Engineering Research Center for Power Optimization for Electro-Thermal Systems (POETS)

University of Illinois at Urbana-Champaign (lead institution)

Enabling electrified mobility in air, highway, and off-road vehicles through dramatically increased power density

A National Science Foundation Engineering Research Center since 2015

Partner Institutions:

- Howard University
- Stanford University
- University of Arkansas

There is a clear and long-term trend towards increased electrification in all modes of mobility and transport. From cars to construction to aircraft, there has been a steady increase in the number of electrified vehicles as well as an increase in the amount of electric power on-board each vehicle. These trends have persisted over several decades and, if anything, seem poised to accelerate. With current international legislation calling for a gradual reduction, and in some cases phase-out, of fossil fuel-powered automobiles, the next several decades will see a tipping point in electrified mobility and transport. For all these systems to continue to proliferate throughout modern society, there is a strong drive to increase the power-to-weight or -volume ratio for their electrified components including motors, power electronics, batteries, etc. The goal of the NSF Engineering Research Center on Power Optimization for Electro-Thermal Systems (POETS) is to become a key enabler in providing that increase in power density with advanced technology and workforce development.

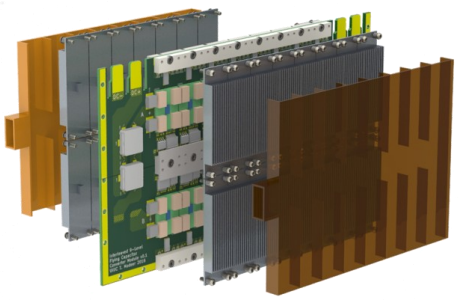
The primary barrier to increased power density is the heat buildup associated with electrical current flow. Managing the thermal power flow in conjunction with the electrical power flow is at the heart of what POETS' researchers do. The technical areas involved span a wide range of topics including: electrical circuit design, multi-phase flow in micro scale heat transport, design optimization, electronic packaging, and materials science. It is this tight synergy across disciplines that sets the POETS research agenda apart from the conventional practice.

The POETS educational agenda also bridges the gaps between disciplines by offering novel ways for students to appreciate the interplay of electrical and thermal power at many different stages of education. The goals include increasing the number of students who can think in-depth about technical problems as well as broadly across disciplines to come up with next-generation technologies as members of complex teams.

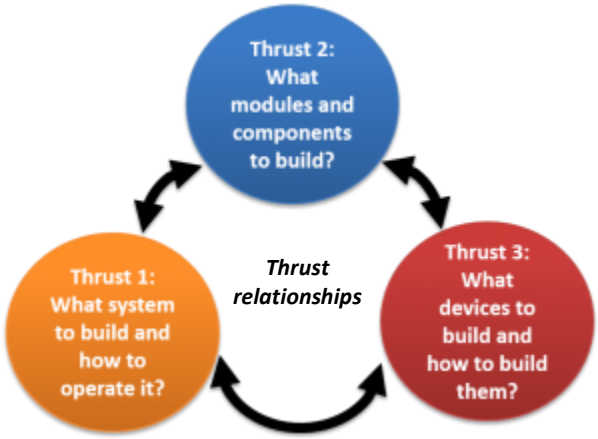
Research

Many engineered systems develop their electrical systems first and then use these to set thermal systems requirements. POETS considers both the electrical and thermal systems from design concept and optimization through deployment in fielded vehicle testbeds. The aim of the Center's efforts is to break down the silos between different disciplines (electrical, mechanical, materials) and co-design as well as co-operate power-dense electrical systems. The success of POETS will result in a 10X to 100X increase in power density over the state of the art at the start of the Center.

To create integrated electro-thermal systems, where thermal power can be directed as easily as electrical power, POETS will need to develop some basic capabilities that do not exist. For example, POETS is building the thermal equivalent of electrical solid state circuits. These include thermal switches and diodes that are coupled to thermal capacitive and variable resistive elements. Some of these are active elements and some are due



"High power density inverter incorporating integrated microfluidic thermal management"



to the behavior of specifically tailored and engineered materials. In parallel with the new thermal circuitry, new designs for wide bandgap and other types of power electronics are being pursued. With these building blocks, POETS will be able to lay out electrical and thermal circuit designs simultaneously.

To organize this research, POETS has three Research Thrust areas.

Thrust 1: Optimization and Control – This thrust focuses on the design optimization of novel electrified systems, including layout and sizing. The design phase of optimization is coupled with the operational phase, where this thrust takes the as-designed systems and determines the best way to utilize them respecting electrical and thermal constraints.

