect Distillation for Magnesium Alloy Recycling

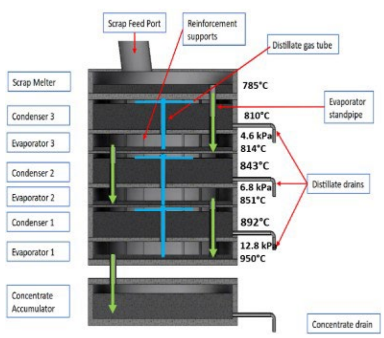

Fig: Gravity Multiple Effect Distillation System

- **OBJECTIVES**
  - To produce more magnesium (Mg) domestically (China share 87%)
  - The approach is to develop low-cost distillation to make high-quality Mg from scrap.
  - The success is to perform demonstrations and cost models show fitness for scale-up.
  - The potential success is improving domestic supply chain for an essential defense material.
- **HIGHLIGHTS**
  - G-METS is an advanced distillation system under development for the conversion of low-grade magnesium scraps.
  - This multiple-effect system uses the weight of magnesium as a compressor → to build pressure differences between each effect of the condenser-evaporator → modifying boiling points and enabling transfer of vaporization enthalpy.

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12

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Recycling of PPE– “Moving towards a new sustainable model”

OBJECTIVES

- Study the possibility and economic feasibility of recycling of PPE Scrap and thereby making the stream valuable part of plastics supply chain.
- Identify challenges to economical collection of PPE scrap.
- Finding possible uses of Post Consumer Resins (PCRs) made from recycling this stream of PPE Scrap.

HIGHLIGHTS

- PPE originally destined for landfill was diverted, collected and sorted into various streams like masks, gloves, gowns and hairnets.
- To achieve recyclability, each stream was further broken down into its individual components. E.g. in mask alone, PP, PET, spandex & metal were extracted.
- The extracted PP fraction from mask & gowns were converted into recycled pellets through extrusion.
- Recycled pellets were sold to plastic lumber industry to study the economic viability and applicability.

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13

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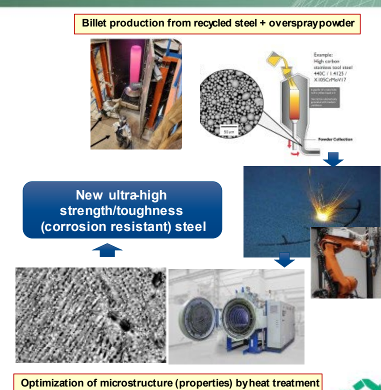
Microstructure Optimization of Additively Manufactured High Carbon Steels Fabricated from Powders of Recycled Steel

OBJECTIVES

Develop new high (impact) toughness / high strength materials based on cheap *recycled high carbon steel powder*

HIGHLIGHTS

Increase the carbon/nitrogen content to stabilize austenite; the materials can now be manufactured with AM (directed energy deposition, laser powder bed fusion, binder jetting etc.)



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14

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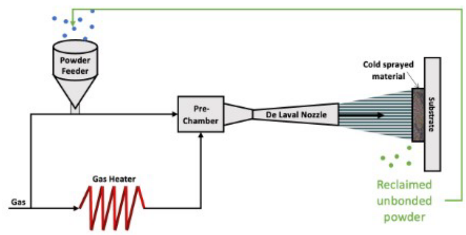
Recycling Metal Feedstock Powder after Cold Spray Processing

GOAL: To reclaim the undeposited powder particles. Powders will be recovered, characterized, and ideally re-processed to enable them to be reused again in subsequent sprays.



OBJECTIVES

- To develop an intermediate system to capture the un-deposited powder particles during cold spray processing.
- To fully characterize un -deposited Ti alloy powder particles after cold spray processing.
- Using computational thermodynamic and kinetic simulations, develop a thermal -chemical heat treatment to pre -treat the Ti powder particles for re-use in cold spray processing.
- Using the treatment developed in Objective 3, heat treat the Ti powder in the rotary tube furnace.
- Spray the reclaimed cold spray powder, with varying amounts of virgin powder added to the feedstock to observe processability and deposition efficiencies.

WPI

15

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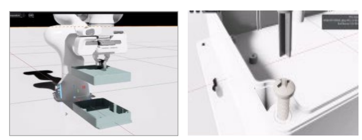
Automated RoboticUnmanufacturingof End-of-Life Vehicles

OBJECTIVES

Construct a robotic work cell for **robust and efficient autonomous disassembly** tasks of an end -of-life mobility product

HIGHLIGHTS

- High-fidelity simulated robotic manipulator operations & unscrewing in Nvidia Isaac Sim
- Learning-based model for real -time screw detection using camera data



Pick & Unscrewing Operation

Screw Detection in Simulation & Lab

WPI

16

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Thermochemistry of Na-Fe-Si-O-based System for Recovery of Critical Metals via Slag Fuming

OBJECTIVES

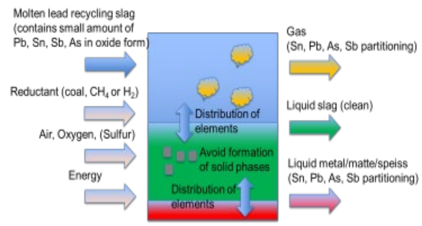
- Experiment: Produce > 200 experiments to fix interaction parameters between components of the slag, metal, matte, speiss
- Model: Create predictive thermodynamics-based computational tool to develop and improve fuming process for Na-Fe-Si-O-(Sn, Pb, As, Sb, S) elements

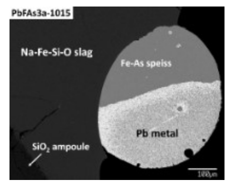
HIGHLIGHTS

- Opportunity exist for recovery of Critical metals (Sn, Sb) via Na-Fe-Si-O Slag Fuming
- And to produce a clean slag as by-product of lead production and recycling of lead batteries

APPROACH

- Integrated experimental investigation and thermodynamic modelling study





WPI

17

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Recovery of Rhenium from Superalloy Swarf, Grindings, and Scrap

OBJECTIVES

- Develop and test a novel recycling process to recover Rhenium and Nickel from superalloy swarf.

HIGHLIGHTS

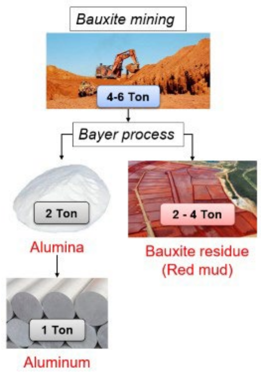
- Success in this project would allow:
  - a domestic supply of Re in the US
  - economically and environmentally friendly use of superalloy swarf.

W

18

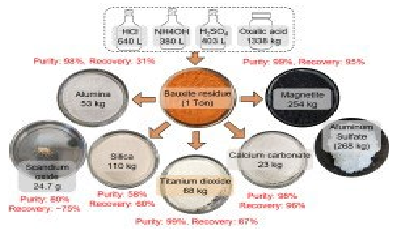
SYMPOSIUM

Value-added Products Recovery from High Iron Oxide Wastes



Advantages of hydrometallurgical recycling:

- High purity products.
- Comprehensive utilization and value recovery.
- Fully established at bench scale.
- Energy and cost effective, near zero waste.
- Key products: magnetite, alumina, titanium dioxide, scandium oxide, calcite and silica.



WPI

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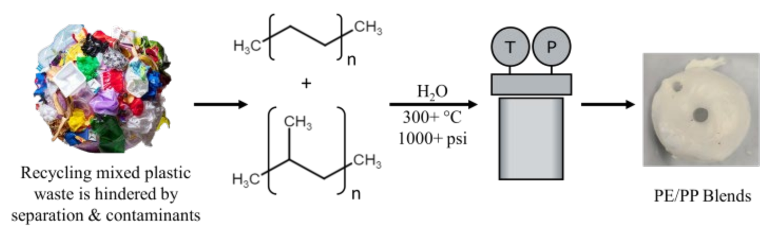
Robust Strategies for Handling Mixed Plastic Waste Streams for Military Recycling

OBJECTIVES: Create a blend of two immiscible polymers, polypropylene (PP) and polyethylene (PE) using water



Using water, which is typically thought of as a destructive solvent in chemical recycling, will allow for polymer swelling and better interfacial adhesion between the two materials.

We have successfully compatibilized a low molecular weight wax, and high molecular weight blend using this process.

WPI

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Environmentally Friendly Recovery of Valuable Metals from E-Wastes

OBJECTIVES

- Develop an effective process to recycle valuable metals from e-waste.
- Evaluate the environmental friendliness of the developed process.
- Expand the efficient procedure to an industrial level.

HIGHLIGHTS

- An easy-to-implement and easy-to-scale-up process for recovering valuable materials from e-waste.
- A clear understanding for reusing and recycling of chemicals utilized in this process.

WPI

21

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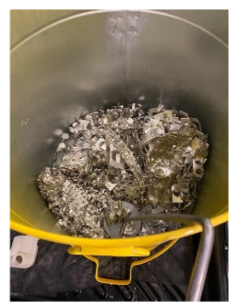
Reclaiming of Scrap Lithium Foil

OBJECTIVES

- Develop a safe and efficient reclaim process for scrap lithium webbing.
- Remove foreign organic (mineral oil) films from the scrap lithium webbing.
- Cast the cleaned scrap lithium webbing to billets. Maximize lithium yield by reducing dross formation.
- Form lithium foil of specified dimensions for anode preform production.
- Achieve the minimum lithium purity required for anodes for portable battery packs (99.8 wt. %) and medical implantable batteries (99.9 wt. %).

HIGHLIGHTS

- Initial work on removing the mineral oil from the scrap lithium webbing is progressing well.
- This demonstration program has the potential to close this lithium recycling loop.



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22

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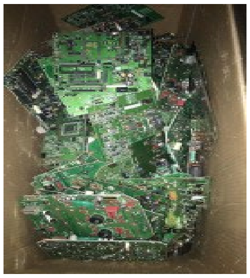
Refining of Secondary Tin Recycled from EOL Electronics



OBJECTIVES

- Develop a safe and efficient refining process for secondary tin produced from EOL electronics.
- Achieve the London Metal Exchange primary tin quality of 99.85 wt. % (minimum) conforming to BS EN 610:1996.
- Obtain tin recovery rates greater than 90 %, which is typical for primary tin extraction.
- A secondary objective includes the recovery of other metal values present as contaminants in the secondary tin supply.

HIGHLIGHTS

- Secondary tin produced from EOL electronics is a poor -quality metallic tin product (about 65 wt. % or less) that is highly contaminated with numerous impurities.
- This project has the potential to close this tin recycling loop.

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23

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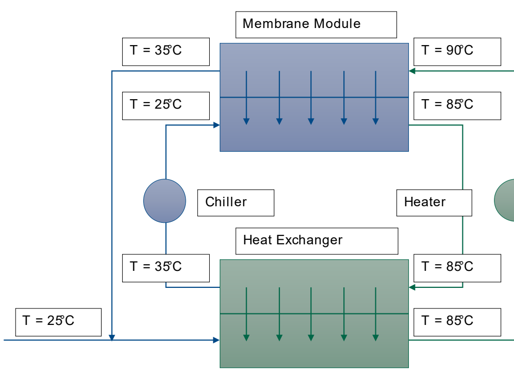
Electrolyte Recovery from Lead-Acid Batteries



OBJECTIVES

- Reclaim electrolyte from spent LAB
- Reduce ion contamination
  - Nanofiltration
- Raise acid concentration
  - Membrane distillation

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24

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Resources from Car Recycling Waste

Car Recycling: Current Situation

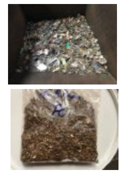
20% of a car's material is landfilled or incinerated;

20m tons/yr. waste produced worldwide;

Containing:

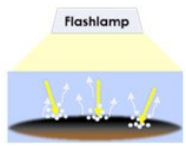
- 5-20% metals
- 70-80% hydrocarbons
- 10-30% silica

Project Focus: Recover of Materials



Metals:

- Recovering Cu, Al and Fe mechanically;
- Small modular process;
- Ready for commercial scale pilot plant.



Hydrocarbons:

- Using Photolysis to break C-C C-H bonds;
- Producing H_2, Carbon.

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On-Demand Rapid Fabrication of Components Using Forward Operating Base Al Waste

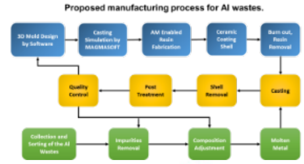
OBJECTIVES

- Create an effective sorting, chemical composition monitoring and composition adjustment process for Al wastes at FOBs that enables quality control of the material for subsequent rapid casting.
- Establish additive manufacturing (AM) enabled rapid casting (IC) using Al wastes from FOBs as the cast material.
- Develop post process treatments for ensuring or improving the quality of cast parts.

HIGHLIGHTS

- A database of typical metal wastes from military bases.
- An agile manufacturing process that creates replacement or repairing parts on demand using waste materials.
- An effective model to prescribe heat treatment processes and predict mechanical properties.

Proposed manufacturing process for Al wastes.



