WELCOMING REMARKS

The Center for Laser Applications (CLA) at the University of Tennessee Knoxville Space Institute at Tullahoma is pleased to present our annual report of research projects funded by the Center.

This has been another transformative year for CLA. The CLA has established capabilities, both in Faculty and equipment, that are unique for both the state and the nation. The strengths and interest in the applications of lasers for diagnostics and materials processing represent a unique university-based combination that is critical for many industrial, defense, and basic science application areas. Our capabilities now include combustion systems and jet engine/space propulsion systems development, laser materials processing, ground-based (simulated) aerospace testing, electro-optics, non-linear optics, quantum optics, molecular spectroscopy, and laser induced assisted chemical reactions. All of these areas fit with CLA’s original and current Mission. They have obvious relevance to the future competitiveness of technological industries and institutions of the state, region, and nation.

We continue to move our strategic plan forward by bringing faculty and researchers from different disciplines to work together, each bringing a different expertise to the table. These include Bio/Nano-photonics, Material Science, Laser Material Interaction, Laser Spectroscopy, Laser Based Measurement/Diagnostics, Advanced Clean-Combustion Strategies, Reacting Flows, Alternative Fuels, as well as Thermal Management and Thermal Runaway for Li-ion Batteries and Non-Equilibrium Fluid Physics. Our multidisciplinary collaborations with the MABE faculty have the potential to open many new opportunities. The process has already expanded our capabilities by allowing budgetary carry-over that is being used to purchase new and up to date equipment, with more to come.

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CENTER FOR LASER APPLICATIONS
ANNUAL REPORT 2020 - 2021

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On the cover:

What you see is a 3D surface image of a series of microwells micromachined on the surface of a fused silica wafer using an ultrafast laser. Each well is 20 microns deep and 40 microns wide. The 3D surface image was generated by the newly purchased Leica DMV6 digital microscope. The microscope images the sample at different depths and then reconstructs the 3D surface image automatically. The red path shown on the image denotes the location of a height profile selected by the user.
INTRODUCTION

CLA has established capabilities that are unique for both the state and the nation. The strengths and interest in the applications of lasers for diagnostics and materials processing represent a unique university-based combination that is critical for many industrial, defense, and basic science application areas. Examples of the strengths and interests include combustion systems and jet engine/space propulsion systems development, laser materials processing, ground-based (simulated) aerospace testing, electro-optics, non-linear optics, quantum optics, molecular spectroscopy, and laser-induced assisted chemical reactions. All these areas fit with CLA’s original and current Mission. They have obvious relevance to the future competitiveness of technological industries and institutions of the state, region, and nation.

One of the strengths CLA possesses is the ability of faculty from different disciplines to work together, each bringing a different expertise to the table. These include: Bio/Nano-photonics, Material Science, Laser Material Interaction, Laser Spectroscopy, Laser Based Measurement/Diagnostics, Advanced Clean-Combustion Strategies, Reacting Flows, Alternative Fuels, as well as Thermal Management and Thermal Runaway for Li-ion Batteries and Non-Equilibrium Fluid Physics. These multidisciplinary collaborations have the potential to open many new opportunities for CLA.

MISSION STATEMENT

The original purpose and mission of CLA remains relevant as described in the original 1984 proposal. It has evolved to stay abreast and ahead of science and technological needs. This evolutionary process was the exact intent of the original proposers and better serves the needs of Tennessee by adding goals and objectives to an existing solid foundation.

Education

- Attract nationally recognized faculty and student scholars
- Produce well-trained graduates for employment in Tennessee
- Disseminate state-of-the-art information on laser application technology to the industrial and scientific communities
- Provide quality educational experiences for multidisciplinary students
- Generate opportunities for undergraduate and high school student research
- Assist businesses in development and implementation of technology
- Increase interest in STEM areas, i.e., support science education for students and teachers

Research

- Develop state-of-the-art experimental facilities for research on a variety of laser application problems
- Develop a world class reputation for research and innovation to meet the needs of science and industry
- Utilize center funds for the exploration and development of new research areas
- Enhance the amount of research support from industrial and governmental organizations
- Transfer new laser application technology to state and regional industry and scientific organizations
- Enhance the research capability of other UTSI research groups through development of advanced laser-based measurement techniques
FOCUS AREAS

The focus of the mission-related research programs of the Center is the application of lasers and associated technology. These focus areas of specialization were selected to correspond to known areas of scientific and engineering challenges and to areas of development and regional and national needs.

Bio/Nanophotonics
- Lino Costa - devices for cellular chemotaxis
- Jacqueline Johnson - storage phosphor materials for dental imaging
- Christian Parigger - photo-acoustic imaging, diagnostics, and applications
- Feng-Yuan Zhang - MEMS/NEMS, micro/nanofluids

Materials Science
- Lino Costa - phase transformations, laser cladding and modeling of direct metal deposition
- Christian Parigger - laser-induced materials physics
- Jacqueline Johnson - nanoparticles for medical theranostics
- Charles Johnson - Mössbauer spectroscopy
- Saeed Kamali - Mössbauer spectroscopy
- Lee Leonard - glasses and glass ceramics for radiographic imaging and dosimetry
- Feng-Yuan Zhang - micro/nanomanufacturing multifunctional materials

Laser Materials Interaction
- Lino Costa - laser cladding and femtosecond laser machining
- Trevor Moeller - laser ablation dynamics and modeling of laser ablation for space propulsion
- Christian Parigger - laser-induced ablation physics
- Feng-Yuan Zhang - micro/nanomanufacturing multifunctional materials
- Phillip Kreth - laser-based heating of material samples for high-enthalpy flows

Laser Spectroscopy
- Christian Parigger - ultrasensitive spectroscopy and combustion diagnostics
- Feng-Yuan Zhang - tomography, diode-laser absorption spectroscopy, thermography

Laser Measurement and Diagnostics
- Phillip Kreth - laser-induced fluorescence, radar REMPI, Raman scattering, molecular tagging velocimetry
- Mark Gragston - I-MHz Burst Mode Laser, particle image velocimetry, Krypton tagging velocimetry and laser-induced fluorescence

