Center for Materials Processing

2022 Annual Report

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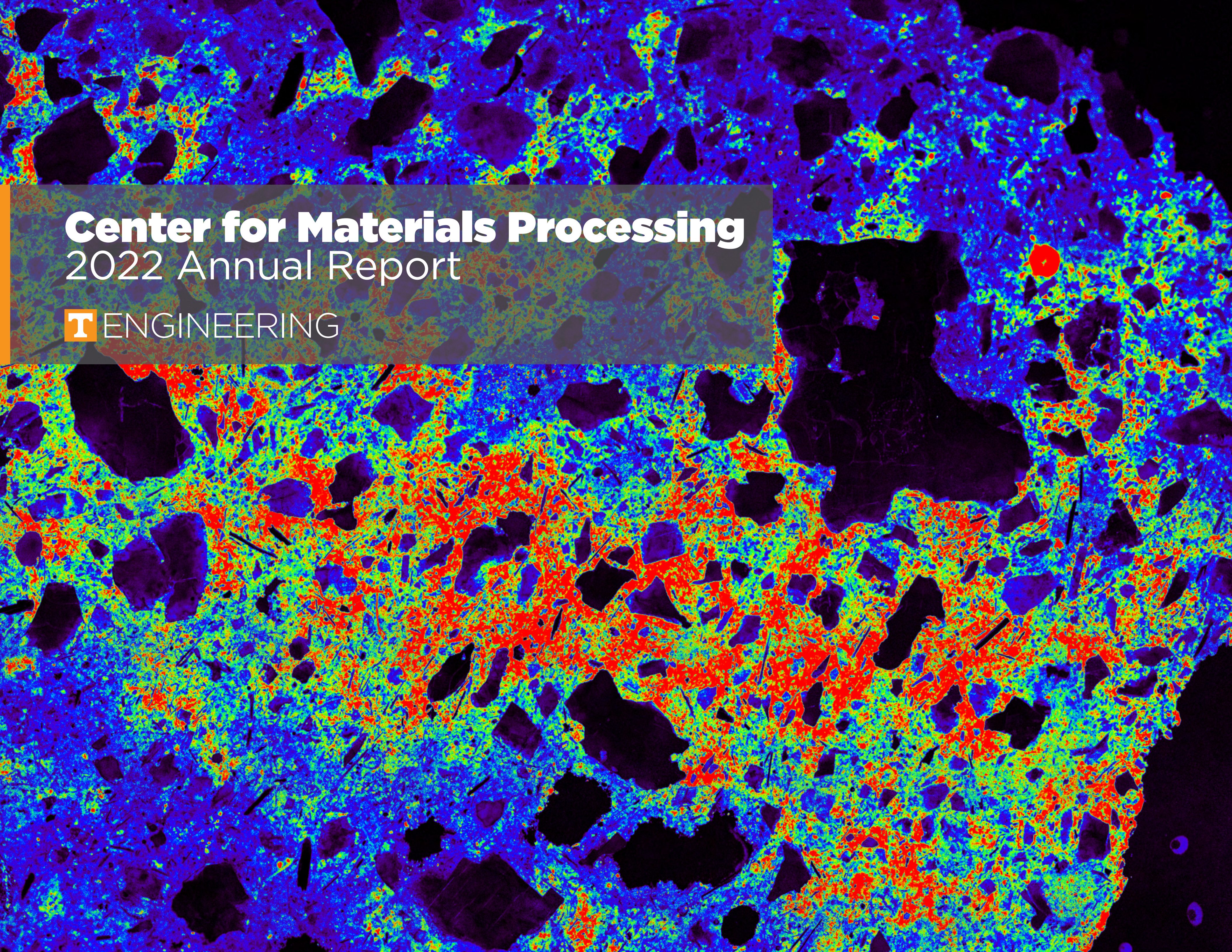

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On the Cover: Confocal image of a printed concrete. | Photo Credit: Debalina Ghosh | Project Manager: Melissa Callahan | Designer: Wes Baldwin

Advisory Committee

Established in early 2014, the CMP Advisory Committee works with the CMP director and associate director for industrial partnerships regarding various areas of research that the CMP can advocate for and invest in for the future. The CMP leadership and the Advisory Committee work together with the goal of bringing positive recognition to the CMP, the Tickle College of Engineering, and the University of Tennessee in areas related to materials processing.

The Advisory Board met at the Institute for Advanced Materials and Manufacturing on June 20, 2022. As in past meetings, the CMP Advisory Committee included discussions focusing on how the CMP can help provide a link between local industry and the University of Tennessee.

William Dunne
Associate Dean – Research and Facilities
Tickle College of Engineering
University of Tennessee, Knoxville

Veerle Keppens
Professor and Head, Materials Science and Engineering
Tickle College of Engineering
University of Tennessee, Knoxville

Danny Norman
Advanced Manufacturing Consultant
Center for Industrial Services
University of Tennessee, Knoxville

Tom Rogers
President and CEO
Cherokee Farm Development Corporation

Jon Phipps
Interim Director, Institute for Advanced Materials and Manufacturing
Director, Core Facilities
Office of Research, Innovation, and Economic Development (ORIED)
University of Tennessee, Knoxville

Jesse Smith
Manager
Industrial and Economic Development Partnership Team
Oak Ridge National Laboratory

Mission Statement

The Center for Materials Processing supports teaching and conducting basic and applied research emphasizing relationships between processing, structure on various scales, and properties of all classes of materials. This support improves existing processing and synthesis techniques, develops new materials and technologies, transfers improvements to the applied sector, and equips students to thrive in the broad field of materials science and engineering. The Center fosters interdisciplinary activities and establishes partnerships with industries and other institutions as appropriate.

Executive Summary

As the pandemic with its extraordinary circumstances added levels of complexity to both work and everyday life, the Center for Materials Processing (CMP) embraced the message from Chancellor Donde Plowman to be creative, compassionate, and flexible. In doing so, the CMP increased the number of both facility level and full memberships, graduate and undergraduate students supported, and more than doubled the publications from the previous year. Eleven graduate students that have been affiliated with the CMP graduated and are continuing their careers in research, including positions in the private sector and as post-docs at national laboratories. Several of the undergraduate students partially supported by the CMP to conduct undergraduate research under the supervision of faculty members have achieved high profile awards, including Fulbright Scholarships, an NSF Graduate Research Fellowship, and top honors from the Office of Undergraduate Research at the annual Exhibition of Undergraduate Research and Creative Achievement (EURēCA) event.

CMP Staff

Claudia Rawn
Director

Claudia Rawn has been director of the Center for Materials Processing (CMP) since July 1, 2012. She is as an associate professor in the Department of Materials Science and Engineering at the University of Tennessee and has taught Introduction to Materials Science and Engineering, X-ray Diffraction and Structural Characterization of Materials, Principles of Ceramics, and is one of the original faculty associated with the Materials Processing course that was first introduced to MSE in 2005. Rawn has served as the chair of the Undergraduate Affairs Committee in the department, the Materials Advantage faculty advisor, and is on the University of Tennessee's Undergraduate Research Advisory Committee. Her research interests include investigations of crystal structures, phase transitions, and thermophysical properties of a variety of materials using in-situ X-ray and neutron scattering methods. Rawn is the PI and site director of the UT site of the Manufacturing and Materials Joining Innovation Center (Ma²JIC), funded by the National Science Foundation (NSF) Division of Industrial Innovations and Partnerships (IIP) and individual industrial memberships. She received her bachelor's in materials engineering from Virginia Tech, her master's in chemistry from George Mason University, and her doctorate in materials science and engineering from the University of Arizona.

Chad Duty
Associate Director for Industrial Relations

Chad Duty began in the role of Associate Director for Industrial Relations with the CMP on April 1, 2021. Duty joined the University of Tennessee in August 2015, is an Associate Professor in the Department of Mechanical, Aerospace, & Biomedical Engineering at the University of Tennessee, and maintains a Joint Faculty appointment with Oak Ridge National Laboratory's (ORNL) Manufacturing Demonstration Facility (MDF). Prior to joining UT, he was a Senior Research Scientist and Group Leader of the Deposition Science & Technology Group at ORNL. Duty's research focuses on advanced materials and process developments for additive manufacturing(i.e., 3D printing). This work led to the commercialization of a large-scale 3D printer for polymer composites called BAAM (Big Area Additive Manufacturing) and the manufacturing of the world's first 3D printed car (the Strati). Duty received his bachelor's in mechanical engineering from Virginia Tech in 1997 and his doctorate in mechanical engineering from Georgia Tech in 2001. After spending a few years with Lockheed Martin on the redesign of the C-5 Galaxy, he joined ORNL as a Wigner Fellow in 2004.