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26

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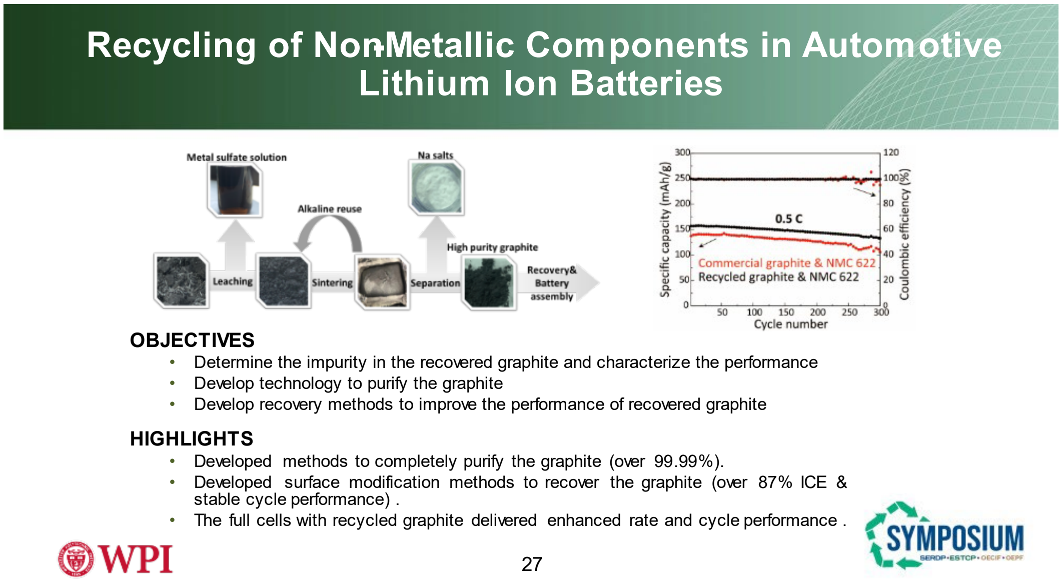


4.3 Technology Enhancements to Ensure Robust Domestic Supply of Secondary Aluminum

Presentation slides from Dr Sean Kelly are provided in this section.

Technology Enhancements to Ensure Robust Domestic Supply of Secondary Aluminum

Sean Kelly, PhD
Co-Founder – Solvus Global
sean.kelly@solvusglobal.com

Agenda

- Who am I and what do we do at Solvus Global?
- Introduction to the ~~Problem~~ Opportunity
- Start of a Solution to Enhance Scrap Aluminum Recycling
- Takeaways

Who Am I?

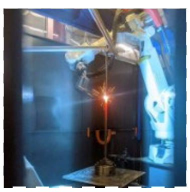
Co-Founder of Solvus Global, LLC

PhD in Materials Science & Engineering

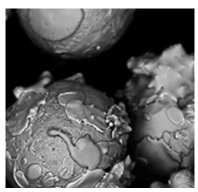
Background in Sustainable Material Management

3

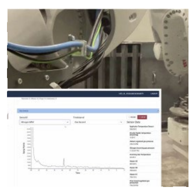
Solvus Global's Enterprise Brands & Spin-Outs



Large Format Casting & Forging Replacements



Metal Powder for Additive Manufacturing



Manufacturing Intelligence Software for AM

Solid State Li-Ion Batteries for UAVs

Software Tools to Enhance Recycling Profitability

4

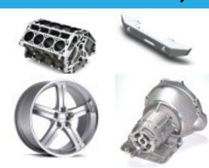
Who does Solvus Global work with?

Intro: The ~~Problem~~ Opportunity

Focus: Sustainable Management of Aluminum in Transportation (passenger vehicles)
(***Think about where else we need the technologies discussed here***)

~280 million passenger vehicles in use in the US

Average vehicle weight: ~4,100lbs.

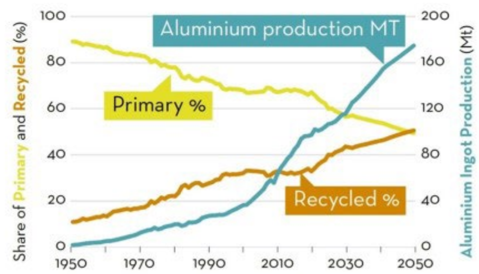


~7% of passenger vehicle curb weight in US is aluminum

~36 million MT of aluminum in use today…that will need to be recycled

6

Intro: The ~~Problem~~ Opportunity



Ducker Frontier
International Aluminum Institute

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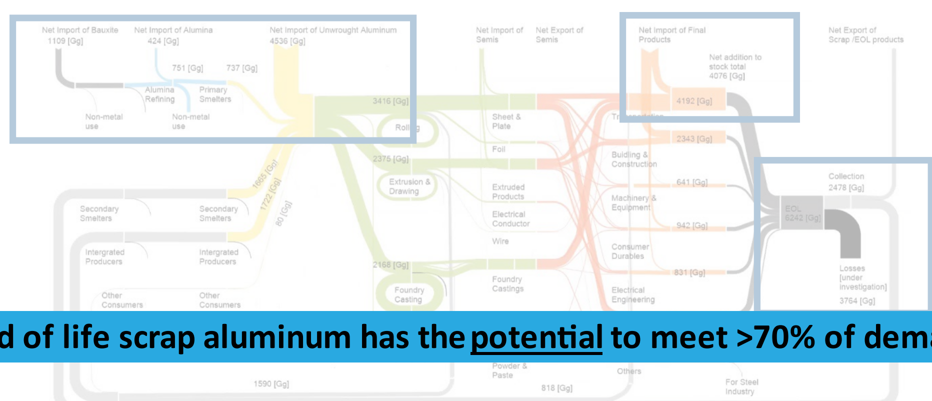
Intro: The ~~Problem~~ Opportunity

The U.S. aluminum cycle in 2017 (all values in million metric tons)



End of life scrap aluminum has the <u>potential</u> to meet >70% of demand

Intro: The ~~Problem~~ Opportunity
High-Level View of End-of-Life Vehicle Processing

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Intro: The ~~Problem~~ Opportunity
What is Twitch?

Auto-shred Aluminum Scrap (Twitch)
90-98 wt.% of mixed aluminum alloys

Source	Si	Fe	Cu	Mn	Mg	Zn
Site A	3.8 ± 0.75%	0.62 ± 0.11%	1.2 ± 0.34%	0.22 ± 0.05%	1.9 ± 1.2%	0.95 ± 0.38%
Site B	4.8 ± 0.94%	0.68 ± 0.06%	1.4 ± 0.36%	0.23 ± 0.05%	1.9 ± 0.54%	1.0 ± 0.41%

Si, Cu: Significant amount of alloying required

Mg: Significant amount of demagging required

319	5.5 - 6.5%	0 - 1%	3 - 4%	0 - 0.5%	0 - 1%	0 - 1%
380	7.5 - 9.5%	0 - 2%	2 - 4%	0 - 0.5%	0 - 1%	0 - 3%

What other aluminum alloys are in this mixture?
- 5000-series: 5-10 wt.%
- 6000-series: 20-30 wt.%
- 7000-series: 1-3wt. %

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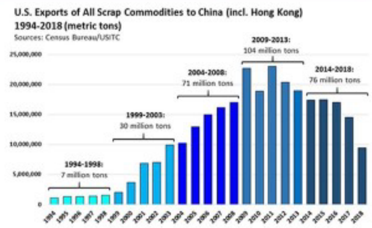
Intro: The ~~Problem~~ Opportunity



DOWNCYCLING

- High value material is blended into low value alloys when scrap is not sorted into alloys/alloy families
- Increases need for consumption of primary aluminum
- Increases costs in the industry and reduces sustainability

EXPORT of MIXED COMMODITIES

- Increased restrictions limit scrap processors' export opportunities
- Limitations increase as international consumers raise standards
- Creates need to meet growing standards both for domestic and international consumers

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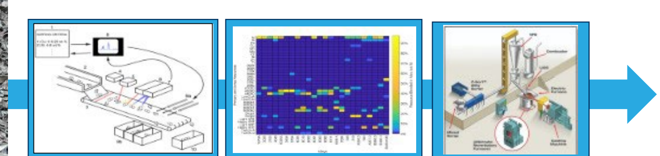
Start of a Solution to Enhance Scrap Aluminum Recycling



What is the most optimal processing route?

What are the material flows & optimal blending procedures?

How do we tie it all together and create new applications for secondary resources?

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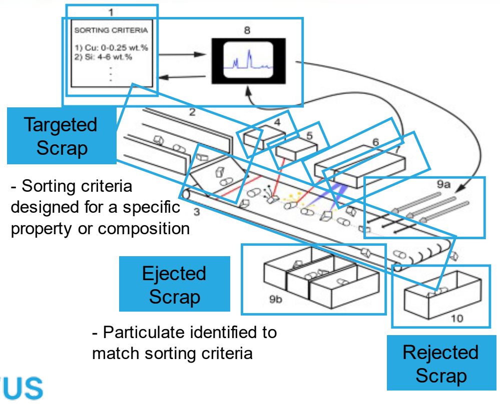
Optimal Processing: Sensor-Based Sorting Systems



Targeted Scrap - Sorting criteria designed for a specific property or composition

Ejected Scrap - Particulate identified to match sorting criteria

Rejected Scrap - Particulate that does not match any sorting criteria

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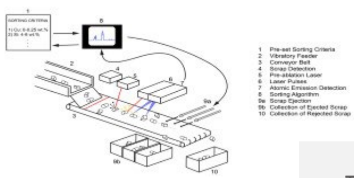
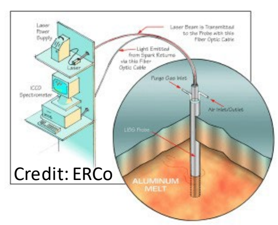
Optimal Processing Route: Adding Intelligence to Process

SENSOR-BASED SORTERS



MELT QUALITY ANALYSIS



Credit: ERCo

VALIS:

- Takes the uncertainty out of scrap metal recycling
- Our AI and optimization models suggest sorting criterion to maximize process efficiency and sustainability and ensure melt quality

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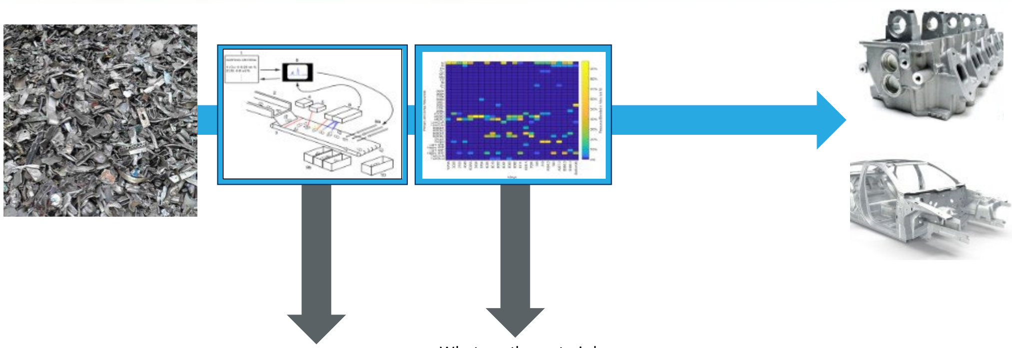
Start of a Solution to Enhance Scrap Aluminum Recycling



What is the most optimal processing route?

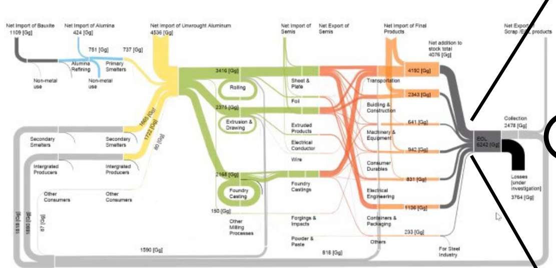
What are the material flows & optimal blending procedures?

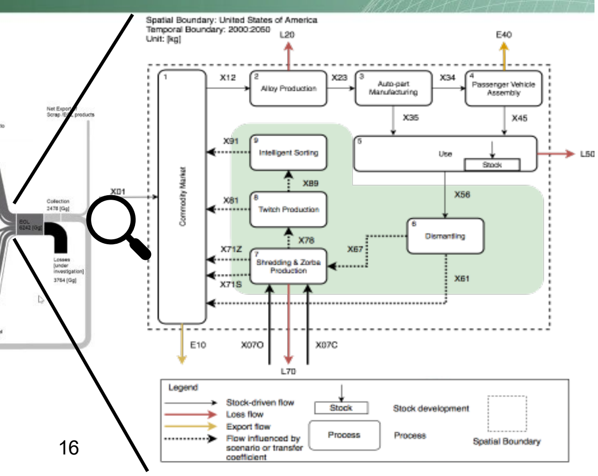
15

Material Flow Analysis & Optimal Melt Blending
Expanding Feedstock Resources

What is Material Flow Analysis (MFA)?