Thrust 2: Systems Design and Analysis – This thrust develops basic design topologies for new electronic components such as inverters, power converters, motors, storage, etc. Thrust 2 uses some of the fundamental new components developed in Thrust 3 and combines them using the design optimization tools of Thrust 1 to elicit novel designs.

Thrust 3: Materials and Fabrication – This is the most fundamental thrust, as it examines basic materials and their integration into electronic components. These materials include well-known wide bandgap materials with well-understood electrical behavior, as well as new autonomic materials that change their behavior as a function of temperature.

In addition to building the technical elements, long-term research goals for POETS are to build the right type of innovation ecosystem that allows for new ideas to enter through the addition of new core faculty and students as well as new partnerships with other organizations including industry, government and academia.

Education

Broadening the participation of and strengthening the K-20 STEM pipeline is a critical, overarching goal for POETS' education and workforce development efforts. We are achieving this by targeting three strategic thrusts: Pre-College, Undergraduate, and Graduate students, each with focused objectives (dark blue boxes) and methods (light blue boxes).

Pre-College

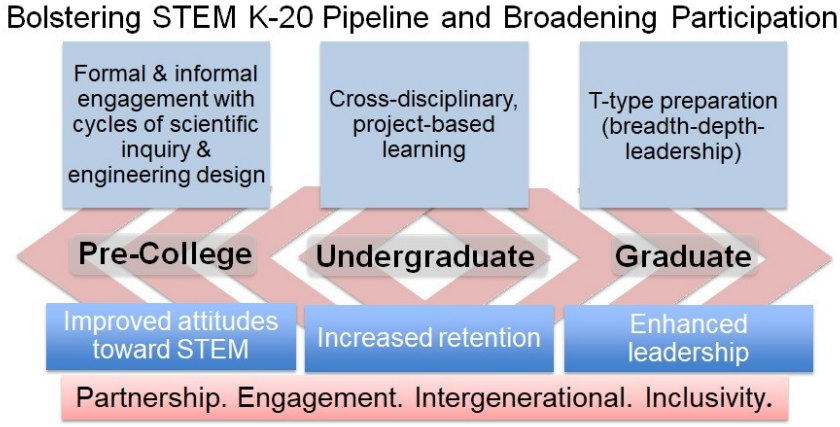
The aim of our pre-college efforts is to increase interest and engagement in STEM subjects and/or careers. We focus on improving understanding of science and engineering processes via Next Generation Science Standards (NGSS) and fostering students' scientific identity through several inquiry-based activities:

- The RET program is focused on the development of a multi-week, NGSS-aligned middle school module to achieve concrete, long lasting impact.
- The Young Scholars program targets underrepresented minority high school students and provides opportunities to work with POETS graduate students and post-docs in authentic research projects at a POETS institution.
- Engineering Competitions and Clubs provide hands-on, design-based learning opportunities during the academic school year, during or after school hours.
- Informal outreach activities, led by POETS RET teachers, REU students and the SLC outreach team, allows for intergenerational learning and mentoring.

Undergraduate

To improve retention of undergraduates we provide opportunities for students to be involved in multi-week projects that are meaningful, relevant, and interdisciplinary. Our goal is to increase students' self-efficacy in science and engineering fields and their ability to thrive in interdisciplinary teams through the following programs:

- The summer REU program prepares promising undergraduates for a broad range of STEM careers while providing professional development opportunities. Students are trained in interdisciplinary research under mentorship of POETS faculty and students.
- Undergraduate research during the school year allows students to obtain long-term mentorship through a research project.
- The first-year engineering design course brings freshman engineering students from various engineering disciplines together to solve complex problems with societal benefit.
- The interdisciplinary senior design capstone breaks down the silos of engineering disciplines by training electrical, materials, and mechanical engineering together in cross-discipline coordination. These students work closely with POETS industry partners.



POETS' education approach across the P-20 spectrum.

Graduate

We are seeking to prepare effective, innovative leaders of tomorrow. Graduate student are trained to be T-shaped leaders: Technical breadth and depth with overarching professional skills. We will achieve this by providing:

- A series of formal and online courses to help students develop their technical expertise in POETS-related fields and expand their ability to work on an interdisciplinary team
- Seminars, workshops, and online courses to help students develop skills in leadership, innovation, systems thinking, entrepreneurship, and scientific communication.
- STEM outreach opportunities with K-12 and undergraduate students reinforce students' teaching, innovation, and scientific communication skills.