Non-Equilibrium Fluid Physics
- Trevor Moeller - plasma dynamics and combustion
- Christian Parigger - laser-plasma physics, combustion, and fluid physics and computational physics
- Feng-Yuan Zhang - hypersonic flow and reaction, electrochemical reaction
- Phillip Kreth - diagnostics development for hypersonic flow
- Peng Zhao – clean combustion, reacting flows, alternative fuels, thermal management and thermal runaway for Li-ion batteries.
Dr. Brian Canfield, Research Scientist I

Dr. Brian Canfield (Ph.D. in Physics, Washington State University) contributes to a wide range of CLA’s research projects in applied and nonlinear optics, in particular, ultrafast laser materials processing. Technologies relying on these processes include machining of microfluidic/nanofluidic systems, large-scale roll-to-roll replication template fabrication, custom foil mesh drilling for energy production and storage, surface modification for improved physical environmental interaction, and thrust and charge dissipation schemes for orbiting satellites. He has also been instrumental in the development of experimental systems for ultrasensitive fluorescence detection and single-nanoparticle trapping and tracking for biotechnology applications. Recently, Dr. Canfield has implemented turret-mounted Bessel beam optical systems for laser-machining very high aspect ratio holes and channels through various transparent substrates including polymers, glasses, and crystalline materials like diamond and sapphire. His current research highlights determining how these materials respond to laser pulses to determine the optimal laser pulse conditions (such as length, energy, and number needed) for both conventional Gaussian-focus and Bessel-beam machining in each material. Towards this goal, a newly acquired spatial light modulator in the ultrafast laser machining system will allow much greater flexibility in beam-shaping for future laser materials processing.

Alexander Terekhov, Research Specialist III and Manager of CLA Research Engineering and Operations

Mr. Alexander Terekhov (M.S. in Physics, Moscow State University; M.S. in Materials Science, University of Illinois Urbana-Champaign) has the responsibility of maintaining the Laser Systems, Laser Safety, and other technical hardware at CLA. Mr. Terekhov is a co-author on many scientific papers in a variety of fields.

Doug Warnberg, Research Specialist III

Doug is a United States Air Force veteran and has an Associate’s degree in Applied Science from Motlow State Community College and the Community College of the Air Force. He also has a diploma from the Tennessee College of Applied Technologies-Shelbyville in Industrial Maintenance. Doug takes care of the physical plant of CLA and is an expert in HVAC and facilities operation. The many vacuum systems, Class 1000 clean room, and the Rigaku SmartLab X-ray Diffraction System as shown on Page 4, are all maintained by Mr. Warnberg. If you need a hand with any task Doug is always there to help.
Dr. Lu Liu (Ph.D. in Chemistry, University of Maryland) has more than 10 years’ experience in experimental design, material synthesis, testing and screening, including magnetic materials, battery electrode materials, metal/metal oxide nanoparticles w/o coating, and functional polymeric materials and composites. She joined UTSI in February of 2021 she has been working exclusively on FeNPs synthesis. She has developed experimental apparatus for both thermal-decomposition and reduction methods to synthesize Fe NPs with different size distributions and crystalline structures. She has also participated in preliminary characterization of the FeNPs using TEM, XRD, Dynamic Light Scattering (DLS) and Mössbauer Spectroscopy and she will continue working further on surface modification of FeNPs for magnetic particle imaging (MPI) tracers’ design and engineering.
Collaborations

A significant fraction of the research and development program of the Center is supported by state, regional, and national industries. CLA actively collaborates with the Center for Industrial Services to provide studies for Tennessee industries, and CLA has also formed long-term research partnerships by the traditional federal agencies, the National Institutes of Health, the National Science Foundation, and National Laboratories at Oak Ridge and Los Alomos as well as numerous collaborations with national and international Universities, and the nearby Arnold Engineering Development Center. These diverse research activities along with our outstanding facilities, and low student-to-faculty ratio, combine to offer a very productive academic experience for diligent graduate students.

Graduated Students

Please congratulate our recent degree recipients as follows:

Cameron McTiernan Craig  MS ES
Joshua Lee Osborne       MS ME
Phillip Lee Jones        MS ME
Zachary William Smith   MS AE
Albert Velazquez         MS AE
Scott Lee Burnett        MS ME
Isaiah Hutson Salinas   MS ME
Caleb H. Bell            MS AE
Austin Thomas            MS BME
Christopher M. Helstern PhD Physics
Charles Bond             PhD BME
Adam Evans               PhD BME
EXECUTIVE SUMMARY

Foreword

CLA is quickly moving to becoming a world class operation that is increasing its notoriety nationally and internationally. CLA has established capabilities that are unique for both the state and the nation. The strengths and interest in the applications of lasers for diagnostics and materials processing represent a unique university-based combination that is critical for many industrial, defense, and basic science application areas. Examples of the strengths and interests include combustion systems and jet engine/space propulsion systems development, laser materials processing, ground-based (simulated) aerospace testing, electro-optics, non-linear optics, quantum optics, molecular spectroscopy, and laser-induced assisted chemical reactions. All of these areas fit with CLA’s original and current Mission. They have obvious relevance to the future competitiveness of technological industries and institutions of the state, region, and nation.

CLA Leadership

Dr. James Simonton - Interim Director

Dr. Jacqueline Johnson - Program Manager

New Faculty Alliances

An important part of the original mission of CLA was the formation of alliances that would foster multidisciplinary work. Drs. Trevor Moeller, Phillip Kreth, Feng Zhang, Jackie Johnson, Lino Costa, Lee Leonard, Peng Zhao and Mark Gragston of the Mechanical, Aerospace, and Biomedical Engineering Department (MABE) are now using lab space in CLA. Dr. Christian Parigger is a member of the Physics Department faculty and also a CLA researcher. They are utilizing lasers to develop research related to measurements and diagnostics of hypersonic flow, combustion characteristics as well as clean hydrogen augmented turbine engine propulsion. We are also pleased to add battery research to our cross disciplinary work this year. These areas are of high interest to the DoD, NASA, private industry and the citizens of Tennessee.

New Equipment Purchased

Our growth in grants and contracts this year has allowed CLA to carry over funding from last fiscal year which in turn has provided us the opportunity to replace/add equipment and capabilities. In 2021 we invested $120,294 in new equipment while encumbering an additional $746,631 for new equipment that will not hit the ledgers until 2022. Our two largest purchases were a state-of-the-art X-Ray Diffractometer Machine and a Scanning Electron Microscope. Both are replacing old unreliable high maintenance cost machines. Other equipment purchased were: An Olympus Objective for Optical Microscope, Undercounter Glassware Washer, Beckman Centrifuges, Milling Machine, EV + Accel RTE Calorimeter System, and a Dual-Pulse YAG Laser System.