Amber White
Administrative Specialist

Amber White has served as the administrative specialist for the CMP and the RMC since November 2016. Before joining the university, she spent five years in social work, specializing in low-income senior housing and fair housing regulation.

Karen Boyce
Financial Specialist

Karen Boyce is the financial specialist for the CMP, the Scintillation Materials Research Center (SMRC), the Reliability and Maintainability Center (RMC), and the Manufacturing and Materials Joining Innovation Center (Ma²JIC) University of Tennessee, Knoxville, site. She has been working within various university systems since 1995 and joined UT in June 2011. Boyce was awarded the 2021 Tickle College of Engineering Pass the Torch Award recognizing a staff member that had demonstrated all-around achievement and exceptional service to the college.

Gerald Egeland
Student Supervisor

Gerald Egeland is the Center for Materials Processing student supervisor and works with the undergraduate students on CMP Industrial Membership sponsored research. He has a joint appointment with the Department of Materials Science and Engineering serving as the undergraduate laboratory manager and the departmental safety officer. Egeland graduated with his bachelor's in Materials Science and Engineering in 1997, a master's in 2000, and a doctorate in Materials Science in 2005 from New Mexico Institute of Mining and Technology. His graduate work focused on biomimetic materials, carbon nanotubes, nuclear-fuel and radiation damage characterization and was performed at Los Alamos National Laboratory. After obtaining his doctoral degree, he was a Postdoctoral Research Associate at the Paul Scherrer Institute in Switzerland before transferring to Idaho National Lab and eventually the University of Nevada, Las Vegas. His personal research has included working on radiation damage of alloys, ceramic powder processing for advanced fuel, and fuel-cladding interactions. Over the years in his various capacities, Egeland has supervised students and technicians and began teaching while at UNLV, including teaching a graduate SEM course. He also taught chemistry part-time at both Nevada State College and the College of Southern Nevada.

Photo Credit: L. Yu, Caption: Deep blue lignin-based quantum dots

Catalyzing Student Growth

Writing by Meghan McDonald. Photography by Yvette Gooden.

Gabriel Goenaga-Jimenez, PhD, serves as senior research associate to Thomas Zawodzinski, UT-ORNL Governor's Chair for Electrical Energy Conversion and Storage. And he serves as undergraduate research director for the Department of Chemical and Biomolecular Engineering. And as the faculty advisor for the ChemE car team. It may sound like too much, but Goenaga-Jimenez thrives at the busy intersection of research and relationships.

"My roles are interconnected," Goenaga-Jimenez says. "I mentor undergraduates predominantly through research, and it's such a rewarding experience.

"In Zawodzinski's labs, we develop materials for devices that store energy and produce electricity in a clean manner, like hydrogen fuel cells and metal-air batteries, which have active metal on one side and react with oxygen to create electricity."

Specifically, Goenaga-Jimenez focuses on developing alternative catalyst materials for the oxygen reduction reaction in these devices.

"The catalyst materials are composites of metal and carbon. The most efficient material is based on platinum, which is expensive and scarce," he says. "I'm trying to replace platinum with another metal source that is cheaper and more readily available, such as iron or cobalt."

He's also been thinking outside the box (and the battery) to try out alternative sources of carbon, like biomass. As a "pet project," Goenaga-Jimenez first collected wood and leaves from his backyard. Then inspiration struck: "Here in the South, we see kudzu everywhere, and the damage it causes our ecosystems," he says. "Because I hate it so much, I decided to try to make something good out of its abundance: catalysts."

"I get to see them grow and make their own path. And that is a great reward"
—Gabriel Goenaga-Jimenez

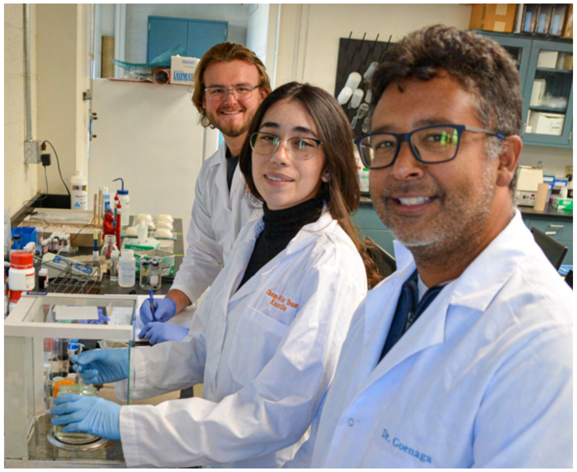
Without funding, however, there was only so much he could do. That's where the Center for Materials Processing stepped in. "The CMP provided funds to support undergraduates who can work on this," Goenaga-Jimenez says. "At the same time, that allows me to offer more undergraduates an experience in the lab."

"In our labs, they get the unique opportunity to make materials from scratch, characterize them, and test their performance," he says. "Through research, I can identify their individual skills and potential. And research with me means also presenting at conferences and networking. I guide them towards life after their undergraduate degree."

Since 2010, Goenaga-Jimenez has also advised an undergraduate team that participates in American Institute of Chemical Engineers competitions by designing and building a car powered by electrochemical reactions. "In recent years, the team has qualified for nationals twice using a car that runs on aluminum-air batteries we have made," he says. "The batteries used the kudzu-based catalyst to create the oxygen reaction. It really can work!"

"As an experimentalist, something can always go wrong, though," he adds. "You have to be patient. I tell students this is very important to learn: if you're passionate, something going wrong is an opportunity to investigate why and make it better."

It's in these learning moments that Goenaga-Jimenez shines brightest. "It's really nice for me to see them come here with no idea what research or grad school is about," he says. "I get to see them grow and make their own path." And that is a great reward.



A Structure for Quality

Writing by Meghan McDonald. Photography by Yvette Gooden.

PhD candidate Hannah Maeser decided to study carbon fiber composites thanks to her high school rowing coach. “I watched him repair a carbon fiber boat,” Maeser explains. “He applied carbon fiber fabric and glue, and it kept us afloat!”

Now in her fourth year as a Tickle College of Engineering graduate student, Maeser has focused her studies not on boats but automobiles. “Carbon fiber is stronger and lighter weight than steel and aluminum, but it costs so much more to use in cars,” she says. “Plus, conventional manufacturing methods require a lot more time and labor with carbon fiber.” She aims to help change this. She’s creating safety and performance inspection methods to evaluate new low-cost carbon fiber material systems — and ultimately reduce their time and labor intensity.

“I would love to see greater application of carbon fiber composites for light-weighting vehicles and making them more efficient or suitable for electric motors,” Maeser says. “But in the commercial automotive industry, you’ve got to finish a car to the tune of ‘Twinkle, Twinkle Little Star.’ We need ways to evaluate composites that, like the ideal manufacturing time, are quick.”

Fiber structure and alignment play a key role in determining whether a low-cost carbon fiber composite will meet industry safety and performance standards. Maeser is characterizing how manufacturing processes affect those two key factors.

Her faculty advisor, Dayakar Penumadu, originally developed the concept in collaboration with Matt Kant. Maeser is “taking it to the finish line” by refining thermal digital image correlation (TDIC) as a non-destructive quality control method. It enables her to analyze differences in thermal strain across large swaths of a composite part.

Thermal strain is her cue that carbon fibers are misaligned or even missing within the composite structure due to manufacturing processes. “A nonuniformity in the fiber structure could cause problems down the line,” she explains. “If you’re using heat to bond paint to a door panel, an air bubble in the composite structure would expand and could crack the door.”