The U.S. aluminum cycle in 2017 (all values in million metric tons)



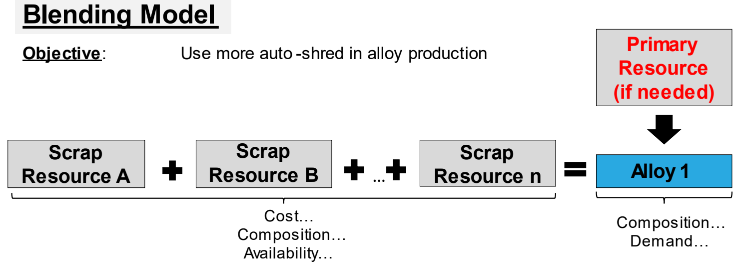


16

Material Flow Analysis & Optimal Melt Blending
Expanding Feedstock Resources

Blending Model

Objective: Use more auto-shred in alloy production



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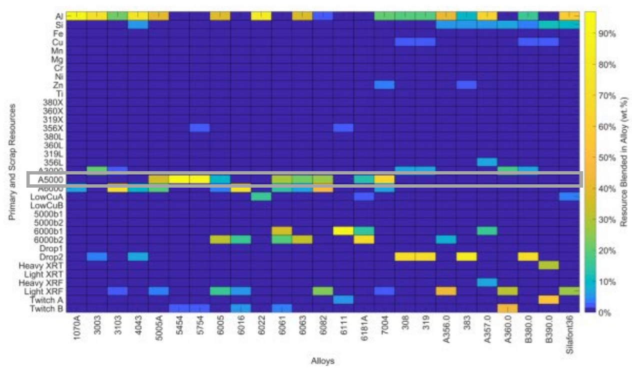
Material Flow Analysis & Optimal Melt Blending
Expanding Feedstock Resources

Closed-Loop

Raw Material	Al	Si	Fe	Cu	Mn	Mg	Zn
A5000	97.0%	0.2%	0.3%	0.1%	0.2%	2.2%	0.0%

Twitch Sorted into 5000-series bin (A5000)



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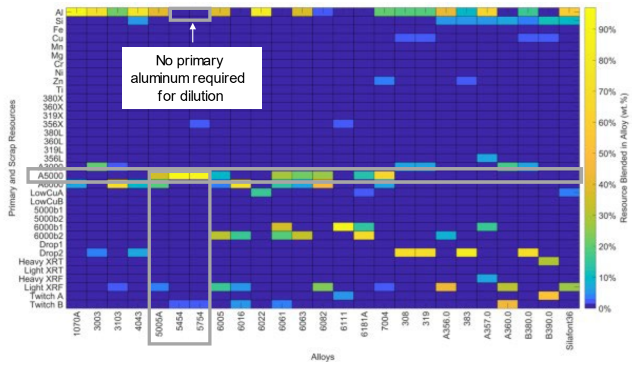
SYMPOSIUM

Material Flow Analysis & Optimal Melt Blending
Expanding Feedstock Resources

Closed-Loop

Raw Material	Al	Si	Fe	Cu	Mn	Mg	Zn
A5000	97.0%	0.2%	0.3%	0.1%	0.2%	2.2%	0.0%

Alloys Produced	Al	Si	Fe	Cu	Mn	Mg	Zn
5005A	97.9%	0.3%	0.5%	0.1%	0.1%	0.9%	0.2%
5454	95.7%	0.3%	0.3%	0.1%	0.8%	2.7%	0.0%
5754	95.6%	0.4%	0.4%	0.1%	0.2%	3.1%	0.1%



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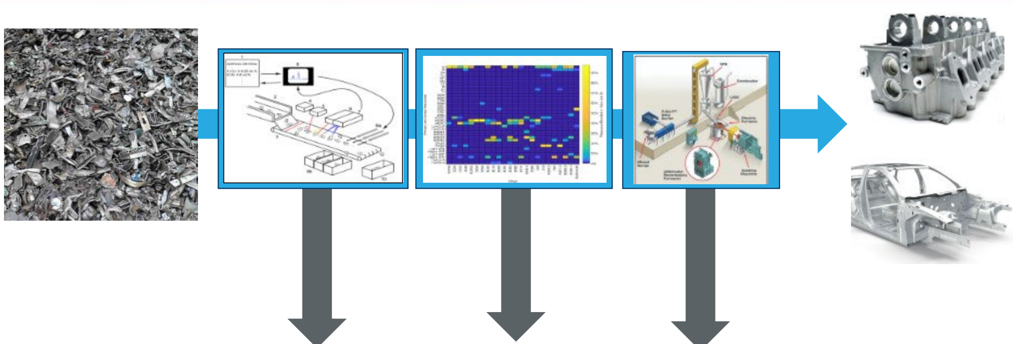
Start of a Solution to Enhance Scrap Aluminum Recycling



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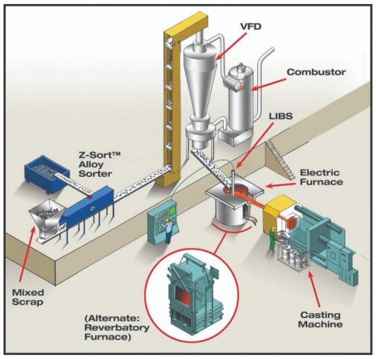
Start of a Solution to Enhance Scrap Aluminum Recycling
Aluminum Integrated Mini -mill



Auto-shred Scrap Aluminum to High Value Recycled Semi-products

Future Work/Opportunities:

- Integrated process for other material systems (titanium, tantalum etc.)
- Forming final products from mill beyond just semi-products
- Producing feedstocks for additive manufacturing processes like cold spray (powder), friction stir additive (bar stock), etc.

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Takeaways

- The transportation sector uses a **large amount of aluminum**, and this amount is only **growing but there is a lack of focus on closing the recycling loop and upcycling/upgrading scrap products**
- There is a **"stock-pile" of aluminum in use in the US today** that needs to be tapped to **meet the demands for this material in the future across multiple sectors**
- **Investment in technological advancements and application development** for secondary aluminum is key **to tap the potential that this stock-pile provides**
- **Consumption of all types of scrap aluminum to make high -value aluminum alloys** is not only possible but is **required to ensure a robust supply chain for aluminum in the US** now and well into the future

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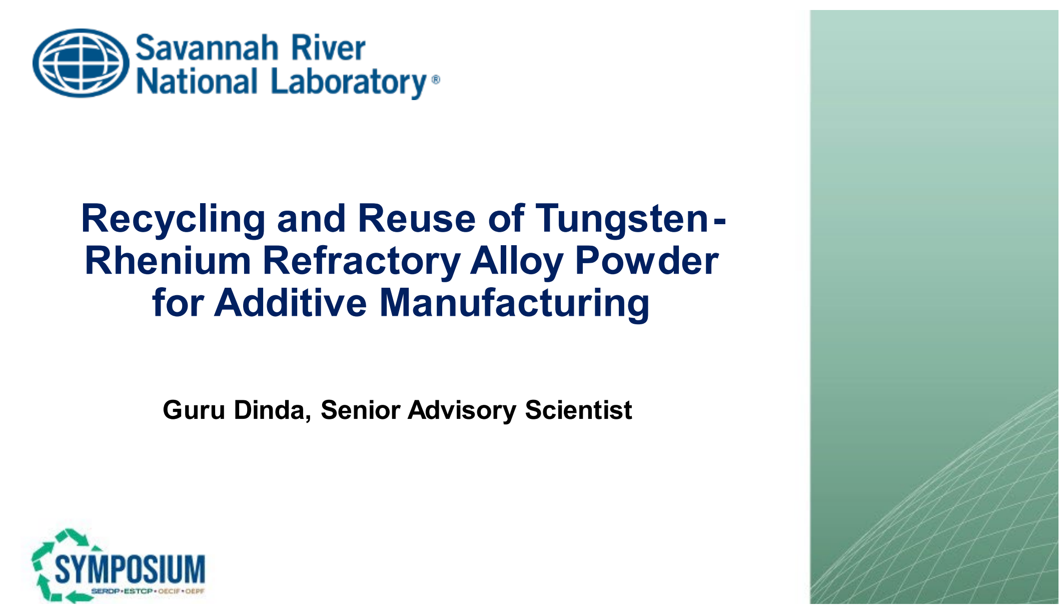
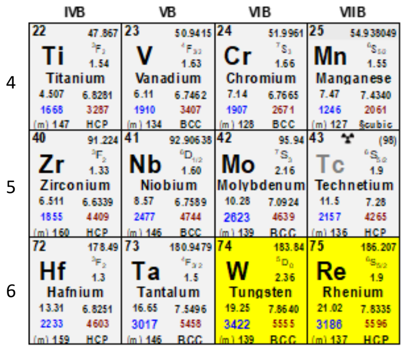
4.4 Recycling and Reuse of Tungsten–Rhenium Refractory Alloy Powder for Additive Manufacturing

Presentation slides from Dr Guru Dinda are provided in this section.



Background



Refractory Metals

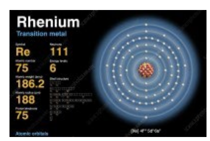
- Extreme-environment applications require refractory materials.
- W (3422 ^{o}C) and Re (3186 ^{o}C) are the two highest melting point metallic elements.
- W has excellent mechanical properties at elevated temperatures.
- W exhibits a high brittle-ductile transition temperature (300 - 400 ^{o}C).
- Additions of Re to W result in improved low-temperature ductility, high-temperature strength.

Savannah River National Laboratory

2

SYMPOSIUM

Background



- Rhenium is one of the expensive and rarest metals.
- Global extractable Re will be depleted in about 130 years.
- W-Re alloys are extremely tough materials for deformation processing and machining.
- Tremendous interest in developing AM processes of W-Re alloys.
- A fraction of the powder is melted, and rest of the powder contaminated due to the oxygen pickup during AM.
- Recycling of W-Re alloys is the primary alternative solution for future advanced technological use of Re.

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Background

- W-Re alloys are extremely tough materials for deformation processing and machining.
- The buy-to-fly ratio for complex components is very high, which makes W-24Re complex components very expensive.

Subtractive manufacturing

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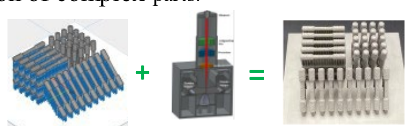
- There is a tremendous interest in developing AM processes of W-Re alloys, particularly for the fabrication of complex parts.



Additive manufacturing

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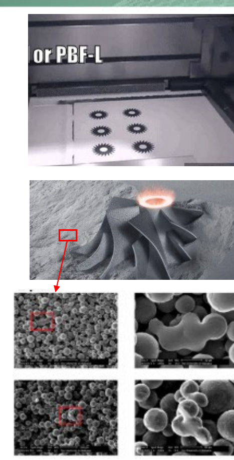
Background

- During AM, only a fraction of the powder is melted, and the unmelted powders are available for reuse.
- W-24Re powder become contaminated due to the oxygen and moisture pickup during AM and powder handling processes.
- A small fraction of powder around the build agglomerated due to the very high temperature at the build/powder interface.
- To keep AM more affordable, there is a tremendous need to develop a robust powder reconditioning method of out-of-spec AM powders.



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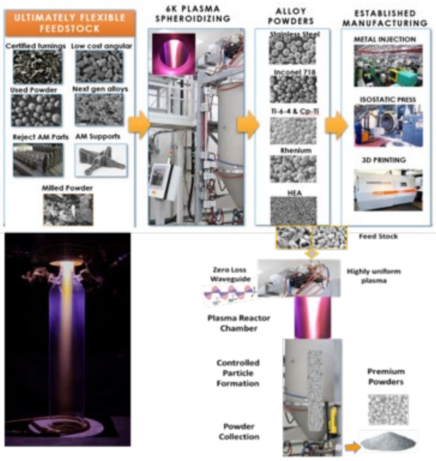
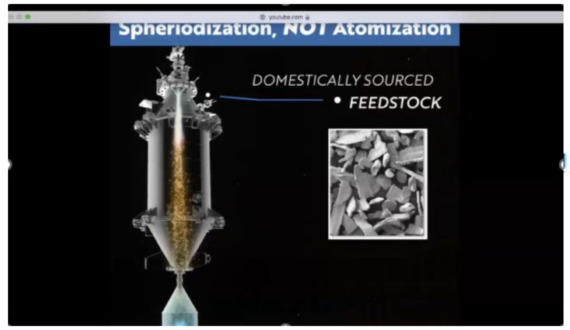
Powder reconditioning (deoxidation) technology

Develop powder reconditioning (deoxidation) technology based on plasma spheroidization process





Plasma spheroidization process in the presence of hydrogen

6K Additive (https://www.6kinc.com/metal-powder-for-additive-manufacturing)

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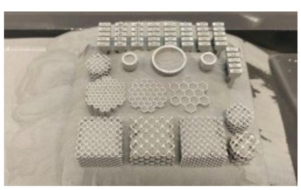
Research Objectives

Develop laser and electron-beam powder bed additive manufacturing processes of the W-24Re alloy.

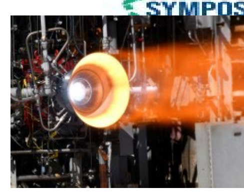


Additive Manufacturing

Develop powder reconditioning (deoxidation) technology.

Powder Reconditioning

Investigate the performance of W-24Re components produced using virgin and recycled powders.



Hot Fire Test of AMed Rocket Nozzle

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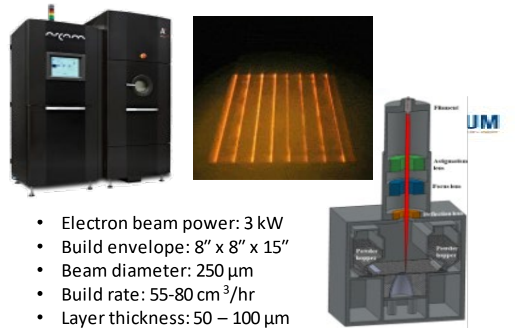
Technical Approach

Develop laser powder bed fusion (L-PBF), and electron beam powder bed fusion (E-PBF) of W-24Re alloy

Laser Powder Bed Fusion

- Laser beam power: 200 W
- Build envelope: 4″ x 4″ x 4″
- Beam diameter: 75 µm
- Build rate: 1 - 9 cm^3/hr
- Layer thickness: 15 – 30 µm

Electron Beam Powder Bed Fusion



- Electron beam power: 3 kW
- Build envelope: 8″ x 8″ x 15″
- Beam diameter: 250 µm
- Build rate: 55-80 cm^3/hr
- Layer thickness: 50 – 100 µm

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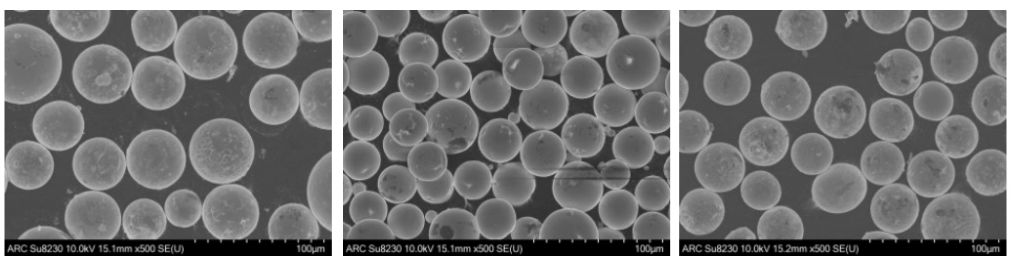
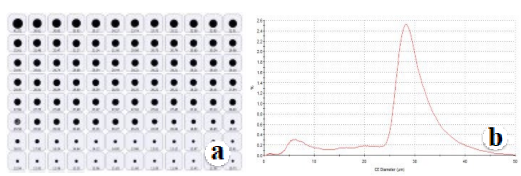
As-received powder morphology