Community Outreach

The Covid Pandemic has severely hampered our outreach and STEM activities. We are currently working with our faculty, students and staff to increase our outreach activities as soon as this health crisis has ended.

One bright spot in outreach was our 2021 summer intern program. With much preparation and appropriate precautions, we were pleased to have interns for the first time since the summer of 2019.
We had 16 total undergraduate interns from a pool of over 120 applicants. Of the 16 total selected by the faculty, 4 interns worked directly with CLA faculty and graduate students. The program provided the undergraduates with current work within active research programs to get a real-life experience of what faculty and graduate students do on a day to day bases. Interns were required to summarize their research and give presentations at the end of the program. Feedback from the interns was overwhelmingly positive.

Our plans are to expand the program while maintaining a quality experience for each student. From our recruiting efforts, we are expecting over 300 applications for the summer 2022 intern program!

Pictured here, adjacent to the glovebox, are Anna Bull and Daniel Wood, a GRA and intern respectively, in Jackie Johnson's group.
Activities

In FY 2021 CLA associated staff and faculty had 57 peer reviewed articles published and/or accepted into press, 1 book chapter, and 27 national/international presentations.

Percent Allocation of CLA Total Expenditures ($445,385)

- Salaries and benefits 50%
- Equipment related expenditures (repair, supplies, and new) 15%
- Travel 0%
- Student Fees 5%
- Assistantships 8%
- Maintenance 14%
- Supplies 8%

The end of the year carryover was $935,562.

This carryover will be utilized toward major equipment purchases as described in the New Equipment Purchased section.
RESEARCH ACCOMPLISHMENTS AND FIVE- YEAR BENCHMARK

Our research mission is growing. The funding provided by the Tennessee Higher Education Commission, coupled with support from the university, provided valuable leverage for sponsored research. The research awards continue to increase. This growth is possible because of the dedication of our faculty and the support of THEC and UTSI.

CLA remains active in Outreach and Business Development. The faculty are active in scientific conferences and local business meetings. Productivity among Center faculty has been outstanding during the last five-year period. During fiscal years 2017 through 2021, Center faculty published 179 peer-reviewed articles and 7 books, and presented or have had abstracts accepted at 79 regional, national, and international meetings.

**Benchmark Data**

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<th>FY2017-2021 Cumulative</th>
<th>FY 2017</th>
<th>FY 2018</th>
<th>FY 2019</th>
<th>FY 2020</th>
<th>FY 2021</th>
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<td>7</td>
<td>1</td>
<td>12</td>
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**FUTURE DIRECTIONS**

Hypersonics research has grown tremendously over the past two years and from all projections, growth will continue. CLA is strategically placed to benefit from the associated funding. CLA’s current involvement, through laser measurement and diagnostics will be a key element in our future. This alliance will spur growth related to our material science area in the form of thermal protection materials and bonding of those materials. The alliances we have formed, with the Hypersonics and Propulsion Groups at UTSI, have the potential for introducing CLA capabilities to a much wider audience in the Aerospace and Defense sectors. To help bolster our presence in one of the largest aerospace and defense markets, Huntsville, Alabama, we have opened an office in the 2nd largest research park in the country. We have staffed the office to enable us to make the connections necessary to expand our funding with private, DoD and public entities located in the area.

In 2021 UTSI has added three new faculty members that are working directly or indirectly with CLA in their research areas. We are presently working on filling a Propulsion Chaired position (Boling Chair) and three or more faculty positions by Fall 2022. These new faculty will contribute to the utilization of CLA assets and lab space. With the additional funding these researchers will bring, we will continue updating CLA with the most applicable equipment and staff to meet current and future research needs.
## CENTERS OF EXCELLENCE ACTUAL, PROPOSED, AND REQUESTED BUDGET

### Expenditures

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<th>Institution</th>
<th>The University of Tennessee</th>
<th>Center</th>
<th>Space Institute</th>
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<td>FY 2020-21 Actual</td>
<td>FY 2021-22 Proposed</td>
<td>FY 2022-23 Requested</td>
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<td>Matching</td>
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<tr>
<td>Faculty</td>
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<tr>
<td>Other Professional</td>
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<td>Clerical/Supporting</td>
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<td>Assistantships</td>
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<td>$129</td>
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<td><strong>GRAND TOTAL</strong></td>
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**Revenue**

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<th>FY 2021-22</th>
<th>FY 2022-23</th>
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<td>New State Appropriation</td>
<td>$883,218</td>
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<td>Carryover State Appropriation</td>
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<td>New Matching Funds</td>
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<td>$310,552</td>
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<td><strong>Total Revenue</strong></td>
<td>$222,039</td>
<td>$1,380,947</td>
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Materials Science Research

Dr. Lino Costa
Research Assistant Professor of Mechanical, Aerospace, and Biomedical Engineering
Ph.D., University of Lisbon

Dr. Costa continues to explore the unique micromachining capabilities of ultrafast lasers to develop new approaches to difficult fabrication problems. Ultrashort laser pulses, nominally as short as a few picoseconds, can directly etch micrometer-scale structures with precise and sharp geometries on virtually any surface without a photomask and in just a single step.

Materials directly exposed to the ultrashort laser radiation ablate away so rapidly that virtually no transfer or accumulation of heat occurs in the surrounding material. In addition, ultrafast lasers promote non-selective ablation of materials, a characteristic that is useful when working with composites. These characteristics make ultrafast lasers ideal tools for cutting, trimming, drilling, and patterning many opaque materials including metals, ceramics, and composites, and enables all sorts of novel and interesting applications, especially when it comes to extremely hard and brittle materials, and thin foils, that are traditionally difficult to work. Also, ultrafast lasers can clean, texture, and increase the surface energy of materials at very precise locations to enhance wetting of and adhesion to other materials. For certain transparent dielectric materials, both surface and sub-surface (embedded) structures are possible. Under certain conditions, one can form structures that cannot be attained using conventional lithography. For example, the highly nonlinear nature of the photon absorption process on the instantaneous irradiance of a tightly focused ultra-short laser pulse, allows sub-diffraction limited features to be precisely etched. In addition, filament propagation, that is, propagation of the laser beam through the material without diffraction due to self-focusing, can produce waveguides and microcapillaries with ultrahigh aspect ratios. These unique capabilities are explored extensively on lab-on-a-chip microfluidic devices for biomedical research applications.