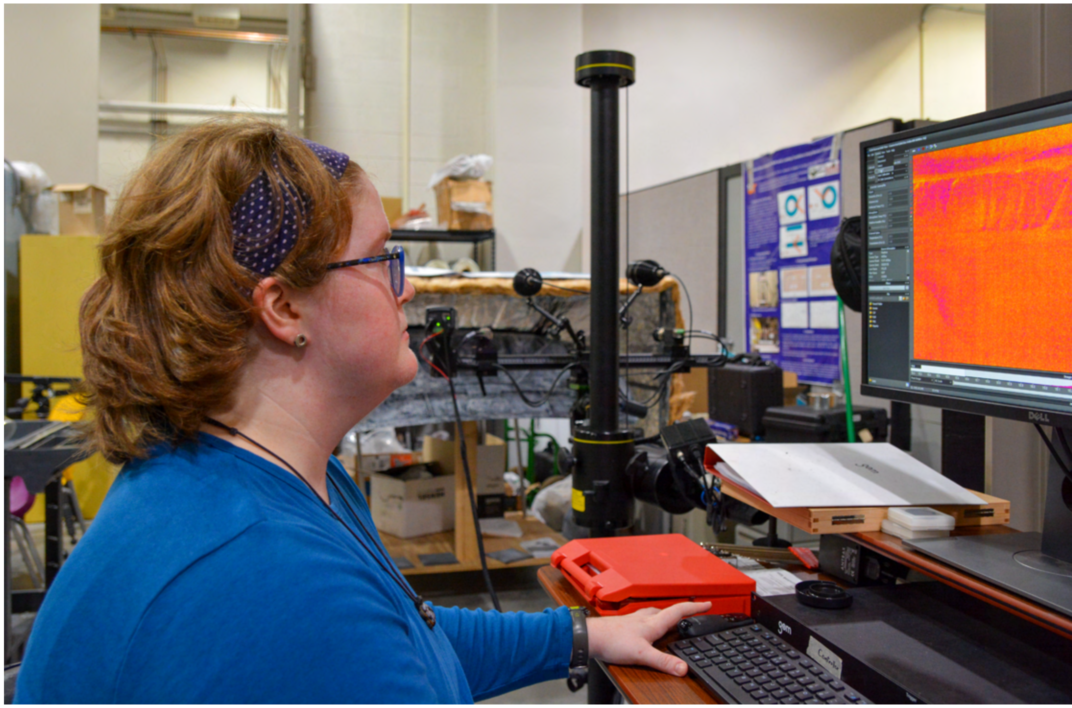
Maeser is creating guidelines to enable automotive workers to quickly understand the TDIC visuals so they can alter processing steps to correct for fiber defects. “On the assembly line, they’d put a speckle pattern on the part, snap pictures, and apply the guidelines to say, ‘That’s an allowable amount of strength,’ or, ‘We need to adjust fiber placement in the mold.’”

This fall, Maeser is starting destructive testing — cutting up her composite samples to physically confirm what she’s seen via TDIC — and wrapping up her first authored paper.

“Hannah has made tremendous contributions as a CMP PhD fellow,” Penumadu says. “I expect her to be a great leader and scholar in advanced manufacturing and materials.”

“I’m grateful the CMP supports my research and exposes me to other environmentally minded engineering projects,” Maeser says. “It fosters cross-curricular connections that will benefit the field in the long run.”

She’s also thinking about her own long-term goals. “It’s important to have industry experience,” she says. “I plan to return to academia after building industry connections to help advance new materials research.”



Ghosh Develops Greener, Faster-Drying Concrete

Writing by David Goddard. Photography by Shawn Poynter.

Concrete is the most widely used manufactured material on the planet and the second-most used material in the world, after water.

It's a composite, with aggregate materials that can be found nearly everywhere. Buildings, roads, and bridge construction projects depend on concrete for its high compressive strength of about 3,000–7,000 psi.

Concrete accounts for a large percentage of global carbon dioxide emissions due to the way it is made. The four billion tons of concrete made each year is responsible for about 8 percent of the world's carbon dioxide emissions— more than either the entire agricultural industry or the heavily polluting aviation industry.

All of this is on the mind of civil engineering doctoral student Debalina Ghosh, studying under Professor John Ma, who teamed up with researchers at Oak Ridge National Laboratory and in collaboration with the Precast–Prestressed Concrete Institute.

Ghosh developed a new formula for precast concrete with two main features important to the industry: a quicker drying time and a reduced carbon footprint.

She is still trying to determine the exact carbon footprint of her mix.

"I am working on a life cycle assessment of this concrete," she said. "This assessment considers the raw material use and energy consumption throughout the manufacturing process and provides a comparative impact on environment."

Precast concrete—manufactured into a structure like a wall or slab and transported to the construction site instead of being poured in place—is more cost-effective and offers better quality control than cast-in-place concrete. Ghosh's concrete has demonstrated qualities that could double production capacity for the precast industry because it gains adequate strength in six hours, compared to several days needed for comparable concrete.

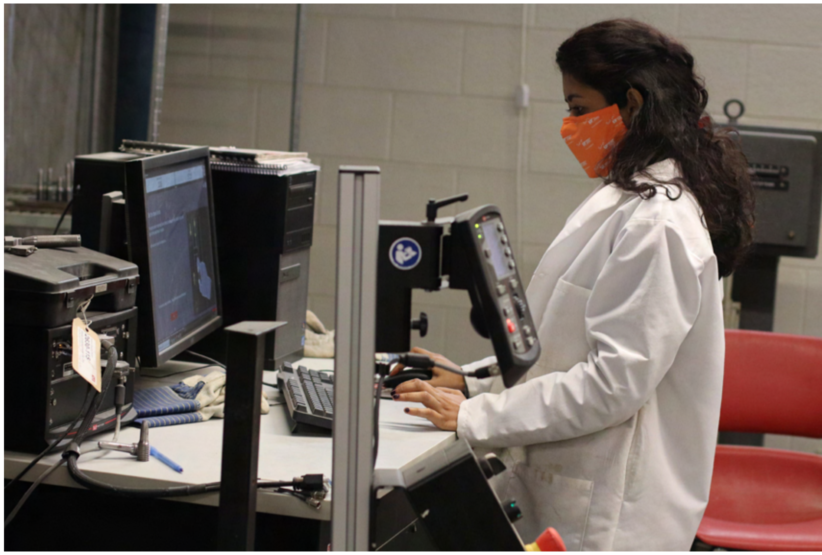
Ghosh's formula uses calcium sulfo-aluminate (CSA) cement, which emits 62 percent less carbon than the industry standard, which is Portland cement. This requires less tempering and grinding during manufacturing.

The drying and hardening of concrete occur through a chemical reaction that emits carbon dioxide, and CSA has a faster reaction in an early stage of drying. Reducing the drying time also reduces the amount of labor needed, allowing for quicker placement.

Ghosh's concrete contains slag, a byproduct material, to replace 60 percent of traditional Portland cement, further reducing the overall impact on the environment.

Additionally, Ghosh evaluated commercially available components—including steel, glass, and carbon fibers—and came up with a self-compacting mix that maintains its workability for 30 minutes.

She chose to add steel fibers to increase the flexibility of the concrete, giving it greater bending strength and therefore making it more durable in situations where most concrete can snap.



CMP Supported and Associated Graduate Students

In FY22, the CMP supported nineteen graduate students, the majority of whom received funding through its competitive application process. These students, along with students supported by industrial memberships and contracts affiliated with the CMP, are featured here. These students are the force behind the publications and dissertations listed in this report.

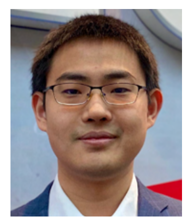
James Brackett, MABE

What is your thesis topic? In-situ multiple material processing in large scale material extrusion additive manufacturing.

How is materials processing involved in your research? My research utilizes advances in instrumentation to improve the multiple material (MM) processing capabilities in large-scale material extrusion additive manufacturing (AM). A g-code enabled dual-hopper attachment allows for on-the-fly material switching during printing, which enables complex site-specific properties. By studying the processing conditions and blending behavior during material switching, my research will provide the information necessary to tweak processing conditions and control material placement within the printed structures. This improves processing capability and allows AM to fulfill requirements for advanced applications using MM that single-material structures struggle with.

Provide an example of where the material, process, or properties you are studying might find an application. Multi-material additive manufacturing (MMAM) provides the capability to deliberately place a given material anywhere within a geometrically complex structure. Specifically with the dual-hopper on the big area additive manufacturing (BAAM) machine, the improvements in control over the deposition process provided by my research will allow for distinct regions of different capabilities. For instance, a simple core-shell structure is achievable with this improvement by selecting a flexible, impact-resistant material for the outer shell and a strong and stiff material for the inner structure to provide resistance against deformation. With characterization of the processing capabilities of the dual-hopper, a finely tuned core-shell structure will be possible.