Re **W** **W-22Re**



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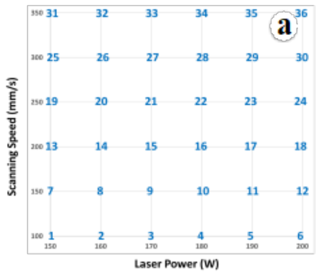
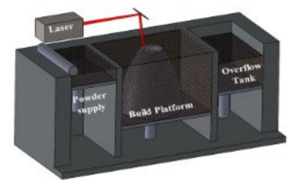
Laser Powder Bed Fusion (LPBF) of Pure W



Design of Experiments Matrix

- **Laser Power: 150– 200 Watts**
- **Scan Speed: 100– 350 mm/s**
- **Layer Thickness: 20 µm**



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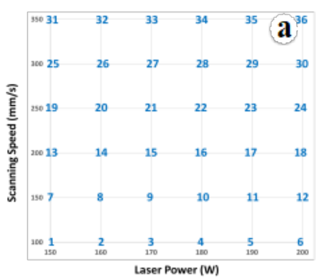
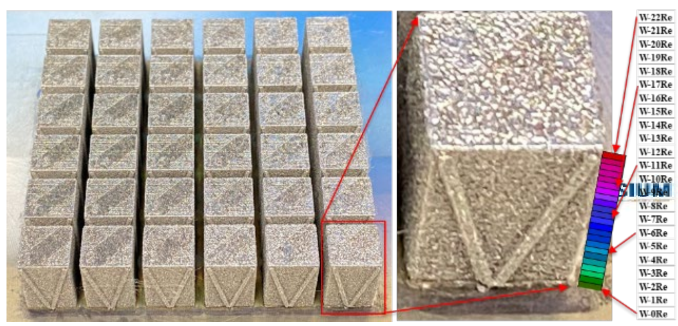
Design of Experiments for LPBF of W-Re Gradient Materials



Design of Experiments Matrix

- **Laser Power: 150– 200 Watts**
- **Scan Speed: 100– 350 mm/s**
- **Layer Thickness: 20 µm**



Concentration of Re gradually increased from 0 wt.% at the bottom to 22 wt.% at the top.

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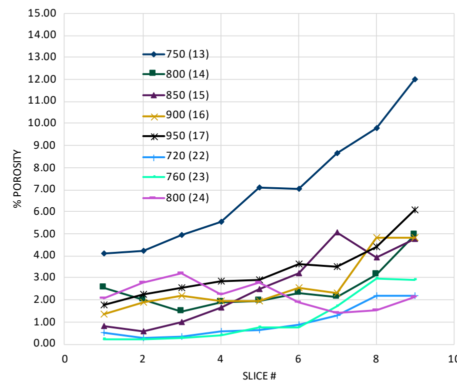
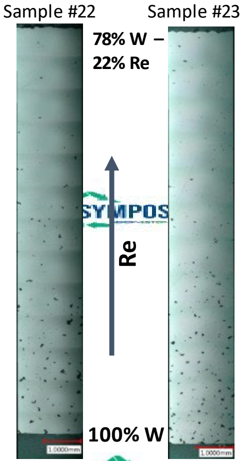
Laser Energy Density vs. Porosity

Sample ID	Laser Power	Scanning Speed	Volumetric Energy Density
6	200	100	2000.00
5	190	100	1900.00
4	180	100	1800.00
3	170	100	1700.00
2	160	100	1600.00
1	150	100	1500.00
12	200	150	1333.33
11	190	150	1266.67
10	180	150	1200.00
9	170	150	1133.33
8	160	150	1066.67
18	200	200	1000.00
7	150	150	1000.00
17	190	200	950.00
16	180	200	900.00
15	170	200	850.00
24	200	250	800.00
14	160	200	800.00
23	190	250	760.00
13	150	200	750.00
22	180	250	720.00
21	170	250	680.00
30	200	300	666.67
20	160	250	640.00
29	190	300	633.33
19	150	250	600.00
28	180	300	600.00
36	200	350	571.43
27	170	300	566.67
35	190	350	542.86
26	160	300	533.33
34	180	350	514.29
25	150	300	500.00
33	170	350	485.71
32	160	350	457.14
31	150	350	428.57

78% W – 22% Re → 100% W





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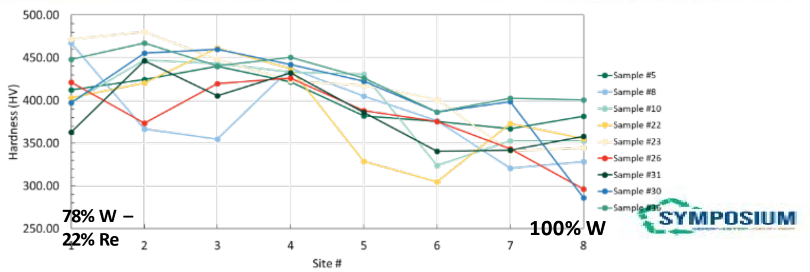
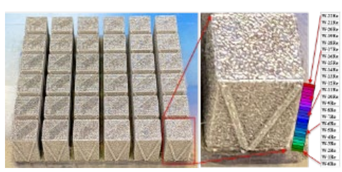
Hardness Distribution





Scanning Speed (mm/s)						
350	31	32	33	34	35	36
300	25	26	27	28	29	30
250	19	20	21	22	23	24
200	13	14	15	16	17	18
150	7	8	9	10	11	12
100	1	2	3	4	5	6
Laser Power (W)	150	160	170	180	190	200

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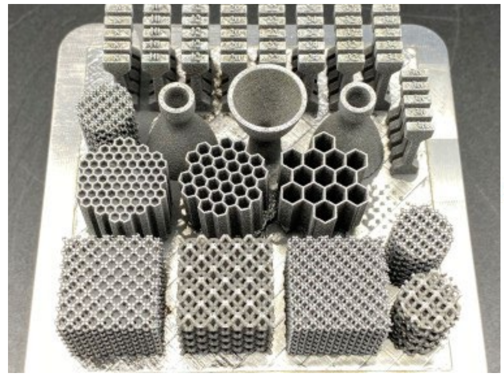
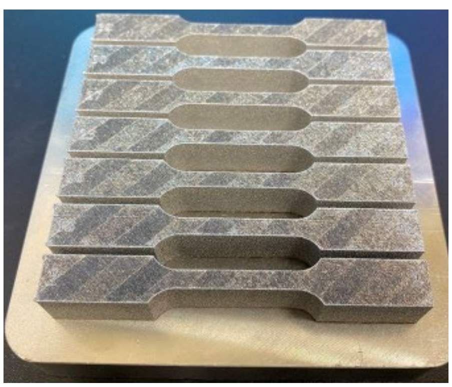
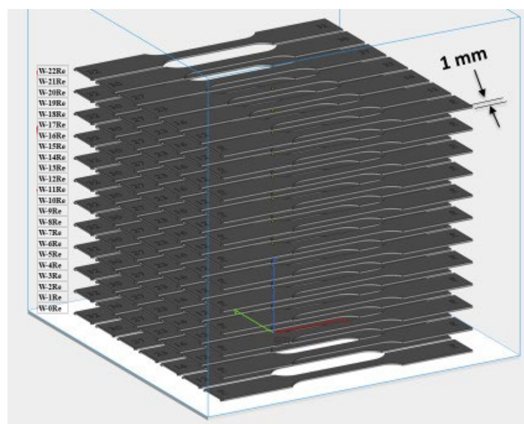
As-deposited W-22Re Components



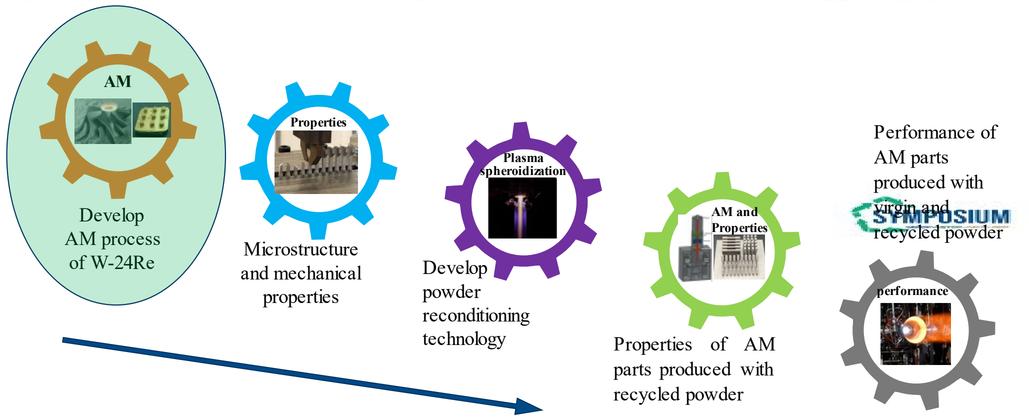
- Laser beam power: 180 W
- Scanning speed: 250 mm/s
- Beam diameter: 75 µm
- Layer thickness: 20 µm

As-deposited W/W-22Re gradient tensile test coupons





Future Work



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16

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Acknowledgements

Financial support from the Strategic Environmental Research and Development Program (SERDP) for this work is gratefully acknowledged.

We would like to thank Dien Li and John Bobbitt for technical inputs, and Bryt'ni Hill and Raden Gustinvil for metallographic analysis.

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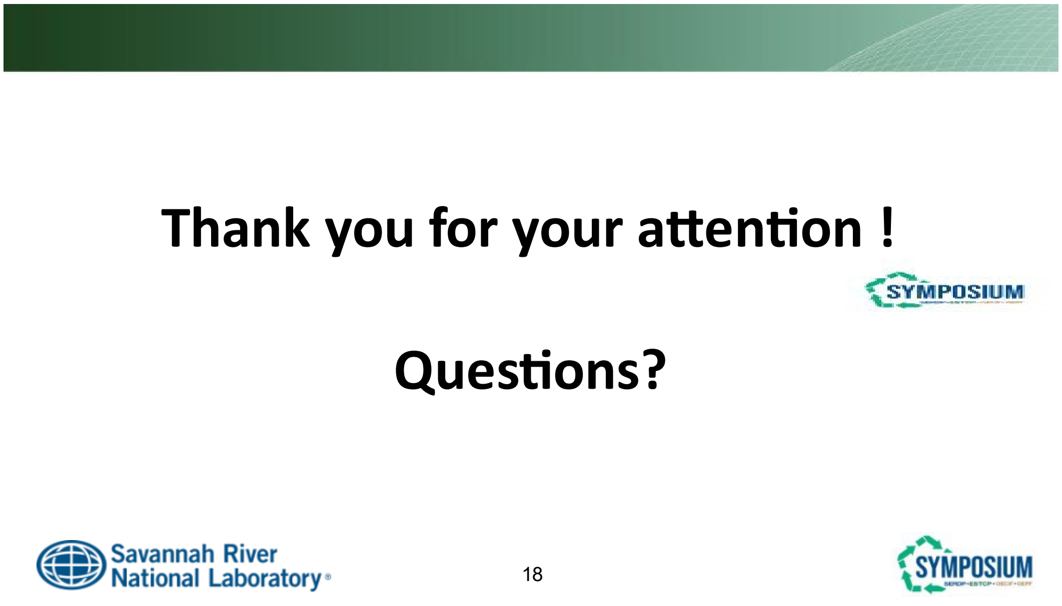
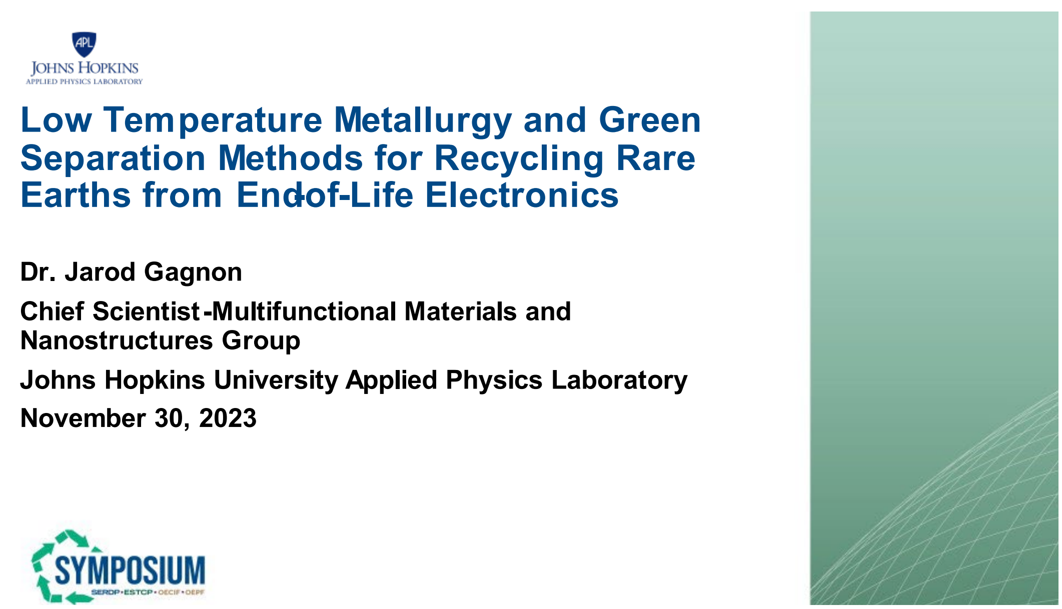


4.5 Low Temperature Metallurgy and Green Separation Methods for Recycling Rare Earths from End-of-Life Electronics

Presentation slides from Dr Jarod Gagnon are provided in this section.