A novel application under development at UTSI involves next-generation electric micro-propulsion thrusters for Cubesats. The micro-propulsion technology being developed at UTSI, by Dr. Costa and Dr. Moeller, called Micro Scalable Thrusters for Adaptive Mission Profiles in Space (µSTAMPS), uses ionic liquid (IL) propellants to generate thrust via well-known electrospray mechanisms, and has electrospray emitters formed using ultrafast lasers. Dr. Costa is also exploring alternative IL propellants with properties that surpass those of propellants currently used. Compatibility with the thruster materials, wetting behavior, electrical conductivity, cation/anion ratio, and other properties are critical to optimizing the operation and life-time of an electrospray thruster. In the last year, a proprietary IL propellant, developed by Streamline Automation, LLC, was tested as part of a phase I STTR program.

Dr. Costa continues to support the research activities of several local Tennessee companies. In the past year, Dr. Costa received additional funds from International FemtoScience, Inc., to continue research on the processing and characterization of nanodiamond dispersions in diverse media, as part of a collaboration with Tennessee Tech. Additionally, International FemtoScience, Inc., awarded Dr. Costa funding to characterize the performance of diamond-based diode for two separate programs. Ultra Small Fibers, LLC awarded Dr. Costa with several grants for the development of a proprietary nanoimprinting process. Moreover, two projects that are part of the UT-lead $50 million Advanced Manufacturing Project for the Army, have been approved and are expected to be awarded this fall. These two projects will focus on manufacturing applications of ultrafast lasers.

Dr. Costa is grateful for the hard work and the many contributions by research support staff members Mr. Alexander Terekhov, Mr. Doug Warnberg, and Dr. Brian Canfield.
Dr. Mark Gragston

Assistant Professor

Aerodynamics Research Center for Advanced Diagnostics and Engineering (ARCADE)

Dr. Gragston’s research focuses on developing and applying aerodynamic measurement technology (AMT), particularly optical techniques and devices, to measure and characterize phenomena such as boundary layer transition, shock-boundary layer interactions, aerodynamic heating, and more, in high-speed flows. He is the head of the ARCADE research center and is a member of the HORIZON hypersonics research group at UTSI, working alongside Dr. Phillip Kreth and Dr. John D. Schmisseur.

During the 2020-21 academic year, Dr. Gragston worked on the development of a new variation of the focusing laser differential interferometry (FLDI) technique. The variation, known as linear array FLDI (LA-FLDI), greatly improves the efficiency of measuring flow fluctuations at multiple locations in high-speed flow environments. This information is useful for studying hypersonic boundary layer transition and turbulent dynamics. Dr. Gragston demonstrated LA-FLDI in various facilities, including the TAMU Mach 6 quiet tunnel, AEDC Tunnel D, the Mach 6 high-Reynolds facility (M6HRF) at Wright-Patterson AFB, and the 48” Mach 10 facility at Calspan-University of Buffalo Research Center (CUBRC). He is also participating in testing at the NASA Langley Mach 10 facility, where LA-FLDI will be used for studying shock-boundary layer interactions in collaboration with the University of Texas-San Antonio and the University of Maryland.

Dr. Gragston has developed a new velocimetry technique, laser-induced schlieren anemometry (LISA), that utilizes high-speed schlieren imaging of residual packets of heated gas produced via laser-induced plasma in high-speed flow. This technique was demonstrated at 10 kHz in the UTSI Mach 4 Ludwieg tube and in the M6HRF at Wright-Patterson AFB. The LISA technique can be useful for characterizing primarily inviscid flow fields during tunnel commissioning and calibration, as it provides information about velocity, Mach number, and static temperature.

Through an AFOSR Summer Faculty Fellowship, Dr. Gragston worked with AFRL-RQHX at Arnold AFB on readying the LISA technique for use in AEDC facilities and also helped develop FLDI capabilities for Tunnel D.

Figure 1: The LA-FLDI technique can be used to measure the frequency content associated with transitional and turbulent processes in the boundary layer, and even enables a two-dimensional array of points. LISA can be used to measure the velocity, Mach number, and static temperature in high-speed flows.
Charles Johnson does research on solid materials using Mössbauer spectroscopy. Antimony-doped float glass (SiO₂-Na₂O-CaO) is important as it gives a potential low-cost high-energy radiation-resistant material. When float glass is irradiated with γ- or x-rays, defects are formed, which tints the glass, reducing its transparency. When the glass is doped with Sb₂O₃ the transparency is restored. ¹²¹Sb Mössbauer spectra (Figure 1) show that small doses (0.2 MGy) of radiation initially oxidizes Sb³⁺ to Sb⁵⁺ which decreases for larger doses (2.0 MGy) and increases again for even stronger doses (5.0 MGy). It is believed that the formation Sb⁴⁺ ions for small doses causes these anomalies. High Entropy Alloys (HEAs) which have particularly strong mechanical properties have been developed at Oak Ridge National Laboratory for use in nuclear reactors. Their magnetic properties provide a valuable way of characterizing them. ⁵⁷Fe Mössbauer spectra of a series of equiatomic HEAs have been measured and compared to magnetization measurements. FeNi and FeNiCo show 6-line ferromagnetic splitting similar to iron with hyperfine fields of about 310 kG. FeNiCr and FeNiCoCr are unsplit at room temperature, but at low temperatures show a spread of hyperfine fields characteristic of spin glasses. The maximum hyperfine fields (187 and 110 kG respectively) are relatively small as are the Curie temperatures, Tc, of 200K and 110 K. The addition of palladium produces FeNiCoCrPd, which is ferromagnetic and shows a broad 6-line pattern at room temperature corresponding to an average hyperfine field of 160 kG increasing to a saturated value of 254 kG at low temperatures.