Xuesong Fan, MSE



What is your thesis topic? My thesis work focuses on the mechanical properties of high-entropy alloys (HEAs), including improving the ductility of body centered cubic (BCC) HEAs and enhancing the strength of face centered cubic (FCC) HEAs. The first part involves utilizing the concept of phase-transformation-induced plasticity (TRIP) to improve the tensile ductility in compositions with the TiZrHfNb refractory HEA system with BCC structures. The second part of my thesis work focuses on designing and developing new FCC HEAs that are enhanced by introducing nano-precipitates.

How is materials processing involved in your research? To design and develop new HEAs, synthesis of metallic samples is first and foremost. Fabrication methods such as arc-melting, drop-casting, and suction-casting are usually used to combine four or more metallic elements to form a single phase solid-solution. Additionally, thermomechanical processes (e.g., rolling, homogenization, annealing, and aging) are generally performed to further improve mechanical properties. By combining different processing methods, the aim is to develop advanced structural materials and understand the relationship among processing-structure-properties.

Provide an example of where the material, process, or properties you are studying might find an application. Similar to commercial Ni-based superalloys, HEAs with FCC structures are considered promising alternatives for high-temperature applications due to their lower cost and better mechanical performance in a wide temperature range. By introducing ordered precipitates as the strengthening phase, the strength of the FCC-based HEAs can be potentially improved due to dislocation-precipitate interactions, which hinder dislocation movements.

Cole Franz, MSE

What is your thesis topic? Our industrial work with Fulton Bellows is focused on failure analysis and process optimization of metallurgical components.

How is materials processing involved in your research? The processing of metallurgical bellows is a finely tuned balance between bulk material properties, microstructural integrity, and aesthetics. I am often tasked with analyzing broken parts and subsequently with recommending the respective improvements in quality control. This means I utilize metallographic skills and the related fields of study to provide insight on how to best move forward.

Provide an example of where the material, process, or properties you are studying might find an application. Metal bellows are simply a flexible, airtight vessel made of metal. Because of their simple function, they are utilized in just about every industrial application, from gas-drills to satellites. It is often the case that customers will employ us for metallurgical consultation on a new design or ask us to analyze a failed part that saw service within their industry.

Debalina Ghosh, CEE

What is your thesis topic? My research focuses on investigating the effects of materials parameters on the early age properties of rapid setting and 3D printed concrete.

How is materials processing involved in your research? Concrete is a composite material made of cement, sand, gravel, and water in its simplest form. Some specialized concrete can also have fibers, admixture, and other cement-like material. My research explores the effects of parameters like fiber surface area, quantity of gypsum, and time span for printing to optimize the mechanical performance of concrete. We are also developing specialized concrete for rapid construction, exploring the hydration process of alternative cement with a low carbon footprint, and investigating the effects of the printing process on additively manufactured concrete.

Provide an example of where the material, process, or properties you are studying might find an application. I developed a fast-setting concrete that can double the productivity of precast concrete plants while reducing the carbon footprint up to 20% compared to traditional concrete. A large-scale trial was successfully tested at an Atlanta-based precast plant. A provisional patent was jointly filed with ORNL. The research on low carbon alternative cement can be used in cold weather construction and rapid construction to analyze and predict concrete performance. My research on 3D printed concrete suggests an optimal time range for the time gap between two printed layers that has the least negative impact on printed concrete strength.

Candice Kinsler-Fedon, MSE

What is your thesis topic? My research focuses on the synthesis of high-entropy oxides (HEO) with the pyrochlore structure using solid state synthesis and growing crystals using the optical floating zone technique. Subsequent characterization determines their magnetic, mechanical, thermal, and irradiation resistant properties. The goal of this project is to gain a better understanding of high-entropy oxides in order to discover potential applications.

How is materials processing involved in your research? The synthesis of novel HEO pyrochlores involves solid state reactions of precursor oxide powders that are combined, ball milled for homogenization, pressed into pellets using either a hydraulic or hydrostatic press, and then sintered at high temperatures (1200 to 1600°C typically) to form a single-phase solid solution. Likewise, ion-irradiation and Rutherford backscattering spectrometry are employed to understand the amorphization resistance in HEO single crystals. In particular, ion-irradiation is an experimental technique that can be used for ion-implantation or tuning ceramics by producing defects.

Provide an example of where the material, process, or properties you are studying might find an application. HEO pyrochlores may be promising materials for thermal barrier coatings (TBCs) due to their discovered high temperature phase stability, low thermal expansion coefficients, and low thermal conductivities. These ceramic materials could also be altered or "fine-tuned" by utilizing ion-irradiation to enhance their ionic or electronic conductivities for use in fuel cell technology.

Subhadeep Koner, MABE

What is your thesis topic? Brain inspired organic electronic devices and systems for adaptive signal processing, memory, and learning.

How is materials processing involved in your research? The goal of my research is to understand the contribution of materials architecture in the resistive switching and memory in emerging biomolecular and polymeric thin film neuromorphic devices and tune material composition/combination to maximize reproducibility of these devices. Therefore, materials analysis and innovative materials processing techniques are crucial to the construction of devices and for their reproducibility for integration in commercial electronic circuits.

Provide an example of where the material, process, or properties you are studying might find an application. I study both biomolecular and polymeric thin film devices that are chemically sound and commercially cheap. These devices work at low voltages and are capable of adaptive signal processing depending on the frequency of the input and forming memory. Therefore, these devices can find application as neural models for studying biological neural networks, signal processing and memory units in biomedical devices, wearable electronics, and in flexible neuromorphic hardware like neuromorphic skin.

Zongyang Lyu, MSE

What is your thesis topic? My thesis topic is “Synergistic Fatigue Performance in High Entropy Alloys with Novel Precipitates and Metastable Phases.” In-situ diffraction techniques are used to understand the deformation behaviors of high-entropy alloys (HEAs) under fully reversed low-cycle fatigue.

How is materials processing involved in your research? In order to generate the novel precipitates and metastable phases, several materials processing methods are involved. Vacuum-induction melting and casting are used to get the original alloy plate. The alloy plate is then treated with the hot-isostatic-pressing (HIP) process to reduce the microdefects formed during casting. Hot rolling and cold rolling are performed to reduce the grain sizes, which can prompt the nucleation of the novel precipitates and metastable phases. Next, different heat treatments are used to tune the microstructures for improving the tensile and fatigue properties of HEAs.

Provide an example of where the material, process, or properties you are studying might find an application. HEAs are promising structural materials with excellent strength, fracture toughness, and fatigue resistance. These materials could fulfill the requirements needed in extreme conditions, such as in space and deep sea. With the strengthening of novel precipitates and metastable phases, there is a large space for further developments of outstanding HEAs to meet different applications as structural materials.

Hannah Maeser, CEE

What is your thesis topic? Fiber alignment and mesostructure play a key role in tailoring the anisotropic properties of carbon fiber reinforced polymer composites (CFRC) for use in automotive applications. My dissertation topic focus is to develop novel non-invasive methods for characterizing the effect of composite manufacturing processes on micro/meso structure and to relate the resulting structure to mechanical properties.

How is materials processing involved in your research? Discontinuous CFRCs are susceptible to fiber misalignment during high-throughput molding and manufacturing methods, such as the compression molding technique using sheet molding compounds. Aspects such as how the partially cured material is placed into the mold or the length of the molding time can affect how the fibers flow and orient around the part geometry. I am developing a novel non-destructive evaluation (NDE) method called thermal digital image correlation (TDIC) to determine the preferred fiber orientation that results in the part during manufacturing. I seek to develop a set of guidelines, confirming against TDIC, on how to process the uncured composite material during molding to reduce or control fiber misalignment. I am also exploring the use of thermography for identifying defects such as pores or resin rich regions.

Provide an example of where the material, process, or properties you are studying might find an application. A good example of where my research might find an application in the field is in quality control of composite automotive parts. Discontinuous composites offer a low-cost composite solution for light-weighting for fuel efficiency, corrosion resistance, and energy absorption through crushing. However, due to the material’s susceptibility to misalignment during molding to complex shapes, a rapid quality control method is needed to evaluate parts in development and during full-line manufacturing. Refining the TDIC method and using it to develop guidelines for processing discontinuous composites during molding will allow for the expanded use of discontinuous CFRCs for complex molded structural components of automobiles and infrastructure.

Shashi Pandey, Physics

What is your thesis topic? Integrating epitaxial and in situ anisotropic strain for magnetoelastic control of a $J_{eff} = 1/2$ antiferromagnet (AF).