Outline

- Background
- Pure Element Alloying
- Pure Element Separation
- Magnet Alloying
- Magnet Separation
- Technoeconomic Analysis
- Conclusions

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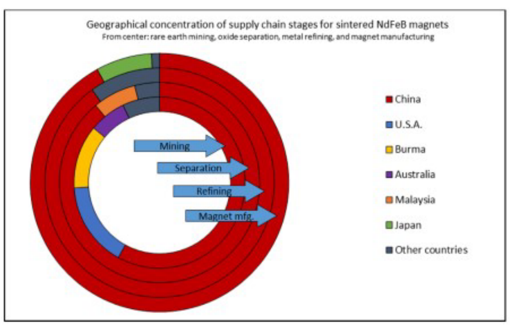
Rare Earth Supply Chain



Geographical concentration of supply chain stages for NdFeB, 2019 (Smith 2022).

- Rare earth oxide production is heavily localized.
- All parts of production must be addressed to create a new supply chain
- How do we address this?
  1. Open new mining, separation, and refining facilities
  2. Reduce Rare Earth Element (REE) need
  3. Find alternative sources of critical elements

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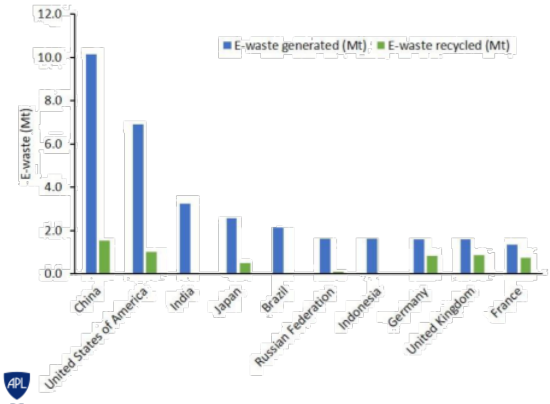
Rare Earth Recycling: Challenges and Potential



- 17% of e-waste was recycled in 2014
- 17.4% of e-waste recycled in 2019
- ~1% of Nd specifically is recycled

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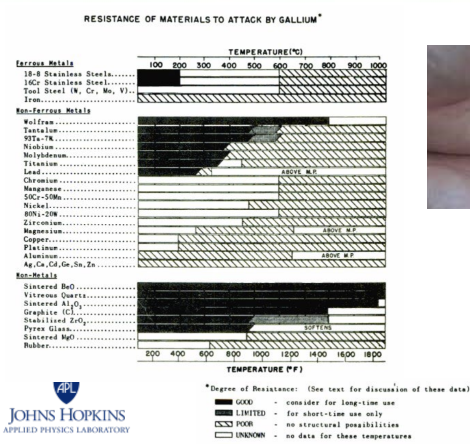
Low Temperature Alloying with Gallium



- Why Gallium?
  - Low T_m (~30°C)
  - Readily attacks metals and other materials
  - Low hazard

Gallium Hazards	
Corrosive to Metals	Category 1
Acute Oral Toxicity	Category 4

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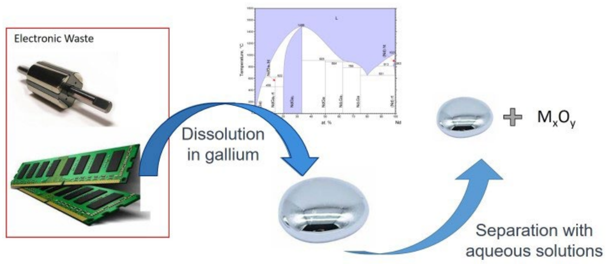
Low Temperature Alloying with Gallium



Goal: Demonstrate gallium-based destruction of COTS parts with simple aqueous separation of rare earth elements

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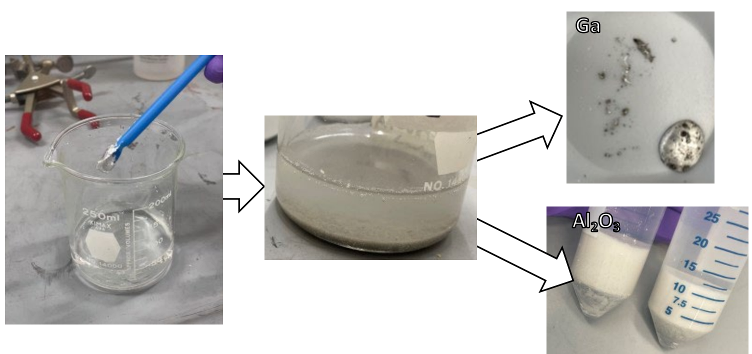
Aluminum-Gallium Separation



- Ga-Al amalgams separate in water
- Test viability with Ga -REE amalgams

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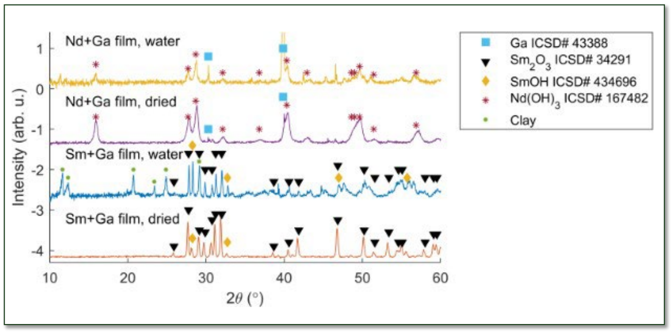
Pure Rare Earth Alloying



- Ambient control is critical for alloying
- Reaction proceeds slowly
- Rare earth hydroxides formed

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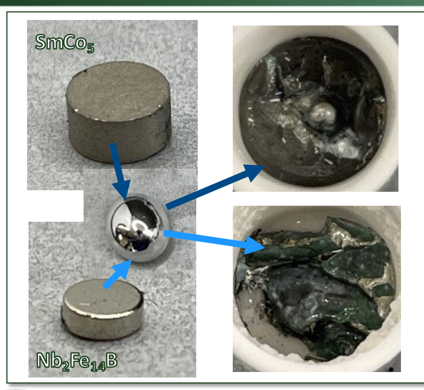
COTS Magnet Dissolution



- Magnets alloy with gallium readily
  - No pre-processing required
- Skin formed upon water exposure
- Resulting products likely require further separation

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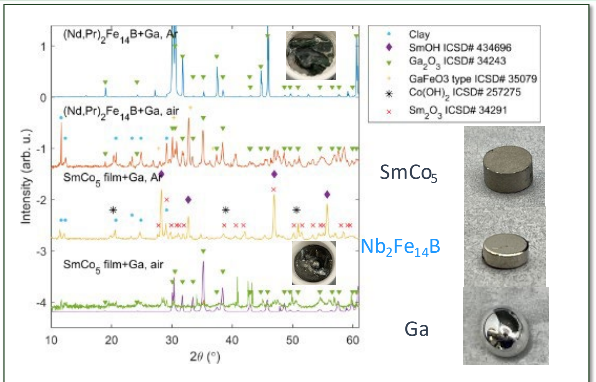
COTS Magnet Dissolution



- Magnets alloy with gallium readily
  - No pre-processing required
- Skin formed upon water exposure
- Resulting products likely require further separation

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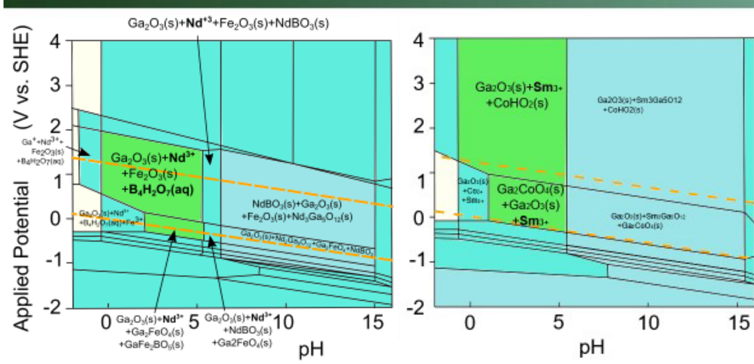
Electrochemical Separation- Background



- Electrochemical separation targets specific ions in aqueous solution
- Applied voltage is not required in these cases

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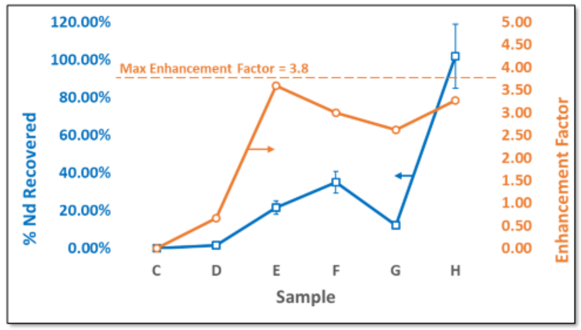
Electrochemical Separation Results

Sample ID	Sample Description
C	Nitric acid w/ agitation
D	Reacidified in nitric acid w/ agitation
E	Acetic acid w/o agitation
F	Acetic acid w/ agitation
G	Increased concentration nitric acid, reacidified, w/ agitation
H	Increased concentration of acetic acid w/ agitation

$$\text{Enhancement } Factor = \frac{Nd_l / (Nd_l + Fe_l + B_l)}{Nd_i / (Nd_i + Fe_i + B_i)}$$

l = concentration in leachate
i = concentration in magnet



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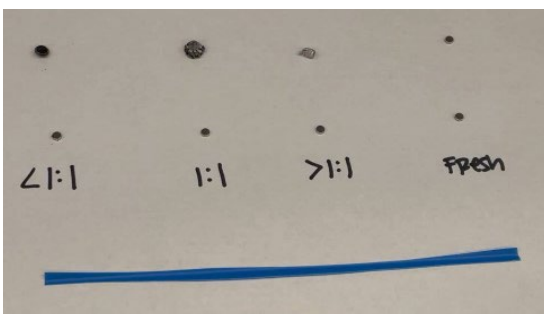
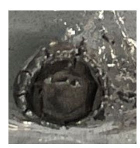
Impact of alloying temperature



- Magnets exposed to different amounts of gallium at 400°C.


Ga:magnet= 0.7


Ga:magnet= 1


Ga:magnet= 3.5

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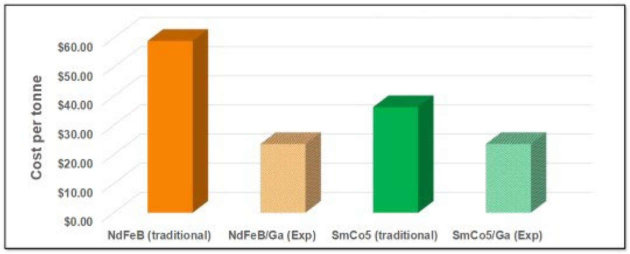
Technoeconomic Analysis



- Variability in reported specific heats and melting temperatures
- Used law of mixtures to estimate relative c and L values
- Melting temperature of mixture from experiment

$$Q_{tot} = m \cdot c \cdot \Delta T + m \cdot L$$

m = mass
c = specific heat
T = temperature
L = latent heat

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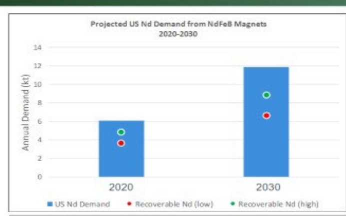
Technoeconomic Analysis



- Projections of potential recycled material from (Schulzea 2016).
- Assuming yields from experiments:
  - Nd: 75 – 100%
  - Sm: 50 – 100%
- Significant potential impact on demand from recycled materials even at lower recycling yields.

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Conclusions

- Gallium alloying has potential to dissolve end -of-life electronics at lower than melting temperature
- Rare earth elements can be separated in aqueous solutions with high yield and reasonable purity
- This research offers a potentially scalable, environmentally friendly alternative to increase recycling of supply -chain critical elements

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Next Steps

- Harvesting Nd product from leachate
  - Current data is calculated from ionic presence in the leachate
  - Other studies show methods for harvesting Nd from aqueous streams
- Optimization of yield and purity in Nd product
  - Leverage precipitation methods to improve purity and optimize yield
- Scalability studies
  - Determine key variables, byproducts, and optimization for process at larger scales

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4.6 Hydrometallurgical Treatment of Lead and Zinc Materials for Critical Metal Production

Presentation slides from Dr Corby Anderson are provided in this section.

Hydrometallurgical Treatment of Lead and Zinc Materials for Critical Metal Production

Dr. Corby G. Anderson PE
Director, Kroll Institute for Extractive Metallurgy
Colorado School of Mines

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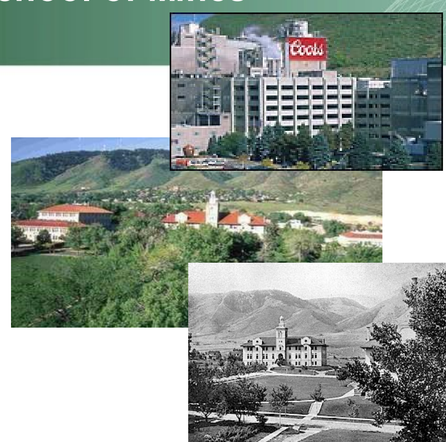
Colorado School of Mines

- Est. 1874
- Golden, Colorado
- 21 Technical Majors
- About 200 Faculty
- About 7000 Students

- "…has a unique mission in energy, mineral, and materials science and engineering…"
- "has the most stringent admission standards of any US public engineering school."
- "QS ranked #1 in the World for Mining and Mineral Engineering" by Business Insider.
- "Ranked as #1 US Engineering school" by USA Today.
- "average starting salary of a BSc Mines graduate is $ 10 K more than an Ivy League graduate."