Figure 1: ¹²¹Sb Mössbauer spectra of Sb-doped float glass for several radiation doses.
DIAMOND-LIKE CARBON THIN FILMS FOR USE AS AN ANTI-FOGGING LAPRASCOPE COATING

Dr. Jacqueline Anne Johnson

Professor
Mechanical, Aerospace and Biomedical Engineering (MABE)
B.Sc., University of Liverpool, England
Ph.D., University of Liverpool, England
Fellow of the American Ceramic Society
Fellow of the Institute of Physics

The Johnson group has continued work on producing an anti-fog coating by pulsed laser deposition from research funded by the National Institutes of Health. This coating will be used to improve the surgical field of view of laparoscopes. Figure 1 shows a laparoscope in use.

As the project draws to a close, we have established the properties that are needed for the coating to succeed commercially as a coating for a laparoscope. Doping with SiO leads to increased hydrophilicity (see Figure 2). Plasma cleaning with argon further increases the hydrophilicity and reduces surface roughness. The coating is biocompatible as tested by our collaborators at Vanderbilt University Biomedical Engineering Department and demonstrates excellent antifogging properties (see Figure 3).

In addition to performing research on diamond-like carbon films, Dr. Johnson oversees projects concerning iron nanoparticles for magnetic particle imaging, carbon composite materials for hypersonic applications, as well as glass and glass-ceramics development for multiple applications, hypersonic seals, and a depaint apparatus.

In the fall of 2021, the Johnson group will embark on a new project developing a cathode from earth-abundant materials in collaboration with George Mason University.

Dr. Johnson continues to serve on federal review panels as well as department planning and hiring committees. She is the Program Manager for the Center for Laser Applications and the Diversity, Equity, and Inclusion Director for the MABE department.

Dr. Johnson is grateful for the hard work of group members, Lee Leonard, Charles Johnson, Saeed Kamali, Lu Lui, Austin Thomas, Anna Bull, Aleia Williams and Emily Moore as well as 2021 summer interns Troy Schneider, Leigha Southall and Daniel Woods.
Spintronics and Superconducting Materials Studied by HE-XRD and Mössbauer Spectroscopy

Dr. Saeed Kamali

Research Associate Professor

Department of Mechanical, Aerospace and Biomedical Engineering (MABE)
M. A. Uppsala University, Sweden
Ph.D., Uppsala University, Sweden

Synchrotron-based High Energy X-Ray Diffraction (HE-XRD) combined with a Pair Distribution Function (PDF) analysis have been utilized to extract valuable structural information of amorphous CoFeB and silicon supported gold nanoparticles (NPs). Furthermore, Mössbauer spectroscopy has been used to investigate the magnetic and structural properties of layered low-dimensional structures.

PDF analysis based on the HE-XRD data for a Co$_{20}$Fe$_{61}$B$_{19}$ amorphous ribbon shown in Figure 1, reveals the short-range atomic ordering of this material. This is possibly due to the high-energy of the synchrotron radiation source at the Japanese synchrotron facility, SPring-8, leading to high Q values. The optimized computational cell based on the PDF analysis shown in Figure 2 indicates the existence of small Co clusters embedded in the Fe matrix, which percolates throughout the structure. The enhanced spin polarization in amorphous magnetic materials can be explained by such morphology.

The same approach has been used for silicon-supported Au NPs, where modeling pure Au (not shown) could not fit the peak around 2.3 Å. Au-Si interfacial modeling was able to explain this short bond, providing unique insight into the Au/Si nano-interface, which is important in designing Lab-on-Chip biosensors for detecting influenza and Covid-19.

$^{57}$Fe Mössbauer spectroscopy has been used to investigate the magnetic structures of low dimensional intercalated iron-chalcogenides, FeS, which have applications as superconducting materials. While [Fe$_{10}$S$_{10}$](C$_2$H$_8$N$_2$)$_4$ is non-magnetic down to 6 K (not shown), the three tetrahedral sites and one of the two octahedral sites in [Fe$_9$S$_{10}$](C$_2$H$_8$N$_2$)$_4$ are magnetically ordered at room temperature (RT) as shown in Figure 3. Detailed analysis shows that, while the magnetic hyperfine fields, $B_{hf}$, for the octahedral site and one of the tetrahedral sites are randomly distributed, the $B_{hf}$ for the other two tetrahedral sites are oriented perpendicular to the plane of the sample.

In a recent study, $^{57}$Fe Mössbauer spectroscopy was employed to investigate the temperature dependent magnetic and structural properties of various lanthanide-based compounds, L$_6$FeSi$_2$S$_{14}$, where L stands for Tb, Gd, Pr, or Sm. At RT, all four compounds are in the superparamagnetic state, giving rise to doublets with the main signal coming from high-spin Fe$^{2+}$. Although, at RT, the Fe atoms have a symmetric environment, surrounded by four equidistant S atoms, the spectra at low temperature, which are magnetically split for Tb-, Gd-, and Sm-based samples, have mixed hyperfine parameters indicating very high asymmetry around Fe atoms, where a full Hamiltonian is needed to analyze the spectra as shown in Figure 4.
Advanced Optical Diagnostics and Flow Control Strategies for High-Speed Flows

Phillip Kreth
Assistant Professor
Mechanical, Aerospace, and Biomedical Engineering
Ph.D., Florida State University

Dr. Phil Kreth’s research interests are focused on the development of advanced optical diagnostic techniques, image-based data reduction methodologies, and novel flow control strategies for application in high-speed and hypersonic flows. Dr. Kreth is an assistant professor within the HORIZON research group (http://horizon.utsi.edu/) which focuses on hypersonic aerothermodynamics and other research areas spanning both aerospace and defense. Dr. Kreth’s Flow Diagnostics Laboratory (FDL) was recently relocated to an area adjacent to the Mach 4 and Mach 7 Ludwieg Tubes in the Tennessee Aerothermodynamics Laboratory (TALon) building. This transition will better facilitate the implementation of diagnostics into the hypersonic wind tunnels located in the TALon lab at UTSI.

In the Flow Diagnostics Laboratory, the HORIZON researchers work with optical diagnostic techniques such as high-speed shadowgraph and schlieren, pressure- and temperature-sensitive paints (PSP & TSP), laser-induced fluorescence (LIF), particle image velocimetry (PIV), and focused laser differential interferometry (FLDI). The optical benchtops are typically used for exploratory efforts and training of graduate student researchers, where smaller-scale configurations can be studied prior to the deployment of these techniques in the Ludwieg Tubes or the supersonic blowdown wind tunnels located in the Propulsion Laboratory.