Innovation Ecosystem

POETS's industrial collaboration efforts involve partnerships with both industry and government agencies, ensuring POETS research addresses technical challenges that will benefit society. By increasing power density in mobile systems, substantial savings can be made in fuel consumption, in extended range of electric vehicles, or by reducing CO_2 emissions. Companies ranging from start-ups to multinationals are POETS members, representing a broad range of industry sectors including passenger vehicles, construction and agriculture equipment, and aerospace systems.

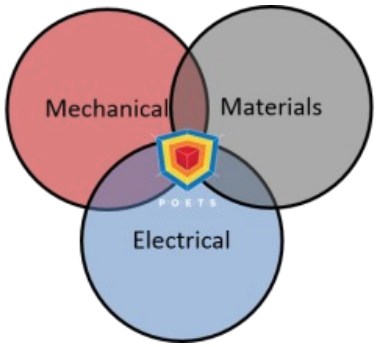
Our innovation ecosystem thrives by active engagement among all partners. Collective and collaborative workshops help focus a subset of near-term activities within POETS on specific technologies in areas of broad relevance. Innovation ecosystem partners actively participate in regular university research meetings in a bi-directional flow of pre-competitive information. Students spend extensive periods of several months in industry internships of mutual benefit to their on-campus research and continue the collaboration while back on campus; many of these students end up working at these companies. Industry/university partnerships within the ecosystem solicit and attract additional resources through competitive proposals to a broad array of stakeholders. This truly multi-faceted and close collaboration ensures that ideas and people get from the academic research setting into the marketplace and industrially relevant problems inform exciting new research ideas.

Our partners engage with more than just the research activities in POETS, supporting our workforce development efforts. Whether providing a webinar on small business opportunities, funding hands-on learning opportunities, supporting scholarships, or hiring interns and full-time employees, companies have access to a talented pool of uniquely trained students.

Additional innovation ecosystem efforts include technology transfer and commercialization activities, and intentional entrepreneurship education efforts. Multiple startups have been formed from POETS activities, oftentimes with the support of the large companies already present in the ecosystem. POETS also has three testbeds for multiple industry sectors, which are designed to support technology development beyond proof-of-concept.

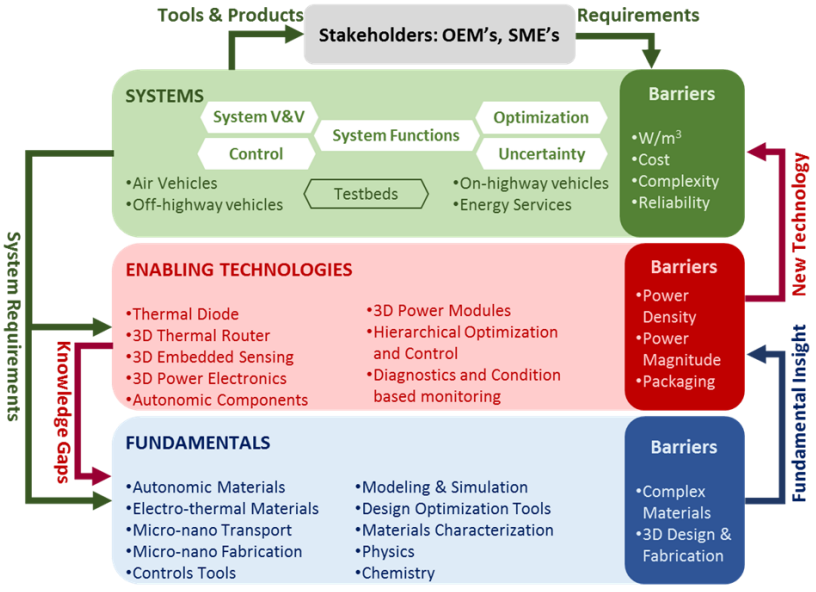
Facilities

POETS has extensive facilities available for fabrication and testing of the types of intricate electro-thermal systems under study. POETS headquarters at the University of Illinois (UI) consists of 5,000-ft^2 of collaborative work space for POETS students, meeting and conference room areas equipped for a 4-50 person webinar, and the POETS administrative offices. A newly constructed 10,000-ft^2 testbed facility, POETS South, includes bay areas, offices, and meeting areas just south of the UI campus. This new testbed facility will allow for high power testing of motors, power electronics,



batteries, etc. In addition, The Grainger Center for Electric Machinery and Electromechanics (CEME) at Illinois has extensive facilities for power systems ranging from 0.1 kW to 100 kW. CEME has been developing advanced high-performance power testbeds since 1999. This includes "hardware-anywhere-in-the-loop" testbeds intended for direct operation of electric and hybrid vehicle subsystems and components in a MATLAB/Simulink environment. Motors, battery packs, and other major components can be swapped with models within the control loop. CEME supports work on power GaN processing and high-performance power electronics.