MINES KIEM Kroll Institute for Extractive Metallurgy

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KIEM Kroll Institute for Extractive Metallurgy

Dr. Corby G. Anderson, PE
Director

Kroll Institute for Extractive Metallurgy

Mining Engineering Department
Colorado School of Mines

Recent Research Partners:
Newmont Mining, Tata Chemicals, Rio Tinto, Freeport McMoran, University of Wyoming, University of Utah, NREL, Ames Lab, Penn State, UNSA, WPI, KU Leuven, ORNL, INL, U of Tokyo, Electra Battery Metals, Lundin Mining, Sibanye Stillwater and many others !

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KIEM Kroll Institute for Extractive Metallurgy

A Research Center Located in the Department of Mining Engineering

- **KIEM was established in 1974 using funds provided by William Kroll who invented processes to produce titanium and zirconium metal from ores.**
- **Over the years, the Kroll Institute has provided support for a significant number of undergraduate and graduate students who have gone on to make important contributions to the mining, minerals and metals industries.**
- **The objectives are to provide research expertise, well-trained engineers to industry, and research and educational opportunities to students, in the areas of: minerals processing, extractive metallurgy, recycling, and waste minimization.**

The presentation of the first William J. Kroll Zirconium Medal to Admiral H. G. Rickover by Professor A. W. Schlechten, Director of the Kroll Institute for Extractive Metallurgy in 1975.

4


KIEM Kroll Institute for Extractive Metallurgy
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PATRICK R. TAYLOR
COLORADO SCHOOL OF MINES
CENTER FOR MINING SUSTAINABILITY
Jihye Kim
Assistant Professor
GERARD MARTINS
BROCK O'KELLEY
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Nitrogen Species Catalyzed (NSC) Leaching Fundamentals

$$3\ MeS_{(S)} + 2HNO_{3\,(Aq)} + 3H_2SO_{4\,(Aq)} \rightarrow 3\ MeSO_4 + 3S^o_{(S)} + 2NO_{(G)} + 4H_2O$$

$$NaNO_{2\,(Aq)} + H^+ \rightarrow HNO_{2\,(Aq)} + Na^+$$

$$HNO_{2\,(Aq)} + H^+ \rightarrow NO^+_{(Aq)} + H_2O$$

$$2MeS_{(S)} + 4NO^+_{(Aq)} \rightarrow 2Me^{+2}_{(Aq)} + 2S^o + 4NO_{(G)}$$

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7

SYMPOSIUM SERDP • ESTCP • OECIF • OEPF

Nitrogen Species Catalyzed (NSC) Leaching Fundamentals

Relative Potentials of Hydrometallurgical Oxidizers.

Oxidant	Redox Equation (pH = 0, H_2 ref.)	E^0_h
Fe^{+3}	$Fe^{+3} + e^- \rightarrow Fe^{+2}$	0.770 V
HNO_3	$NO_3^- + 4H^+ + 3e^- \rightarrow NO_{(g)} + 2H_2O$	0.957 V
HNO_2	$NO_2^- + 2H^+ + e^- \rightarrow NO_{(g)} + H_2O$	1.202 V
$O_{2\,(g)}$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	1.230 V
Cl_2 (g)	$Cl_{2\,(g)} + 2e^- \rightarrow 2\ Cl^-$	1.358 V
NO^+	$NO^+ + e^- \rightarrow NO_{(g)}$	1.450 V

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Nitrogen Species Catalyzed (NSC) Leaching Fundamentals

$$2NO_{(G)} + O_{2(G)} <--> 2NO_{2(G)}$$

$$2NO_{2(G)} <--> 2NO_{2(Aq)}$$

$$2NO_{2(Aq)} + 2NO_{(Aq)} + 4H^+ <--> 4NO^+_{(Aq)} + 2H_2O$$

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9

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Nitrogen Species Catalyzed (NSC) Leaching Fundamentals

$$2MeS_{(G)} + 4H^+ + O_{2(G)} \rightarrow 2Me^{+2}_{(Aq)} + 2S^o + 2H_2O$$

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NSC Hydrometallurgical Treatment of a Gallium Slag

In an eventual industrial pilot plant scenario, slag concentrate from a smelting of a germanium zinc concentrate processing by product was a candidate material.

An unoptimized NSC pressure oxidation leach was performed on this material.

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NSC Hydrometallurgical Treatment of a Gallium Slag

Composition of Gallium Slag

Zn, %	Fe, %	Ga, %	Ge, %	Total S, %
10.6	21.86	1.86	0.02	4.33

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NSC Hydrometallurgical Treatment of a Gallium Slag

Nitrogen Species Catalyzed Partial Oxidation Leach Conditions.

Operating Criteria	Unit
Initial Free Sulphuric Acid	150 g/L
Reactor Working Pressure	620 kPag
Slurry Solids Content	100 g/L
Solids Size	80% -10 micron
Maximum Temperature	105°C
Nitrogen Species Concentration	2.0 g/L
Reaction Time	120 min

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13

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NSC Hydrometallurgical Treatment of a Gallium Slag

Mass Distribution of Nitrogen Species Catalyzed Partial Oxidation Leach Products

	Zn, %	Ga, %	Ge, %	Fe, %
Solution	75.21	75.16	0.90	43.69
Residue	25.79	24.84	99.10	56.31

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14

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NSC Pressure Oxidation of a Lead Concentrate With Base and Precious Metals

A complex polymetallic lead and zinc orebody containing many other base metals and gold and silver was to be developed.

It was desired to selectively leach base and precious metals from the concentrate leaving behind a lead sulphide residue suitable for smelting.

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15

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NSC Pressure Oxidation of a Lead Concentrate With Base and Precious Metals

Lead Concentrate Elemental Analysis.

Pb, %	Zn, %	Co, %	Cu, %	Ni, %	Ag g/T	TS, %	TC, %
21.6	2.66	0.81	2.02	0.66	53.0	18.9	8.5

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16

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NSC Pressure Oxidation of a Lead Concentrate With Base and Precious Metals

NSC Locked Cycle Conditions and Recoveries to Solution

Locked Cycles = 7
Recycle Percentage = 25 %
Grind Time = 10 minutes
Initial Free Sulfuric Acid = 200 g/L
Reactor Working Pressure = 620 kPag
Slurry Solids Content = 100 g/L
Maximum Temperature = 130 C
Total Tine = 60 minutes
Nitrogen Species Concentration = 2.0 g/L
Copper Average Recovery = 95.1 %
Silver Average Recovery = 96.2 %
Cobalt Average Recovery = 97.3 %
Zinc Average Recovery = 98.4 %
Nickel Average Recovery = 96.8 %

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17

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Alkaline Sulfide Hydrometallurgy (ASL)

- **Sodium sulfide, Na_2S, is a very selective lixiviant.**
- **Only As, Hg, Sb, Au, Te and Sn have significant solubilities.**
- **Previously it was used in the USA for copper concentrate treatment and Sb production.**
- **Was industrially for Sb production in USSR, Australia and China.**

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18

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Alkaline Sulfide Hydrometallurgy (ASL)

- **Antimony and Mercury are universally soluble.**
- **Gold, Tin, Tellurium and Arsenic solubility is dependent on mineralogy.**
- **Some solubility of Silver depending on mineralogy.**
- **Some minimal solubility of Copper and Iron.**

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19

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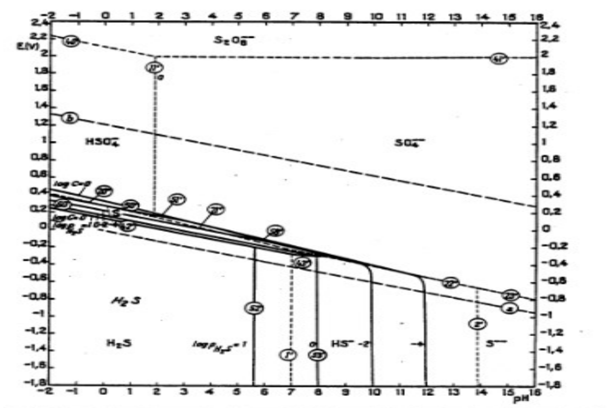
Alkaline Sulfide Hydrometallurgy- Sulfur Stability Diagram



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20

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Alkaline Sulfide Hydrometallurgy

$$4S + 6OH^- \rightarrow 2S^{2-} + S_2O_3^{2-} + H_2O$$

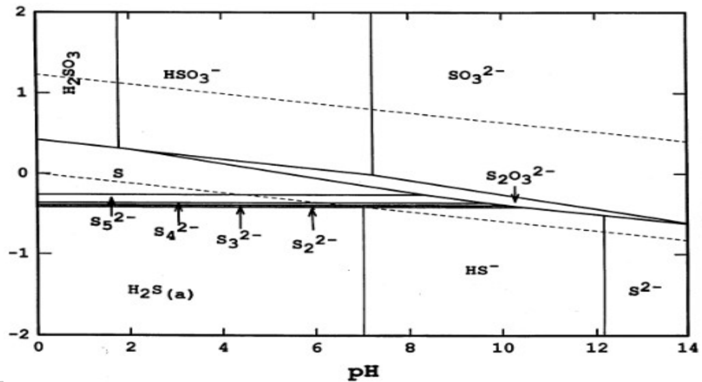
$$(X\text{-}1)S + S^{2-} \rightarrow S^{2-}_X \quad \text{(where X = 2 to 5)}$$

$$S_X^{2-} + 2(X\text{-}1)e^- \rightarrow xS^{2-}$$

$$S_2^{2-} + 2e^- \rightarrow 2S^{2-}$$

Alkaline Sulfide Solutions

Alkaline Sulfide Hydrometallurgy
Sulfur Meta Stable Species Diagram



23

Alkaline Sulfide Hydrometallurgy

$Na_2S + As_2S_3 \rightarrow 2NaAsS_2$

$NaAsS_2 + Na_2S \rightarrow Na_3AsS_3$

$1.5\ H_2O + 2\ Na_2S + \frac{1}{2}\ As_2O_3 \rightarrow NaAsS_2 + 3\ NaOH$

$NaAsS_2 + Na_2S \rightarrow Na_3AsS_3$

24

Alkaline Sulfide Hydrometallurgy

$$Na_2S + Sb_2S_3 \rightarrow 2NaSbS_2$$

$$NaSbS_2 + Na_2S \rightarrow Na_3SbS_3$$

$$1.5\ H_2O + 2\ Na_2S + \frac{1}{2}\ Sb_2O_3 \rightarrow NaSbS_2 + 3\ NaOH$$

$$NaSbS_2 + Na_2S \rightarrow Na_3SbS_3$$

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25

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Alkaline Sulfide Hydrometallurgy

$$Na_2S + HgS \rightarrow Na_2HgS_2$$

$$Na_2S + Hg_2S \rightarrow 2\ NaHgS$$

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26

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Alkaline Sulfide Hydrometallurgy

$Na_2S + SnS_2 \rightarrow Na_2SnS_3$

$H_2O + 2\ Na_2S + SnO \rightarrow Na_2SnS_2 + 2\ NaOH$

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27

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Alkaline Sulfide Gold Recovery Process

Overall Reaction

$2Au + S_2^{2-} + 2S^{2-} \rightarrow 2AuS^- + 2S^{2-}$

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28

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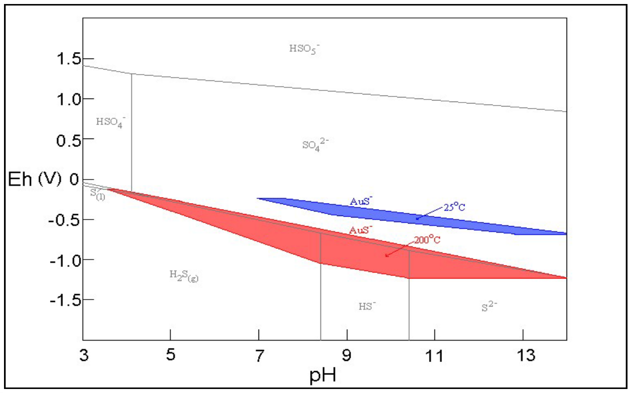
Alkaline Sulfide Gold Recovery Process



29

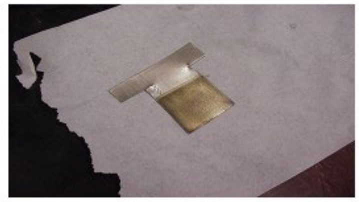
Alkaline Sulfide Gold Recovery Process

- Electrowinning
- Cementation
- Gaseous Precipitation
- Chemical Precipitation
- Solvent Extraction
- Ion Exchange

30

Alkaline Sulfide Gold Recovery Process

Recovery: Electrowinning



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31

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Alkaline Sulfide Gold Recovery Process

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32

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Alkaline Sulfide Gold Recovery Process

Alkaline Sulfide Waste Solution Treatment

$$2\ O_2 + Na_2S \rightarrow Na_2SO_4$$

$$3.5\ O_2 + 2\ NaOH + Na_2S_2 \rightarrow 2\ Na_2SO_4 + H_2O$$

$$8\ O_2 + 8\ NaOH + Na_2S_5 \rightarrow 5\ Na_2SO_4 + 4\ H_2O$$

$$2\ NaOH + 2\ O_2 + Na_2S_2O_3 \rightarrow 2\ Na_2SO_4 + H_2O$$

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Alkaline Sulfide Gold Recovery Process

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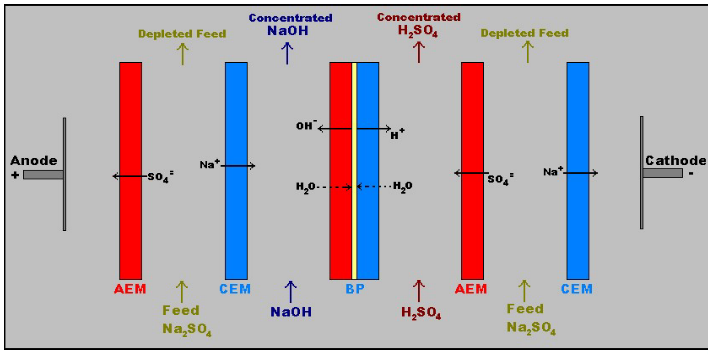
Na_2SO_4 Splitting Through Electrodialysis

Sulfuric Acid and Caustic Production from Sodium Sulfate.