Over the last year, the HORIZON team has been exploring the capabilities of temperature-sensitive paints (TSP) with support provided by Lockheed-Martin Corporation. Additionally, Dr. Kreth’s group has utilized UTSI’s burst-mode laser system in a variety of measurements ranging from the optical benchtops to the Mach 4 Ludwieg Tube. This laser is capable of producing 10 millisecond burst trains with inter-pulse rates up to 1 MHz at the fundamental and three higher harmonics of an Nd:YAG laser (1064 nm, 532 nm, 355 nm, and 266 nm). In one notable benchtop experiment, the laser was used to measure velocity fields of an underexpanded Mach 1.5 jet at a rate of 50 kHz. For the conditions tested, the jet has a characteristic acoustic instability present within the flow, and this instability (known as screech) occurs at a rate of 17 kHz. By using the pulse-burst laser and a state-of-the-art Photron SA-Z ultra-high-speed camera, Dr. Kreth’s group was able to measure the 17 kHz screech instability within the velocity fields as they were acquired at 50 kHz. Some typical results from these experiments are summarized in Figure 1. High-speed schlieren imaging was also used to measure this flow instability using a framerate of 100,000 fps. Results of these experiments were recently published in the AIAA Journal.

Figure 1: Results from 50 kHz particle image velocimetry (PIV) experiments conducted in the Flow Diagnostics Lab at UTSI with the burst-mode laser system. Left: time-averaged streamwise and transverse velocity fields; Right: spectral content extracted from the velocity fields’ time-series data.
Advanced Materials for Radiographic Imaging

Dr. Lee Leonard

Research Assistant Professor
Mechanical, Aerospace and Biomedical Engineering (MABE)
Ph.D., University of Tennessee

Dr. Lee Leonard’s research interests include glasses and glass ceramics, thin films, composite materials, ion batteries, and imaging techniques. He is a member of the American Ceramic Society and has served as a reviewer for the National Science Foundation on multiple occasions. Prior to joining UTSI in early 2009, Dr. Leonard worked for twelve years as a project and tooling engineer in the high-pressure aluminum die casting industry.

Dr. Leonard is developing luminescent glass and glass-ceramic materials for radiographic imaging applications (see Figure 1). The luminescent properties of these materials can be tuned by varying composition and processing conditions. Dr. Leonard’s present focus is on highly efficient x-ray conversion screens for indirect flat panel detectors (I-FPDs). The conversion screens, through a process known as scintillation, convert incident x-ray radiation into visible light, which is detected by the I-FPDs and used to create an x-ray image.

Dr. Leonard, along with fellow CLA researchers, Dr. Jacqueline Johnson and Dr. Lino Costa, is currently investigating the use of lasers to improve the characteristics of glass-based, x-ray conversion screens. This work is in collaboration with researchers at Stony Brook University. University of Tennessee Space Institute graduate research assistant, Ms. Emily Moore, and undergraduate summer research intern, Mr. Troy Schneider, are also participating in this project (see Figure 2). Applications that will benefit include digital radiography, portal imaging, and megavoltage cone-beam computed tomography.

Dr. Leonard is also participating in projects concerning high-temperature carbon-carbon composites, anti-fogging diamond-like carbon coatings, thin-film ceramics for LED and radiography applications, antimicrobial surfaces, and solid-state batteries. These projects are in collaboration with Dr. Jaqueline Johnson.

Figure 1: Photographs of an unpolished glass scintillator sample in (a) in visible light and (b) in 365 nm UV light.

Figure 2: (a) Ms. Emily Moore, a graduate research assistant, prepares to pour a molten glass sample. (b) Mr. Troy Schneider, an undergraduate summer research intern, measures the density of a glass sample by Archimedes’ Method.
Nonequilibrium Fluid Physics

Dr. Trevor Moeller

Jack D. Whitfield Professor

UTSI Program Coordinator and Graduate Programs Director for the Department of Mechanical, Aerospace, and Biomedical Engineering

Ph.D., University of Tennessee

Dr. Trevor Moeller’s research focuses primarily on high temperature gases and plasmas and high-speed flows, including both modeling and experimentation. NASA is highly interested in LCH4/LOX rockets for exploration of Mars. Recently, Dr. Moeller continues to conduct research on liquid methane (LCH4) liquid oxygen (LOX) rocket engines and propellants. Dr. Moeller is currently conducting research on tunable laser absorption spectroscopy (TLAS) in the mid-infrared for diagnostics in high-temperature flows for the Air Force. The sensitive nature of this program precludes the presentation of further details. He is also pursuing research in nuclear thermal propulsion and the development of micro-electric propulsion thrusters. Additionally, Dr. Moeller is conducting basic research in high-speed flows and the development of tools for the modeling of coupled electromagnetic/fluid systems in nonequilibrium. Additional details are provided below.

**Microthruster Development:** Dr. Moeller has experience in electric propulsion systems and has continued development of a micro-electrostatic thruster in a collaborative effort with Dr. Lino Costa. This effort utilizes ultrafast laser micromachining to reduce the scale of features by 10-fold over state-of-art thrusters. As a part of this effort, computer simulations have been performed to determine the trends in critical operating parameters with respect to changes in geometric design (Figure 1). This effort also includes examination of a newly proposed device design utilizing pores in a dielectric material. Drs. Moeller and Costa have a subcontract with a small business through a NASA STTR to further develop the microthruster.

**Mid IR Absorption Spectroscopy Basic Research:** UTSI currently uses a single-zone absorption cell to conduct spectral studies for common combustion products in the mid-IR; however, typical absorption cells suffer from non-uniform temperature distributions that lead to instrument calibration with large uncertainties. As a part of Dr. Moeller’s TLAS research, a three-zone absorption cell was designed to achieve a uniform temperature distribution that exceeds 1000°C for the calibration of mid-infrared spectral lines. Development of the three-zone calibration device is underway through US government funding. This cell will allow for greatly improved accuracy in TLAS measurements, enabling improved characterization of high-temperature flows. Simulation results for the proposed three-zone absorption cell are shown in Figure 2.