How is materials processing involved in your research? My research is focused on applying strain as an external perturbation to complex oxides and studying its effect on the magnetic behavior and other transport properties. We perform layer by layer thin film growth of complex oxide materials using pulsed laser deposition (PLD) on a substrate that is chosen with a deliberate lattice mismatch, which ultimately induces epitaxial strain on the film. In situ strain are then applied with the help of strain cells on such epitaxially strained thin films, which enables us to fine tune the applied strain on the system. The materials processing are involved not only in the growth process of the thin films but also its characterization, study of the transport properties, and x-ray diffraction study.

Provide an example of where the material, process, or properties you are studying might find an application. One example would be Sr2IrO4, a 5d iridate system with J_{eff} = ½ AFM Mott insulating behavior. Studying the strain effect on magnetic behavior of this material, we found that a metamagnetic transition can be significantly driven with the application of in situ strain. Conversely, such a strain can do robust switching between two different magnetic phases, i.e., AF and FM. The study might find an application where the magnetic behavior of a material needs to be fine-tuned without applying external field.

Pengcheng Zhu, MSE

What is your thesis topic? My thesis project is focused on the mechanical properties and microstructural characterizations of thermally aged and irradiated Fe-Cr alloys. The main techniques include state-of-the-art nanoindentation and transmission electron microscopy (TEM).

How is materials processing involved in your research? To simulate the irradiation effects on both microstructures and bulk properties of the structural materials in the reactor, heavy ion beam processing with higher damage rate and low radioactivity was used in my study. We performed nanoindentation tests and TEM investigations on both neutron and ion irradiated Fe-Cr alloys. The correlation between the mechanical properties and microstructures and the fidelity of ion beam surrogation of neutron irradiation was investigated.

Provide an example of where the material, process, or properties you are studying might find an application. High chromium ferritic-martensitic (FM) steels are widely used for fossil and nuclear energy applications, e.g., they are one of the candidate structural component materials for future fission and fusion reactors due to their low swelling rates, low thermal expansion coefficient, good elevated-temperature strength, high conductivity, etc. However, the mechanical study of irradiated Fe-Cr FM steels is limited due to high radioactivity of neutron irradiation and shallow damage volume of ion irradiation. Our research on methods to accurately extract bulk equivalent hardness from shallow depth nanoindentations can be an important aspect of enhanced use of ion beam processing as a surrogate to neutron irradiation. The investigation on how the irradiation temperatures, dose, and dose rate affect the microstructures and mechanical properties of Fe-Cr alloys is important for optimizing ion beam processing conditions for forming similar precipitates, dislocation loops, etc., as caused by neutron irradiations.

Yajie Zhao, MSE

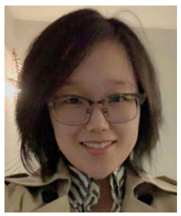
What is your thesis topic? My thesis project focuses on the stability of Cr-enriched alpha prime (α') precipitates in high purity FeCr alloys under heavy ion irradiation conditions.

How is materials processing involved in your research? Ion irradiation is an important and complicated material processing method, which could both destroy the nanoscale precipitates by forming damage cascades and enhance the precipitate formation by accelerating the diffusion process. We performed ion irradiations on high purity FeCr alloys at different temperatures and ion fluxes. Using focused ion beam (FIB) for sample preparation and atom probe tomography (APT) as the main characterization method, the evolution of α' precipitation as a function of irradiation conditions is studied.

Provide an example of where the material, process, or properties you are studying might find an application. Ferritic-martensitic (FM) steels with high Cr concentration are promising structural materials for Generation IV fission and fusion reactors due to their superior void swelling resistance compared to conventional austenitic steels. However, high-Cr FM steels are known to undergo pronounced hardening and embrittlement due to the formation of dislocation loops and Cr-rich α' precipitates. My research helps to understand the kinetics of α' precipitation and provide knowledge about how to mitigate this mechanical degradation problem.

"Yajie has used advanced atom probe tomography and accompanying data analysis to compile what is arguably the premiere worldwide assessment of the stability of Cr-rich precipitates in Fe-Cr alloys for a variety of thermal aging and particle irradiation conditions. Her experimental and data analysis skills demonstrate a deep understanding of important materials science concepts and represent a new standard for characterization of nanoscale precipitates in alloys." **-Prof. Steven Zinkle**

Lu Yu, MSE



What is your thesis topic? My research is focused on converting biomass lignin to high value carbon materials for various applications, especially energy storage and environmental remediation.

How is materials processing involved in your research? Understanding the processing-structure-property-performance relationship is at the heart of this research. Because lignin is a complex nonlinear polymer with a distribution of monomers that varies from one plant to the next, the ability to predictably synthesize a material with a tailored property remains a challenge. To develop lignin-derived activated carbons (AC), carbonization and physical/chemical activations are involved. The flow rate, heat rate, duration, and temperature are all important factors that affect the structures of produced carbon char. In addition, due to the complex structure of lignin, the relationship between lignin and developed carbons is important. By carefully controlling the process, high surface area activated carbons with optimized porous structures were developed for high performance supercapacitors.

Provide an example of where the material, process, or properties you are studying might find an application. As a waste stream of the paper & pulp industry, lignin has great potential for developing high value products due to its high carbon content, unique aromatic structure, and low cost. The produced ACs have been applied as electrodes for supercapacitors. Magnetically activated carbons (mACs) were synthesized for water purification. Lignin derived ACs are also promising as adsorbents for CO_2 capture. We are in the process of testing the CO_2 adsorption performance of lignin derived carbon materials combined with carbon quantum dots (CQDs). Besides ACs, CQDs have been widely used in the field of bioimaging, biosensors, and biomedical applications.

Alumni Spotlight: BWX Technologies, Inc.

John Salasin, materials scientist

What type of work (research) goes on at BWXT Lynchburg?

BWXT is a premiere nuclear manufacturing company. Our research and development campaigns help cure cancer, protect the country, and explore the cosmos. This is achieved through our research in radio-pharmaceuticals, reactor design, nuclear fuel, and advanced manufacturing. As the principal researcher for fuel development, my role is leading development efforts to achieve high temperature fuel forms to increase efficiency and thereby performance. It's hands on, in the lab, working with prototypic material environment.

Did the materials processing aspects of your research at UTK prepare you for your current position (or to succeed) at BWXT (or in industry)?

Coming out of UTK, I was developed into being a maker. Understanding the full life cycle of materials processing (synthesis, forming, and post processing) has allowed our team to be successful in performing aggressive cost and schedule contracts. Without the knowledge and mindset nurtured at UTK under the Center for Materials Processing, our projects would have been much more difficult.

Any advice for future students?

Put yourself out there – get in the lab. Try something. Sitting and reading is easy, but doing is harder. You are going to fail, you are going to perform rework, but that is where the value is. That is the experience you will need moving forward. You cannot experience the world from a book or writing a plan; you experience it with your hands. Go make things, and the rest will follow.

Robert Minneci, materials scientist

What type of work (research) goes on at BWXT Lynchburg?

A wide breadth of research is performed that is aimed at a few key development areas in the nuclear industry. These include medical isotope generation, new terrestrial reactor concepts, space nuclear propulsion and reactors, and fuel development.

Did the materials processing aspects of your research at UTK prepare you for your current position (or to succeed) at BWXT (or in industry)?

I could not have asked for a better background for my position and the research efforts I'm involved in. I have leaned heavily on my education to succeed in materials processing, characterization, and analysis efforts. From hand-polishing cross sections to analyzing X-ray data to understanding crystal growth, my research at UTK has been pivotal in my success at BWXT.

Any advice for future students?

Your graduate advisor is one of the most important people in deciding your future career. I was fortunate to have one of the best. Make sure that they are invested in your development as a researcher and in you as a person. Also reach out to alumni if you're interested in interning or co-oping at their company.

Sabrina McCoy, research scientist

What type of work (research) goes on at BWXT Lynchburg?

At BWXT, we are developing fuels and reactor materials for advanced reactor designs, including small modular concepts and systems for space nuclear thermal propulsion. The primary focus of our research is the synthesis and forming of these materials, as well as testing to understand how they'll behave in a reactor environment.

Did the materials processing aspects of your research at UTK prepare you for your current position (or to succeed) at BWXT (or in industry)?

Absolutely. While at UTK, I learned the fundamentals of ceramics processing at a laboratory scale. The experience I gained making ceramics directly translates to the work I'm doing in the BWXT labs, particularly with the synthesis and characterization of ceramic powders. I am using many of the same tools, albeit at a larger scale now. Getting hands on experience at a small scale in a lab where I felt safe to play around helped develop my confidence working with the equipment and prepared me for many aspects of my current role.