The University of Arkansas has advanced laboratory facilities such as the National Center for Reliable Electric Power Transmission (NCREPT), which started in 2005. These facilities house grid-scale regenerative power electronic drives, circuit breakers, transformers, controls, data acquisition units, and large-scale dynamometers. Key to providing the flexibility and reconfigurability required for this facility are 6 MVA regenerative drives under computer control. The facility itself is a two-story,



POETS 3-plane chart

POETS students visit Proterra as part of the POETS Annual Meeting at Stanford University, 2016.

high-bay facility that is 7000 sq ft in size. This lab has available dc power supplies rated for 45 kW at 800 V and 700 kW at 660 V. The Low-Temperature Co-Fired Ceramics (LTCC) laboratory at the High Density Electronics Center (HiDEC) is one of the few research and prototyping LTCC facilities in North America. High-power and high-temperature power modules are routinely fabricated in this laboratory. HiDEC has one of the most complete power packaging facilities in the country, including thin and thick film processing, direct bond copper and direct bond aluminum processing, patterning, etching, sputtering, and material synthesis and characterization, to name just a few of the capabilities.

Through Stanford University, POETS researchers have access to world-class facilities including the Stanford Nanofabrication Facility (SNF), the Stanford Nanocharacterization Lab (SNL) and the Stanford Nano Center (SNC). These campus-wide shared facilities are part of the National Nanotechnology Infrastructure Network (NNIN) funded by the National Science Foundation (NSF), with management support from Stanford University. In addition, POETS has access to unique characterization equipment for performing a wide range of experiments to study the electrical and thermal properties of devices. The facilities at the SNF enable POETS researchers to build device structures with feature sizes as small as ~10 nm. There are capabilities to deposit a wide variety of materials including oxides, nitrides, and metals. All of the device structures used within POETS can be fabricated using the facilities available here or in HiDEC.

Center Configuration, Leadership, Team Structure

POETS is a collaboration between industry, government, and academia. It consists of a lead institution at the University of Illinois along with 3 core partners: the University of Arkansas, Howard University, and Stanford University. Here we leverage strengths at each institution and collaborate across the disciplines and campuses. Arkansas brings a strong and focused strength in power electronics and Stanford brings a strength in small-scale systems for thermal management. Illinois and Howard bring a broad and balanced portfolio of Mechanical Engineering, Materials Science, and Electrical Engineering. Over 20 faculty and 50 students/post-docs participate and exchange ideas through regular personnel exchanges, center-wide webinars, and biannual conferences.

The center has a Director, a Deputy Director, and three thrust leaders. In addition, the Associate Director for Education and Inclusivity steers our workforce development, from an inclusive perspective, and ensures it is synergistic with the POETS research efforts. The Director of Industry and Innovation manages our Innovation Ecosystem efforts, which includes stewarding the relationships with the companies and government entities involved.

The leadership is drawn from across all core partners, with representation on the POETS management committee by all four schools. Additionally, our industry partners provide steady input into the management process since they are truly part of the POETS team.

Center Headquarters

Center for Power Optimization of Electro-Thermal Systems (POETS)
1304 W. Springfield Avenue
2270 DCL, MC 275
Urbana, IL 61801
www.poets-erc.org

Center Director:
Andrew G. Alleyne, Ph.D.
University of Illinois at Urbana-Champaign
(217) 244-9993 · alleyne@illinois.edu

Deputy Director:
Alan Mantooth, Ph.D.
University of Arkansas
(479) 575-4838 · mantooth@uark.edu

Associate Director of Education and Inclusivity:
Jessica Perez, Ph.D.
(217) 300-5866 · jgperez@illinois.edu

Director of Industry and Innovation:
Karen Bender, Ph.D.
(217) 300-1359 · kbender@illinois.edu

Howard University Lead:
Sonya Smith, Ph.D.
(202) 556-1837 · ssmith@howard.edu

Stanford University Lead:
Kenneth Goodson, Ph.D.
(650) 736-1283 · goodson@stanford.edu

Associate Director of Operations and Finance:
Sonya Chambers, MBA, CFM, CMA
(217) 265-0550 · slc@illinois.edu