**Nonequilibrium Plasma Simulations:** Dr. Moeller’s group continues to research computational plasma dynamics algorithms and develop in-house plasma dynamics simulation codes. Work with our recently developed SUPG finite element solver for the two-fluid plasma model has continued. We have continued to refine our strategy for application of SUPG finite element solver for the two-fluid plasma model has continued. We have continued to refine our strategy for application of discontinuity capturing terms within the solver as this appears critical to the solution quality and efficiency of the solver. Recent work has involved implementing a simultaneously switched discontinuity capturing term for all three of the systems of equations in the two-fluid plasma model. This improved the solver’s ability to simulate problems like the GEM challenge problem with second order time terms as reported in our recent AIAA conference paper: DOI: 10.2514/6.2021-3120.

Figure 1: Schematic diagram of an alternative electrospray emitter design with high aspect ratio capillaries embedded in a transparent dielectric.

Figure 2: A plot of GEM challenge problem simulation.
Professor Parigger’s active research continued in the current reporting period in experimental, theoretical, and computational Physics, with focus in atomic and molecular and optical (AMO) Physics. The work includes fundamental and applied spectroscopy, nonlinear optics, quantum optics, ultrafast phenomena, ultrasensitive diagnostics, lasers, combustion and plasma Physics, nonequilibrium fluid Physics, optical diagnostics, applied optics, biomedical applications. Continued experimental research is associated with plasma diagnosis in combustion, non-equilibrium fluid physics, and study of expansion phenomena that occur at well-above hypersonic and supersonic speeds. High speed imaging is analyzed using laser-spectroscopy techniques, see figure “Shadowgraph” of laser induced plasma in standard ambient temperature and pressure. The figure “Hydrogen gas laser-plasma analysis” illustrates typical results for hydrogen laser-plasma.

Several communications of ongoing research were published in well-respected archived journals. Professor Parigger continues to be strongly committed to postgraduate education, continued engagements with UTK campus Physics, including offering postgraduate-research related courses and Ph.D. program core courses, introducing students of Physics and Engineering to research projects of interest to CLA, and as Senator of the Faculty Senate and President of the UTSI Faculty Assembly.

Christian Parigger’s recent research interrogates applications to diverse fields that include plasma diagnostics, combustion diagnostics, molecular plasma spectroscopy, and selected astrophysics spectra analyses. The analyses of diatomic emission spectra reveal molecular excitation temperatures up to 10,000 K following laser-induced optical breakdown. Cyanide (CN), aluminum monoxide (AlO), titanium monoxide (TiO), Swan bands of C₂, and hydroxyl molecule (OH) signatures are frequently recorded in nanosecond laser-induced breakdown spectroscopy. At UTSI, Christopher M. Helstern completed his doctoral studies and graduated with a Ph.D. in Physics in 2020. Also, Dr. Parigger mentors a new Physics student (since 2020) that is a full-time employee at the Arnold Engineering Complex in Tullahoma, TN.
Nanodynamics and High-Efficiency Lab for Propulsion/Power/Energy (NanoHELP)

Dr. Feng-Yuan Zhang

Associate Professor, Mechanical, Aerospace, and Biomedical Engineering Department
Ph.D., Nagoya University

The research interests of Dr. Zhang's NanoHELP group (http://fzhang.utsi.edu/) lie in thermal-fluid sciences, nanotechnology, and advanced spectroscopies and diagnostics. The goal of his NanoHELP group is to take advantage of nanotechnology and associated engineering for developing high-efficiency, low-cost and sustainable energy, power and propulsion devices, such as fuel cells, electrolyzers, batteries, direct combustion engines, and electric thrusters. The research ranges from fundamental understanding to system optimization with a strong interdisciplinary program for the study of micro/nano-scale reaction, heat/mass transport, fluid mechanics, novel materials, electrochemistry, catalytic reaction, corrosion, 3D printing/additive manufacturing, degradation, and MEMS/NEMS.

One of the recent research studies is on high-efficiency hydrogen and oxygen productions and energy storages with PEM electrolyzer cells (PEMECs). Combining advanced manufacturing and novel material/component design fabrication, state-of-the-art characterization, system testing, and theoretical modeling/simulations, the NanoHELP has revealed a structure innovation to significantly reduce the PEMEC cost, weight and volume. Recently, we have developed a new high-efficiency electrode with significantly reduced catalyst loadings for low-temperature PEM water electrolysis, by taking advantage of an in-situ grown platinum nanowire catalyst layer coupled with a unique thin LGDL. Electrochemical characterizations and visualizations reveal that the PtNW electrode exhibits outstanding catalytic activities, electrode durability and favorable bubble dynamics even at high current densities for HER in aqueous acidic electrolyte. To demonstrate its practical application in the PEMEC, thin PtNW GDE with a low catalyst loading of only 0.2 mg cm$^{-2}$ was integrated into the PEMEC for the first time. A low cell voltage of 1.643 V and high cell efficiency of 90.08% at 1000 mA cm$^{-2}$ were achieved, superior to the state-of-the-art PEMEC performance with high Pt loadings. The improved cell performance is mainly ascribed to the combination of desirable structural and electrical properties, large active surface area of the PtNW catalyst layer and greatly reduced ohmic losses from the thin LGDL. More importantly, our one-step room-temperature catalyst layer synthesis on thin LGDLs can greatly reduce the electrode cost comparing to catalyst coating processes (spraying/sputtering) for CCM or other GDE fabrication methods (electroplating/sputtering). This novel electrode architecture and fabrication approach coupled with green chemical synthesis and thin LGDL design opens new pathways to develop high-efficiency electrodes with significantly improved catalyst utilization and reduced cost for next-generation electrochemical energy storage/conversion systems.

Figure 1: Top: Schematic illustrations of one-step green synthesis of Pt nanowires in-situ grown on planar metal support; Middle: advantages of thin PtNW CCLGDL design (~25um) over the conventional GDE (~300um) for the PEMEC; Bottom: SE-STEM and corresponding HAADF-STEM images of PtNW electrode morphology and nanostructure.
Research on Advanced Combustion and Battery Fire Safety

Dr. Peng Zhao

Associate Professor, Mechanical, Aerospace, and Biomedical Engineering Department
Ph.D., Princeton University

Dr. Peng Zhao joined CLA February 1st 2021. His research interests are focused on the development of advanced clean-combustion strategies, reacting flows, alternative fuels, as well as thermal management and thermal runaway for Li-ion batteries.