Any advice for future students?

I'd suggest getting experience in diverse industries as a student. Internships and co-ops are so valuable for figuring out where you want to go next and developing a broader knowledge base. I never would have envisioned myself working in the nuclear industry until giving it a chance as an intern.

Thesis/Dissertation Titles

Yan-Ru Lin, PhD
"Fundamentals of Cavity Formation in α-Fe and Fe-Cr Alloys"

ADVISOR: Steven Zinkle
CURRENT EMPLOYER: Oak Ridge National Laboratory. Position: Postdoctoral Researcher

Lin was recognized with the American Nuclear Society's Mark Mills Award given by the Education, Training, and Workforce Development Division's Honors and Awards Committee for his paper "Temperature-dependent cavity swelling in dual-ion irradiated Fe and Fe-Cr ferritic alloys" published in Acta Materialia early 2021 and included in CMP FY21 publications.

Katherine (Kate) Higgins, PhD
"Exploration of the Stability of Multicomponent Metal Halide Perovskites utilizing Automated, High-throughput Methods and Machine Learning"

ADVISOR: Philip Rack

Candice Kinsler-Fedon, PhD
"Synthesis and Property Characterization of Rare-Earth High-Entropy Oxides with Pyrochlore-Type Structures"

ADVISOR: Veerle Keppens
CURRENT EMPLOYER: MillenniTEK, LLC. Position: Research and Development Engineer

Grace Pakeltis, PhD
"High Resolution Electron Energy Loss Spectroscopy of Plasmonic Nanostructures"

ADVISOR: Philip Rack
CURRENT EMPLOYER: Current Employer: Taiwan Semiconductor Manufacturing Company (TSMC). Position: Principle Engineer

Hyojin Park, PhD
"Pinless Friction Stir Spot Welding of Ti-6Al-4V Alloy for Aerospace Applications"

ADVISOR: Hahn Choo
CURRENT EMPLOYER: MSE, University of Tennessee. Position: Postdoctoral Researcher

Junyi Yang, PhD
"Emergent phenomenon in J_{eff}=1/2 iridate"

ADVISOR: Jian Liu
CURRENT EMPLOYER: Argonne National Laboratory. Position: Postdoctoral Researcher

Brandon Shaver, PhD
"Evaluation of Uranium Dioxide for Solid-State Direct-Conversion Neutron Detection"

ADVISOR: Howard Hall
CURRENT EMPLOYER: Nuclear Engineering, University of Tennessee, Position: Research Staff Member

Di Xie, PhD
"In-Situ Diffraction Experiments and Multiscale Mechanics Modeling of Fatigue Behavior in Mg Alloys"

ADVISOR: Yanfei Gao
CURRENT EMPLOYER: 3M
Position: Senior Research Engineer

Lu Yu, PhD
"Synthesis and Application of Lignin-Based Carbon Materials with Tunable Structure from the Mesoscale to Nanoscale"

ADVISORS: David Harper and David Keffer
CURRENT EMPLOYER: Oak Ridge National Laboratory. Position: Postdoctoral Researcher

Program Accomplishments and Overview

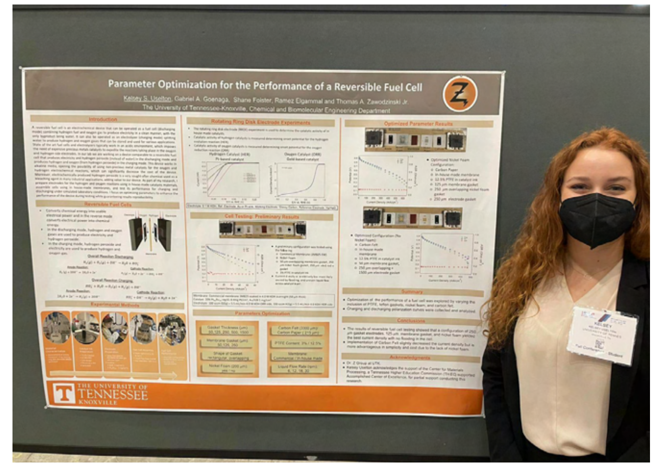
Accomplishments

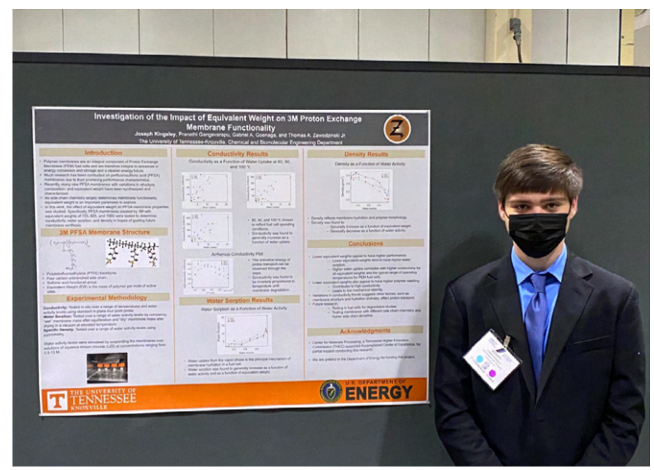
- Two full- and eight facility-level memberships supporting industry while engaging students
  - Fulton Bellows full membership, which is actively supporting a 5-year BS/MS student in MSE, is continuing for another year
- The CMP partnered with two companies associated with the Spark Incubator Program to compete for an NSF I-Corps award and an Air Force STTR, the latter of which supported three undergraduates
- Spark Scholars program established where undergraduate students assist prototype construction for start-up companies
- Support packages for nineteen graduate students
- 29 publications and nine dissertations generated with CMP support
- Over 80 undergraduates participated in research activities, including several with Spark Incubator Program companies and two Spark Scholars, through CMP funding
- Two poster sessions showcasing and promoting CMP-funded student research

Program Overview

One of the first activities in FY22 was the CMP end of summer poster session featuring twelve graduate students from five different departments and ten undergraduate students. The judges were from ORNL, Spark Innovation companies, and research staff from companies with CMP facility memberships. For some of the undergraduates, it was their first time meeting some of the other students and faculty in a face-to-face modality and was much appreciated, which set the academic year off on a very positive note. In February, the CMP and the Oak Ridge Chapter of ASM co-hosted Student Night. Both events took place at the Institute for Advanced Materials and Manufacturing (IAMM), and the CMP recognized the top posters with travel support for taking their research endeavors out to a wider audience. One student, Kelsey Uselton, a senior in CBE, won first place in the Fuel, Peterochemicals, and Energy session for her poster "Parameter optimization for the performance of a reversible fuel cell" at the AIChE Annual Student Conference held in Boston, Ma., in November 2022.

CMP-associated graduate and undergraduate students are the driving force behind our technical accomplishments. Accordingly, assistantship support (graduate and undergraduate) is the largest expenditure for the CMP. The support is





provided via a variety of mechanisms, including graduate stipends, paid undergraduate research opportunities, undergraduate scholarships, funds for using state-of-the-art instruments housed in core facilities, and travel support for students to present their research at professional conferences.

All CMP-supported graduate students are working on amazing projects where materials processing parameters have the potential to improve properties and impact a wide variety of technical applications. CMP-supported graduate student research projects include large-scale material extrusion additive manufacturing, improving the mechanical properties of high-entropy alloys (HEAs) and the ionic or electronic conductivity of high-entropy oxides (HEOs), converting biomass lignin to high-value carbon materials, and investigating Fe-Cr alloys that show promise as structural materials for generation IV fission and fusion reactors. Civil engineering graduate students Debalina Ghosh and Hannah Maeser are highlighted in this report for their important research on 3D-printed concrete and carbon fiber reinforced polymer composites (CFRC) for use in automotive applications, respectively. Gabriel Goenaga-Jimenez, the undergraduate research director for the Department of Chemical and Biomolecular Engineering, is also featured. He supervisors several of the undergraduate students in developing materials for producing and storing electricity.

Highlights of CMP-supported undergraduate students involve undergraduates performing research with several of the start-up companies associated with the UT Spark Innovation Center, including American Nanotechnologies, Inc. (ANI) and SkyNano Technologies. These early collaborations with Spark Innovation partners built the foundation of being able to secure external funding in the forms of an Air Force STTR and an NSF I-Corps award. In the summer of 2022, the Spark Scholars program began with an idea developed between CMP Associate Spark Scholars program began with an idea developed between CMP Associate Director for Industrial Relations Chad Duty and President and CEO of UT's Research Park Tom Rogers, while the day-to-day supervision of the students was led by Jerry Egeland (MSE/CMP) and Thanh (Tom) Duong.