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35

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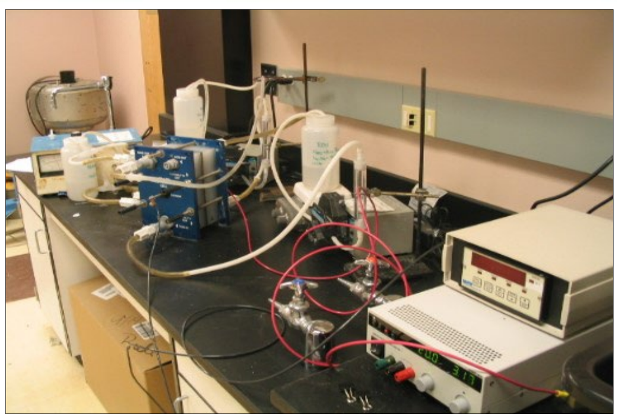
Na_2SO_4 Splitting Through Electrodialysis



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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelt Copper Dross Flue Dust

The formation of arsenic and antimony laden dusts in the processing of lead is commonly encountered.

An example of hydrometallurgical treatment of this material follows.

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37

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelt Copper Dross Flue Dust

Copper Dross Flue Dust Head Sample Assay

In, %	Pb,%	Sb,%	As,%	Zn,%
0.3	46.0	9.0	12.0	11.0

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38

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelt Copper Dross Flue Dust

Leach Testing Conditions

Leach Time = 6 Hr.
Percent Solids = 25%
Leach Temperature = 105 C
Sulfide Concentration = 100 g/L
Free Hydroxide Concentration = 10 g/L

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39

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelt Copper Dross Flue Dust

Leach Test Results

% of Metal Leached

In, %	Pb,%	Sb,%	As,%	Zn,%
0.0	0.0	95.0	99.0	0.0

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40

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelter Tin Removal Salt

The presence of tin in lead smelters is a common occurrence and poses problems.

Alkaline sulfide hydrometallurgy can be effective in treating these types of smelter waste.

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41

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelter Tin Removal Salt

Lead Smelter Tin Salt Head Sample Assay

Pb %	As %	Sb %	Sn %
76.3	0.20	0.53	8.20

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42

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelter Tin Removal Salt

ASL Leach Testing Conditions

Leach Conditions: Time = 8 Hr
Solids = 5%
Temperature = 90^{O} C
Total Sulfur Concentration = 50 g/L
Free Hydroxide Concentration = 0 g/L Leach

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43

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelter Tin Removal Salt

ASL Leach Test Results

% of Metal Leached

Pb %	As %	Sb %	Sn %
0.0	100.0	100.0	91.1

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44

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelter Speiss

The formation of speiss in lead smelters is a common occurrence and poses problems.

Significant levels of precious metals are accumulated in the the resultant arsenides and antimonides.

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45

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelter Speiss

Lead Smelter Speiss Head Sample Assay

Cu,%	Ni,%	Sn,%	Cd,%	As,%	Sb, %	Pb,%	Fe,%	Zn,%	Au g/T,	Ag, g/T
43.5	1.4	0.5	0.1	12.2	3.3	14.8	1.7	0.9	45.0	9000

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46

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelter Speiss

Leach Testing Conditions

Leach Time = 6 Hr.
Percent Solids = 25%
Leach Temperature = 105O C
Total Sulfur Concentration = 100 g/L
Free Hydroxide Concentration = 25

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47

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Alkaline Sulfide Hydrometallurgical Treatment of Lead Smelter Speiss

Leach Test Results

% of Metal Leached

Cu,%	Ni,%	Sn,%	Cd,%	As,%	Sb, %	Pb,%	Fe,%	Zn,%	Au %,	Ag%
0.0	0.0	2.0	0.0	99.1	99.4	0.0	0.0	0.0	9.1	0.0

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48

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Application of Alkaline Sulfide Hydrometallurgy to a Lead Concentrate with Antimony, Arsenic, Gold Silver and Mercury

As a further example of the flexibility of the alkaline sulfide leaching technology the following summary is presented.

In this case, an industrial lead concentrate producer wished to leach as much antimony, mercury, gold and silver as possible before shipping to a smelter.

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49

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Applications of Alkaline Sulfide Hydrometallurgy to a Lead Concentrate with Antimony, Arsenic, Gold Silver and Mercury

Table 12 - Concentrate Composition (%)

Sb	As	Hg	Pb	Au, g/tonne	Ag, g/tonne	TS, %
5.3	0.85	0.11	46.1	640.6	2000.4	32.0

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50

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Applications of Alkaline Sulfide Hydrometallurgy to a Lead Concentrate with Antimony, Arsenic, Gold Silver and Mercury

Table 13 - Alkaline Sulfide Leach Results (%)					
Sb	As	Hg	Pb	Au	Ag
95.4	86.3	95.2	0.0	78.30	19.3
Leach Conditions: Time = 8 Hr, Concentrate = 100 g/L, Temperature = 100^{o} C, Sulphide Addition =50 g/L, Sulphur Addition 5 g/L, Sodium Hydroxide = 10 g/L					

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51

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Hydrometallurgical Treatment of Lead and Zinc Materials for Critical Metal Production

Thank You For This Opportunity To Present !

Questions ?

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52

SYMPOSIUM

4.7 3D Printing with Reclaimed Thermoplastics

Presentation slides from Patrick Ferrell and Samantha Snabes are provided in this section.

3D Printing with Reclaimed Thermoplastics

Patrick Ferrell; Senior Engineer

Samantha Snabes; Co-Founder/Catalyst

Company Overview

- re:3D's revenue is derived from the Gigabot® product line, on-site service & training, additive manufacturing consulting and in-house contract print and design services, with repeat orders, to customers in over 50 countries
- Current customers include hospitals, universities, Fortune 500 companies, government agencies and specialty manufacturers
- As a member of America Makes and an active partner on university grants furthering academic rigor in additive manufacturing, re:3D is on the leading edge of industry R&D
- re:3D maintains a 10,000 sq/ft manufacturing facility with all of the to jigs, fixtures, and know-how necessary to design, test, iterate, and build
- Frequently recognized by leading design, commerce, and technology organizations for innovation and success
- Woman-Owned, Veteran-Owned Small Business
- ITAR Compliant
- 2020 Tibbetts recipient for commercializing hardware and selling outcomes globally from three Phase II SBIR awards

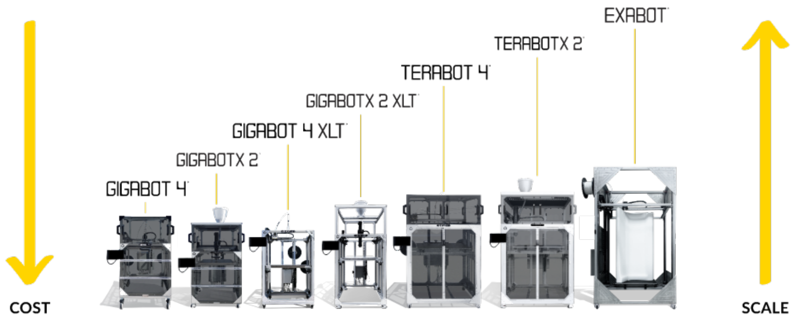
Current DoD/Aerospace Customers

Strategic Partnerships

Media Recognition

2

3D Printer Portfolio



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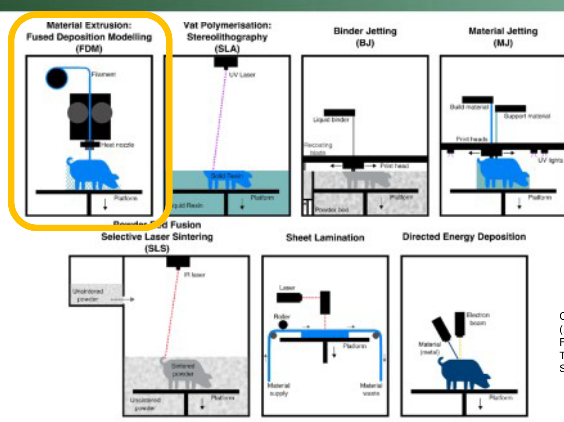
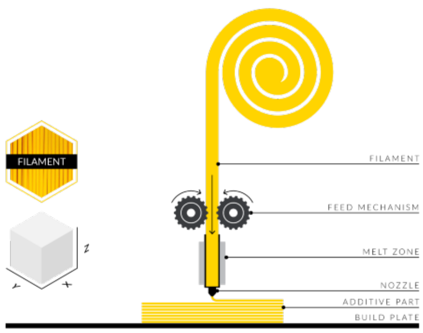
Classifications of Additive Manufacturing Technologies (ASTM F42)



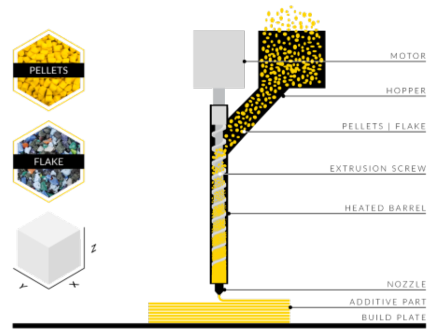
Carew, Rachael & Errickson, David. (2020). An Overview of 3D Printing in Forensic Science: The Tangible Third-Dimension. Journal of Forensic Sciences. 65. 10.1111/1556-4029.14442.

4

Filament Versus Pellet Printing



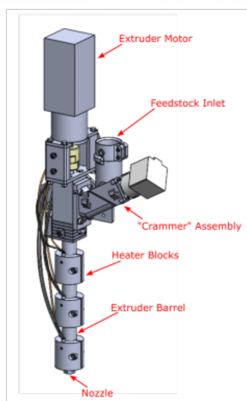
Fused Filament Fabrication (FFF)



Fused Granular Fabrication (FGF)

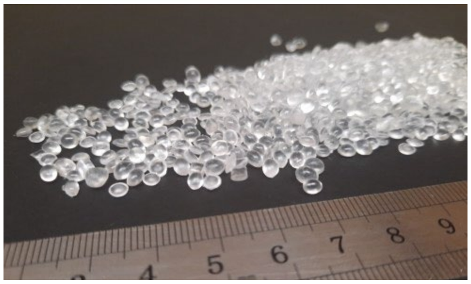
5

GigabotX 2 Pellet Extruder

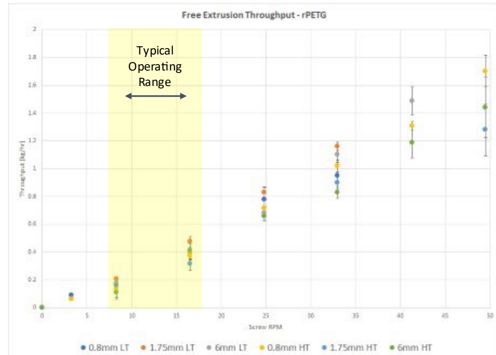


6

GigabotX 2 Throughput Testing



Greengate rPETG Resin Pellets



7

Recent Research Grants

AFWERX SBIR AF191-004 (Phase I & II)
Full-Scale Additively Manufactured Training Aids for DOD

NSF SBIR No. 1853153 (Phase II)
Increasing Maker Manufacturing through 3D Printing with Reclaimed Plastic & Direct Drive Pellet Extrusion

NSF SBIR Phase II: Puerto Rico Science, Technology and Research Trust (Cash Match)

Oak Ridge National Laboratory CRADA
Affordable, Large Scale Granulator Development Designed to Process Reclaimed Feedstock for Sustainable Additive Manufacturing Applications

US Army Advanced Medical Technology Initiative
Additively Manufactured Surgical Instruments for Performing Surgical Operations in Theater

US Air Force SBIR AF211-CSO1 F2-15404 (Phase I & II)
Creating Value from Base Waste with Translation to Austere Environments: 3D Printing in Mobile Recycling Facilities

US Army xTech SBIR A224-016 (Direct to Phase II)
Off Grid 3D Printing of Army Supplies Directly From Discarded Plastic Waste

NSF Convergence 2022 No. 49100423C0002 (Phase I)
Creating Impact from Local Plastic Waste Using Off -Grid Containerized 3D Printers & Practice Based Learning

NASA STTR 2021 T12.05-3097 (Phase I & II)
3D Printing of High Temperature Thermoset Foams for Space Vehicular Thermal Protection Systems

NASA SBIR (Phase III)
Demonstration of 3D Printing from Common Space Waste Streams

NASA SBIR Ignite 2022 (Phase I & II)
On-Orbit Additive Manufacturing Using Recycled Waste

8

NSF SBIR Phase II

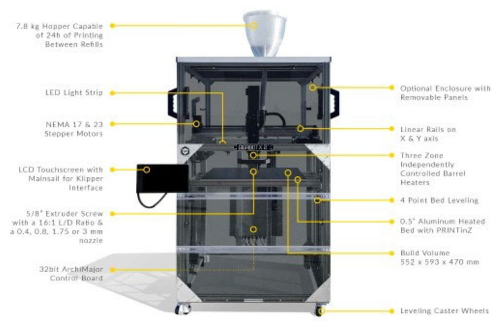
Problem:

- Limited manufacturing and supply chains in resource-limited or remote environments
- High material costs of 3D printing at large scale with filament
- Insufficient recycling infrastructure for plastic waste pollution