In a recent paper published in Combustion and Flame, Dr. Zhao and his coworkers revealed the flame initiation and propagation feature in a mixture with elevated thermodynamic conditions, which is highly representative of the actual engine, gas turbine and supersonic combustors. Their results have shown that due to the non-zero reaction progress in the unburnt mixture, flame initiation, propagation and combustion mode evolution can be fundamentally different. Low reaction progress leads to weakly autoignition assisted combustion and large reaction progress can induce flame substantially driven by autoignition, separated by a transition regime where fast change in flame speed is observed. The results have demonstrated new combustion physics and a substantial knowledge gap with research conducted under laboratory conditions, as shown in Fig. 1.

Other major research thrusts include battery cycling under extreme C rate and temperature conditions, evaluation of battery thermochemical models, development of reduced order models and fast charging strategies, battery thermal runaway initiation and propagation, etc. These are the challenging but key problems at the frontier of decarbonization of future ground transportation. Dr. Zhao’s group has investigated the threshold limit of battery thermal runaway triggered by a hot spot and analyzed the evolution of the electromagnetic field during a typical internal short circuit event. A very important result is shown in Fig. 2, where the threshold limit of thermal runaway is identified as a pair of threshold heat source intensity and duration time.

More recently, Dr. Zhao and coworkers have developed an elegant theory on battery thermal runaway propagation within a single cell, and between different cells in a battery pack. It is shown that the curvature of the reaction front during thermal runaway can substantially affect the propagation speed, and that the abuse condition of nail penetration is potentially more dangerous compared to the local hot spot ignition, due to the weaker curvature effect. As Dr. Zhao is establishing the Laboratory of Advanced Mobility and Power (LAMP) in the CLA building, the state-of-the-art battery cycler, electrical impedance spectrum are both installed for battery testing under a wide range of extreme conditions. Meanwhile, an Accelerating Rate Calorimetry (ARC) as shown in Fig. 3 is being established to measure the battery abusing condition from nail penetration, internal short circuit and local heating.

Zhao’s research is in the frontier of reacting flow, fuel, engine and battery safety, and has been sponsored by US Department of Energy, Los Alamos National Lab, Oak Ridge National Lab, Ford Motor Company and BASF. Prof. Zhao has published 1 book chapter and nearly 50 journal articles in leading combustion and energy journals, including Combustion and Flame, International Journal of Engine Research, Proceedings of the Combustion Institute, etc. He is a Bernard Lewis Fellow of the International Combustion Institute, session Chair of the International Combustion Symposium, organizer of SAE world congress PFL 120 and PFL 180 sessions on advanced propulsion and powertrain, member of the Early Career and Diversity Development Committee of the US Combustion Institute.

Figure 1: Effect of reaction progress on flame speed and combustion mode.

Figure 2: Threshold condition of Li-ion battery thermal runaway.

Figure 3: The accelerating rate calorimetry (ARC) and the testing chamber.
Publications:


Publications


Conference Presentations:


B. Canfield, A. Terekhov and L. Costa, “Responses of Transparent Dielectrics to Gaussian-Focus and Bessel-Beam Laser Machining with Single, Ultrashort Pulses,” in Frontiers in Optics/Laser Science (FiOLS); FTu2C.5; OSA; (2020).


B. Canfield, A. Terekhov and L. Costa, “Responses of Transparent Dielectrics to Gaussian-focus and Bessel-Beam Laser Machining with Single, Ultrashort Pulses,” *Frontiers in Optics/Laser Science* (FiOLS); Washington, D. C., United States; 14-17 September (2020).


**Conference Organizing:**


**Book Chapters:**


**Appointments:**


P. Zhao

- Reviewer for Office of Advanced Scientific Computing Research (ASCR) within the Department of Energy Office of Science, 2021
- Reviewer for Office of Vehicle Technology within the Department of Energy, 2021
- Associate Editor, Frontiers in Mechanical Engineering
- Advisory and Scientific Committee of THIESEL 2022 for Clean Propulsion Powerplants, Universitat Politècnica de València.
- Guest Editor of Special issue “Reactive Flows,” *Fluids*, 2021
- Session organizer of SAE World Congress PFL120 session “Multi-Dimensional Engine Modeling,” 2021
- Session organizer of SAE World Congress PFL180 session “Advanced Propulsion/Powertrain,” 2021
INVENTIONS DISCLOSURES, PROVISIONAL PATENT APPLICATIONS AND PATENT APPLICATIONS


J. Jones, A. Terekhov, B. Canfield, T. Moeller, L. Costa; *Micro Scalable Thrusters for Adaptive Mission Profiles in Space – μSTAMPS*; Disclosure and Assignment to University of Tennessee Research Foundation, UTRF Number: 21047-07, Date of Final Approval: 10/05/2020; Provisional patent application #: 63/127,768, Filed: 12/18/2020.

J. Jones, A. Terekhov, B. Canfield, T. Moeller, L. Costa; *Micro Scalable Thrusters for Adaptive Mission Profiles in Space – μSTAMPS*; Disclosure and Assignment to University of Tennessee Research Foundation, UTRF Number: 21047-07, Date of Final Approval: 10/05/2020; Provisional patent application #: 63/127,768, Filed: 12/18/2020.
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<td>Non-Contact Technologies, LLC</td>
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<td>AFRL RQHX Corner Flow Experimental Support (R024432020)</td>
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<td>Coupled Simulation Tool for Modeling Structural Profile Disruption of Aerovehicles (R011373780)</td>
<td>CFD Research Corporation</td>
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<td>Preliminary Aerodynamic Characterization of Emerging Hypersonic System Configurations (R024432026)</td>
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<td>Light Emitting Diode System for Tunnel A Schlieren System (R024432027)</td>
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<td>Moeller, Trevor</td>
<td>Demonstration of Dual Mode Ionic Liquid Propulsion</td>
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<td>ACE Booster 2 (R024348071)</td>
<td>Gloyer-Taylor Laboratories LLC</td>
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<td>Development of Three Zone Absorption Cell for Spectral Measurement Verification (R024348073)</td>
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<td>Cryo-Tube Testing Support (R024348075)</td>
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<td>Aerostructural Analysis Supporting the Development of Reusable Hypersonic Vehicle Structures (R024427031)</td>
<td>UDRI - University of Dayton Research Institute</td>
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<td>Electrolyzer Integrated Modular (R024421027)</td>
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<td>Integrated Membrane Anode Assembly and Scale-up (R02-TBT)</td>
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