Once again, CMP-supported undergraduates were recognized with a wide variety of awards, including Joseph Kingsley taking second place in the Materials Engineering and Sciences VI session with his poster titled "Investigation of the impact of equivalent weight on 3M proton exchange membrane functionality." Alexandria Carter, mentored by Assistant Professor Kate Page, received a bronze poster prize from the 2021 North American Solid-State Chemistry Conference (NASSC) for her poster titled "The effect of ligand exchange on the structure and properties of ferroelectric nanocrystals."

Many CMP-supported undergraduate students participate in the annual, university-wide Exhibition of Undergraduate Research and Creative Achievement (EURēCA). This year, CMP student Madeline Loveday, mentored by Associate Professor Mariya Zhuravleva, won second place among college entries for her work on "Phase formation of high-entropy rare-earth monoclinic aluminates." Michael Bround, mentored by Professor David Keffer, won an award of merit for his work on "Investigation of preferential CO2 binding and lignin-derived carbon quantum dots through molecular dynamics simulations." Of special note, in the spring of 2022, Alex Greenhalgh became the fifth MSE student whose undergraduate research is partially supported by the CMP to be honored with a Goldwater scholarship.

The CMP continues to support IAMM activities by providing partial support to IAMM

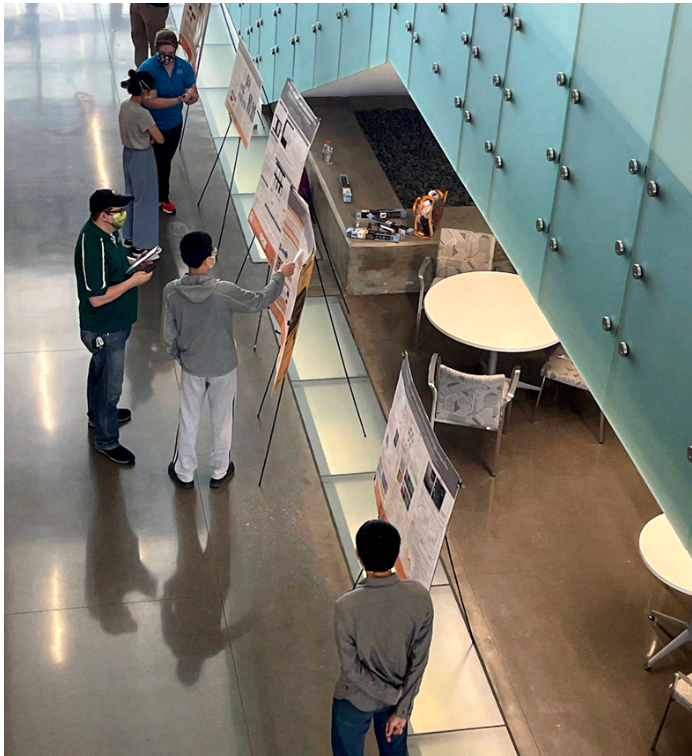
Diffraction (XRD) Facility Laboratory Manager Michael Koehler, who is in charge of the day-to-day operations of the laboratory, which includes helping students and industry members in the collection and analysis of X-ray diffraction data. The IAMM Diffraction (XRD) Facility is part of the University of Tennessee's Core Facilities Program that is intended to provide access to high-end instrumentation, technical support, and expert consultation to both users from across the university and external customers for a fee. A popular part of the graduate student support packages is to use some of their support for covering instrument charges, usually for collecting XRD and/or electron microscopy data.

The CMP has a collection of smaller-scale instruments (e.g., particle size analyzers and a gas pycnometer for measuring density) housed in a laboratory on campus in the Science and Engineering Research Facility under the supervision of Jerry Egeland. These instruments are used by CMP students on both faculty sponsored and CMP industrial membership research and contribute to cost sharing of larger-scale instruments that are marked as part of core facilities laboratories located at IAMM. Specifically, the CMP contributed to the iMicro Nanoindenter system and to an upgrade to one of the IAMM Diffraction Facility diffractometers in FY22 that will allow data for pair distribution function analysis for studying short range order in materials.

In addition to the two poster sessions for highlighting CMP student research, the CMP teamed with the Center for Industrial Services (CIS) to host a collaboration workshop in December. In early June, the CMP staff helped support the Manufacturing and Materials Joining Innovation Center (Ma2JIC) in hosting their first in-person Industrial Advisory Board (IAB) since January 2020. It was a chance to promote some of the wonderful new facilities at UT, including the student union where the meeting was held and the welding and additive manufacturing laboratories that are now available on campus in the Dougherty Engineering building. Attending the meeting were faculty from the other university sites, including The Ohio State University, Colorado School of Mines, Penn State University, and the University of Waterloo. Industrial representatives attending the IAB included staff from Shell, EPRI, and both Oak Ridge and Sandia National Laboratories, to name a few. Lastly, after a several-years break due mostly to changes and avoiding virtual meetings, the CMP Advisory Committee met at the IAMM and focused on ways the CMP can partner and help both large international corporations and small local businesses

Goals and Future Plans

In FY23, the CMP will continue to be valuable collaborators to our existing industrial partners. Additionally, the CMP will meet and establish new industrial memberships with companies based in Tennessee through our partnership with the Center for Industrial Services (CIS). The CMP staff strive towards continually improving the experiences of supported students, both at the graduate and undergraduate levels. At the graduate level, the CMP will continue to leverage our graduate support packages, providing graduate students with professional development activities and supporting the students in collecting data at the state-of-the art microscopy and diffraction core facilities at IAMM. At the undergraduate level, we will seek to identify new partners, especially companies associated with the Spark Innovation Center, to jointly support undergraduate research and provide students with opportunities allowing for growth beyond the level of undergraduate research assistant. The valuable skills these students learn in the laboratory setting will allow them to continue their education at the graduate level (at the University of Tennessee or other institutions) or become members of the technical workforce. The CMP will continue to host events to showcase both graduate and undergraduate students and their research and provide the students with networking opportunities with faculty, Oak Ridge National Laboratory research staff, local technical company staff members, and Spark Innovation Center staff members.



In Memoriam

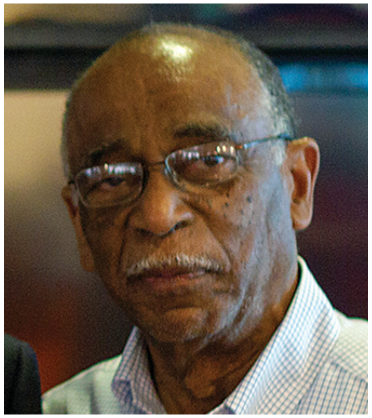
Prof. Carl J. McHargue, 1926-2022

The Center for Materials Processing lost it's longtime advocate and champion when Dr. Carl J. McHargue passed away on February 27,z 2022.

The initial response to Tennessee Higher Education Commission (THEC) proposing the Center for Materials Processing is attributed to Dr. Joseph Sprueill in 1985, the same year he was appointed the UT Materials Science and Engineering (MSE) Department Head. Once established, Dr. Joseph C. Danko served as the first CMP director until the early 1990s. Although there is a gap in records, the CMP Annual report in 1995 lists Dr. Carl McHargue as the CMP Director, and he served in this capacity until 2012. When he accepted the appointment, he was retired from Oak Ridge National Laboratory and did not expect to remain the CMP Director for the next seventeen years. In addition to serving as Director of the CMP, he remained an active member of the MSE Department by teaching classes, supervising graduate students, serving on countless committees, and participating in professional societies and their annual meetings. Carl's outstanding scientific and service contributions were recognized by awards and being a fellow of several professional societies. Of special importance to his contributions to the college of engineering, Carl was active with the Accreditation Board for Engineering and Technology (ABET), the organization that accredits college and university programs in various disciplines, including engineering programs at the bachelor's degree levels, and was recognized as a Fellow of ABET in 2008. For his many significant contributions, Carl was recognized by the MSE Department as the third recipient of the MSE Wall of Fame (2018), which is intended to honor those that have significantly contributed to the UT MSE Department.