NSF SBIR Phase II

Results:

- GigabotX in Regular, XLT, and Terabot build sizes
- 20+ tested materials and a standardized testing procedure
- Nozzle sizes for 0.4mm, 0.8mm, 1.75mm, 2.85mm
- Open Source published paper on 3D printing with rPET flake
- Simplify3D Printing Profiles
- Hopper Gantry design
- Pilot collaboration with Habitat for Humanity ReStore



Puerto Rico Science, Technology and Research Trust

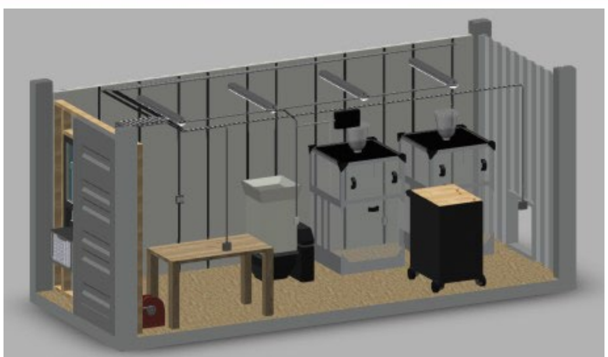
Use Case:

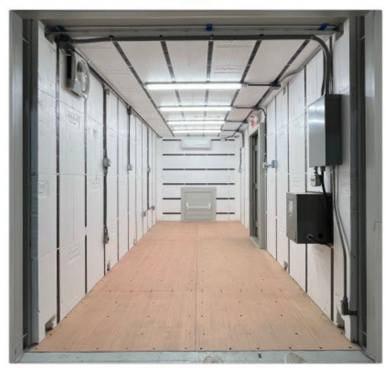
- Limited landfill space
- Single use water bottles deployed after Hurricane Maria
- Infrastructure disruption after natural disasters

Image Credit: CBS News

11

Puerto Rico Science, Technology and Research Trust

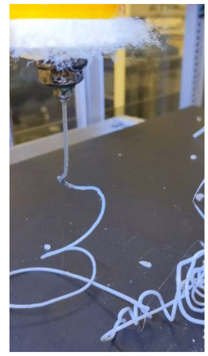




re:3D's first fielded "Gigalab"

12

Oak Ridge National Laboratory CRADA: Granulation



Developing a large-scale granulator capable of accommodating unemptied water bottles for size reduction and separation prior to recycling via 3D printing.

13

GigabotX 2 and the Gigalab: Defense Application Background

Contested environments present unique challenges for maintaining equipment or prototyping on-demand solutions in military operations. Resource scarcity as well as regional considerations must be anticipated in advance in order to ensure that all necessary materials are forward deployed, as well as to remove waste generated [1].

Recent manufacturing advancements offer potential locally based alternatives to reduce the dependence on materials and equipment otherwise imported into theater. For example, the versatility of 3D printers are more frequently becoming available to warfighters in order to support on-site innovation [2].

The ability to source locally available raw material and feed it directly as pellets or shavings/flake into a printer rather than extruded filament could be extremely advantageous for the warfighter by reducing cost and increasing capabilities in prototyping [3].

re:3D's 3D pellet printer and additional waste processing hardware contained in an expeditionary format will support on demand production of prints of value that could be fabricated from water bottles, MRE wrappers or other thermoplastic waste streams sourced from bases in CONUS, disaster response support efforts, or in theater.

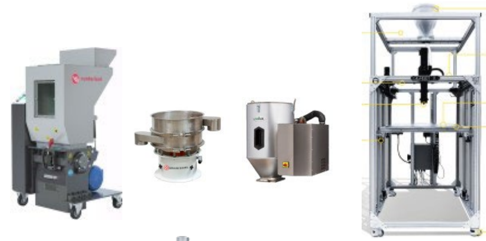
1. Forest, B. D. (2017, March 22). The Future of Additive Manufacturing in Air Force Acquisition. (Unpublished Research Report, Air University). Air War College. doi:http://www.dtic.mil/dtic/tr/fulltext/u2/1038118.pdf
2. TCT. U.S. Air Force to 3D print replacement parts with 3D Systems Figure 4. (2018, April 26). Retrieved from https://www.tctmagazine.com/tct-events/3d-printing-at-rapid-tct/us-air-force-research-3d-print-replacement-parts-figure-4/
3. Shiyi Liu, Peng Zhao, Senyang Wu, Chengqian Zhang, Jianzhong Fu, Zichen Chen, "A Pellet 3D Printer: Device Design and Process Parameters Optimization", Advances in Polymer Technology, vol. 2019, Article ID 5075327, 8 pages, 2019. https://doi.org/10.1155/2019/5075327

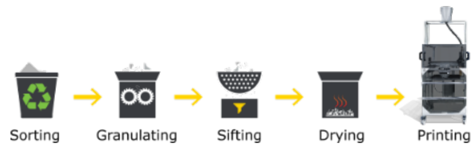
14

GigabotX 2 and the Gigalab: Configuration

- Gigalabs are custom-converted 20-ft shipping containers
- Typically one or two containers per installation depending on application requirements
- Shore power and multiple off-grid power solutions are being developed

A single 20-ft CONEX is sufficient for a GigabotX 2 XLT printer, plus workspace and room for the ancillary equipment required to pre-process the plastic waste.



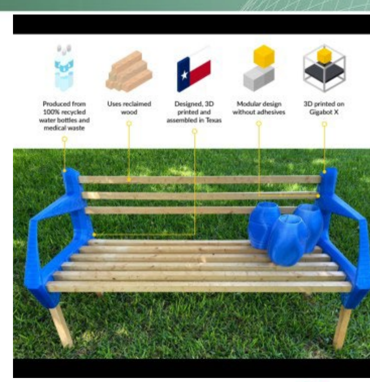


NSF Convergence 2022

Demonstration Site:
Austin Habitat for Humanity ReStore; Austin, Texas

Gigalab Configuration:
- One container
- GigabotX 2 XLT
- Cumberland Granulator, Conair Desiccant Dryer
- Shore power to ReStore run on solar power

Target Waste Streams:
- Low value plastic donated materials
- Bulky Plastic bins
- Water bottles from store operations
- Local manufacturing waste



U.S. Air Force SBIR AF211CSO1 F2-15404

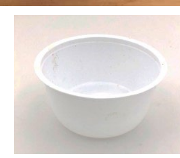
Demonstration Site:
U.S. Air Force Academy (USAFA); Colorado Springs, Colorado

Gigalab Configuration:
- 2 Containers
- GigabotX 2
- Cumberland Granulator, Dehydrator
- Off-Grid Power (solar/wind)

Target Waste Streams:
- Waste PLA from failed/discarded FFF prints
- Dining hall waste plastics
- ???

17

USAFA Waste Collection and Printability Testing



18

U.S. ArmyxTech SBIR A224-016

Demonstration Site:
Contingency Basing Integration Training, Evaluation Center (CBITEC); Fort Leonard Wood, Missouri

Gigalab Configuration:
- Two containers
- GigabotX 2 XLT, TerabotX 2
- Cumberland Granulator, Gerard Daniel Separator, Conair Desiccant Dryer
- Generator power (AMMPS)

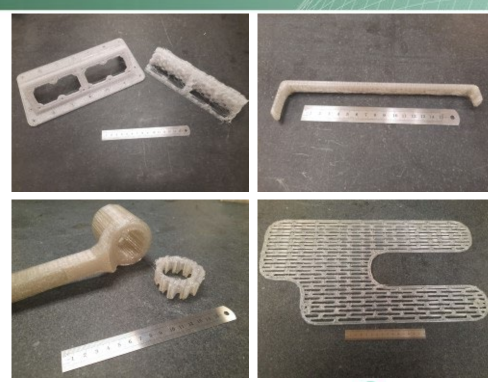
Target Waste Streams:
- PET water bottles
- MRE wrappers
- Shipping waste
- ????

rPETG Resin Pellets Baseline Prints

rPETG pellets are used to baseline theGigabotX 2 performance on part files provided by DEVCOMs or developed in-house for field applications.

These exemplar parts are also printed from granulated recycled waste as appropriate materials are identified.

Top Left: Weatherproof Enclosure
Top Right: DfAM Surgical Chest Retractor
Bottom Left: Generator Wrench
Bottom Right: Generator Fan Guard



U.S. ArmyxTech: Potential Waste Streams


PET waste collection (Fort Leonard Wood)

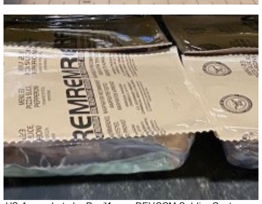

Water can (Fort Cavazos)


Range target (Fort Cavazos)


Shipping waste (Fort Cavazos)

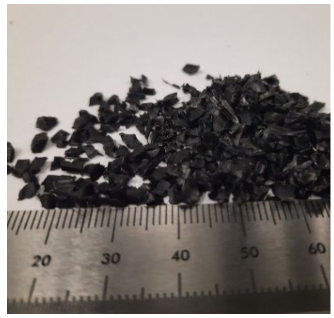
21

HFFS Meal Pouch Film (MRE Wrappers)


US Army photo by David Kamm, DEVCOM Soldier Center

22

Shipping Waste


23

PET Water Bottles


24

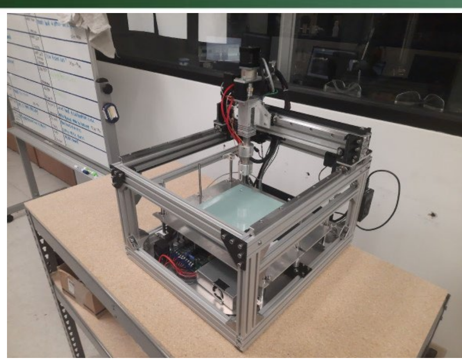
NASA SBIR Phase III (Gateway / Deep Space Logistics)

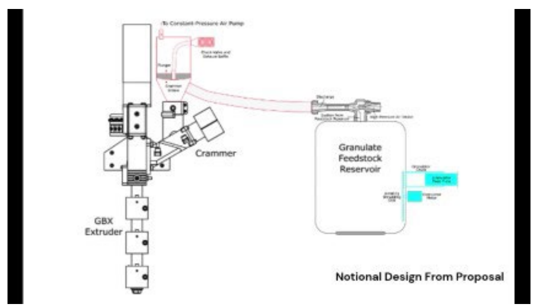
Funded by the Deep Space Logistics team from NASA's Gateway program to identify, analyze and test printability of on-orbit waste streams for potential use in recycling via material extrusion additive manufacturing.

Sample parts were printed using shredded films, polycarbonate regrind, and the precursor resin used to manufacture a flight-qualified stowage foam.

25

NASA SBIR Ignite 2022 Phase I & II



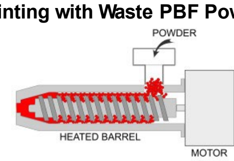


26

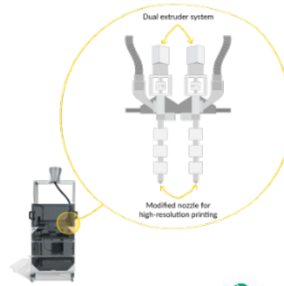
Adjacent Research Interests

Containerbot

Printing with Waste PBF Powder

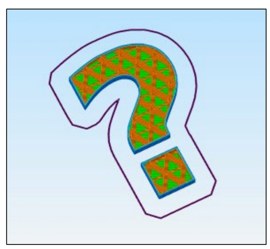


Dual Extrusion System



27

Thank You!



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28

5. Summary

The presentations provided at this forum highlighted research in the extraction of critical materials from waste streams, as well as research into the ability to 3D print directly from recycled thermoplastics. The innovative work was shown to be beneficial not only to the Warfighter, but also to the environment—which aligns with the mission of SERDP. The SERDP mission supports efforts that lead to the development and application of novel environmental technologies to enhance and sustain military readiness.[2,3] It is hoped that this session will lead to increased collaboration in this important technical area, and that this report will be a suitable reference point for scientists and engineers performing similar research.

6. References

1. Silberglitt R, Bartis V, Chow BG, An DL, Brady K. Critical materials – present danger to US manufacturing. RAND National Defense Research Institute (US); 2013. ISBN: 978-0-8330-7883-4.

2. Government Services Administration. Strategic Environmental Research and Development Program (SERDP) core broad agency announcement. Government Services Administration (US); 2023 Nov 2 [accessed 2023 Dec 7]. https://sam.gov/opp/02bfea1ebc674895ad01fc20dc5bc706/view

3. Strategic Environmental Research and Development Program. Catalog of environmental programs 2012. Environmental Protection Agency (US); 2012 [accessed 2023 Dec 7]. https://archive.epa.gov/oig/catalog/web/html/261.html

List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
AAES	American Association of Engineering Societies
AFRL	Air Force Research Laboratory
AI	artificial intelligence
AIME	American Institute of Mining, Metallurgical, and Petroleum Engineers
AM	additive manufacturing
ARL	Army Research Laboratory
ASM	American Society for Metals
CEO	Chief Executive Officer
CSM	Colorado School of Mines
DARPA	Defense Advanced Research Projects Agency
DEVCOM	US Army Combat Capabilities Development Command
DOD	Department of Defense
EMT-B	Emergency Medical Technician-Basic
EPD	Engineering Professional Development
ESTCP	Environmental Security Technology Certification Program
IEEE	Institute of Electrical and Electronics Engineers
LLC	Limited Liability Company
Montana Tech	Montana Technological University
NASA	National Aeronautics and Space Administration
OSD	Office of the Secretary of Defense
SERDP	Strategic Environmental Research and Development Program
SRNL	Savannah River National Laboratory
TMS	The Minerals, Metals & Materials Society
USAF	United States Air Force
WPI	Worcester Polytechnic Institute

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