As the Director of the CMP immediately following Carl's tenure, I often reflect on Carl's impact on my career through his belief in me. Carl cared about the CMP and its future and continued on as the Director well into his 80's, at which point he found someone he felt would be as responsible as he had been over the years. I started as Associate Director on January 1, 2012, and became the Director on July 1, 2012, with Carl staying on through October to produce the 2012 CMP Annual Report. After his retirement as the CMP Director, he stayed active as an unpaid consultant, meeting with me periodically when I would seek advice and draw on his years of experience. He was an amazing person and scientist.

Prof. Roberto S. Benson, 1940-2022



Roberto Benson, born in Panama, earned his bachelor's degree in Physics from the University of Panama. In 1970, he received a scholarship to study in the United States, culminating in a Ph.D. from Florida State University in Physical Chemistry of Polymeric Materials in 1978. Roberto and his family then spent eight years at the University of Utah before joining the polymer science and engineering effort at the University of Tennessee in 1986. The polymer science and engineering effort was distributed between faculty from several departments, including Chemistry, Mechanical Engineering, Materials Science and Engineering, and Textile Science, and it was supported by both the CMP and the Textiles and Nonwoven Development Center. Roberto was part of this early effort and conducted research in the area of biomedical materials, blends, and composites. Over his 32 years in the MSE Department at UT, his contributions were countless. Roberto was especially known for his mentoring and care of students at all levels of their education. Roberto's insight, advice, and collegiality will be greatly missed.

Budget

	FY 2021-22 Actual			FY 2022-23 Proposed			FY 2023-24 Requested		
	Matching	Appropr.	Total	Matching	Appropr.	Total	Matching	Appropr.	Total
Expenditures									
Salaries									
Faculty	$261,346	$136,899	**$398,245**	$262,653	$137,447	**$400,100**	$263,966	$137,791	**$401,757**
Other Professional	$159,805	$46,628	**$206,433**	$160,604	$46,815	**$207,419**	$161,407	$46,932	**$208,339**
Clerical/ Supporting	$124,623	$49,420	**$174,043**	$125,246	$49,617	**$174,864**	$125,872	$49,741	**$175,614**
Assistantships	$437,573	$250,798	**$688,371**	$475,000	$275,000	**$750,000**	$500,000	$300,000	**$800,000**
Total Salaries	**$983,347**	**$483,746**	**$1,467,093**	**$1,023,503**	**$508,879**	**$1,532,382**	**$1,051,245**	**$534,464**	**$1,585,709**
Longevity (Excluded from Salaries)	$4,598	$2,302	**$6,900**	$4,621	$2,314	**$6,935**	$4,644	$2,325	**$6,969**
Fringe Benefits	$200,206	$86,464	**$286,670**	$201,207	$86,896	**$288,103**	$202,213	$87,331	**$289,544**
Total Personnel	**$1,188,151**	**$572,512**	**$1,760,663**	**$1,229,331**	**$598,089**	**$1,827,420**	**$1,258,103**	**$624,120**	**$1,882,223**
Non-Personnel									
Travel	$14,259	$4,393	**$18,651**	$30,000	$10,000	**$40,000**	$36,000	$12,000	**$48,000**
Other Supplies	$17,589	$3,401	**$20,990**	$15,000	$5,000	**$20,000**	$18,000	$6,000	**$24,000**
Equipment	$289,531	$51,135	**$340,665**	$345,000	$114,616	**$459,616**	$12,000	$5,452	**$17,452**
Maintenance	$42,844	$14,637	**$57,481**	$45,000	$17,082	**$62,082**	$51,000	$18,000	**$69,000**
Awards (Scholarships)	$17,000	$4,000	**$21,000**	$12,000	$4,000	**$16,000**	$6,000	$2,000	**$8,000**
Other (Specify):									
Printing, Duplicating, and Binding	$519	$1,231	**$1,751**	$4,500	$1,500	**$6,000**	$5,100	$1,700	**$6,800**
Communication	$860	$248	**$1,108**	$6,000	$500	**$6,500**	$6,600	$600	**$7,200**
Computer Services	$518	$80	**$597**	$600	$200	**$800**	$1,950	$650	**$2,600**
Contractual & Special Services	$57,909	$23,203	**$81,111**	$90,000	$30,000	**$120,000**	$105,000	$35,000	**$140,000**
Other Services and Expenditures	$1,338	$571	**$1,909**	$3,000	$1,000	**$4,000**	$3,600	$1,200	**$4,800**
Utilities & Fuel	$187	$262	**$449**	$3,000	$1,000	**$4,000**	$3,600	$1,200	**$4,800**
Professional Svcs & Memberships	$0	$89	**$89**	$600	$200	**$800**	$660	$220	**$880**
Grants & Subsidies	$48,496	$6,745	**$55,241**	$30,000	$10,000	**$40,000**	$30,000	$10,000	**$40,000**
Total Non-Personnel	**$491,049**	**$109,993**	**$601,043**	**$584,700**	**$195,098**	**$779,798**	**$279,510**	**$94,022**	**$373,532**
GRAND TOTAL	**$1,679,200**	**$682,505**	**$2,361,706**	**$1,814,031**	**$793,187**	**$2,607,218**	**$1,537,613**	**$718,142**	**$2,255,755**
Revenue									
New State Appropriation		$691,343	**$691,343**		$714,569	**$714,569**		$718,142	**$718,142**
Carryover State Appropriation		$69,781	**$69,781**		$78,618	**$78,618**			**$0**
New Matching Funds	$1,679,200		**$1,679,200**	$1,814,031		**$1,814,031**	$1,537,613		**$1,537,613**
Carryover from Previous Matching Funds			**$0**			**$0**			**$0**
Total Revenue	**$1,679,200**	**$761,124**	**$2,440,324**	**$1,814,031**	**$793,187**	**$2,607,218**	**$1,537,613**	**$718,142**	**$2,255,755**

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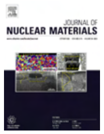

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D. Kim, Y.T. Liu, A.V. Levlev, **K. Higgins**, O.S. Ovchinikov, J.S. Yun, J. Seidel, S.V. Kalinin, and M. Ahmadi, “Unraveling the hysteretic behavior at double cations-double halides perovskite-electrode interfaces”, Nano Energy, **89**, 106428, DOI: 10.1016/j.nanoen.2021.106428 (2021).

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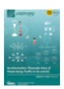

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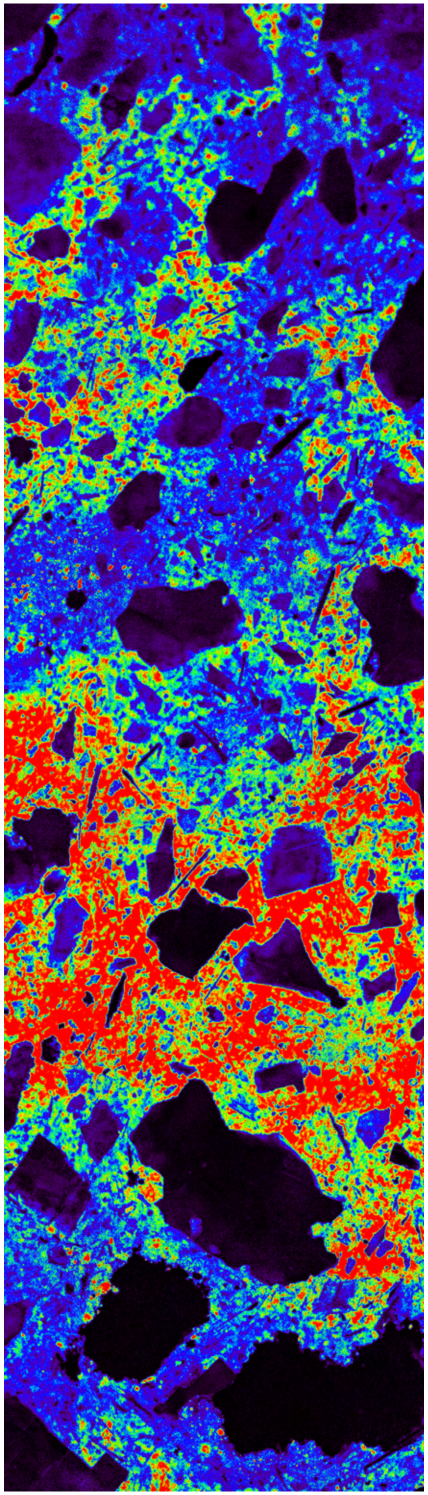

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