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1 Introduction

The John F. and Joan M. Calder Professor in Mechanical Engineering has been a blessing to the growth of my research and to student development. During the last year, funds were used for minor equipment, travel, undergraduate and graduate student support, and for a new initiative with the Titan S-TEM microscope. This report summarizes the people, activities, accomplishments, and a few frustrations of the Microfluidic and Interfacial Transport (MnIT) Lab for the last academic year. The MnIT Lab, which is really the people and not the physical space, was established with a specific goal and philosophy.

**Goal:** Conduct research that generates new knowledge and advances technologies for energy and exploration while preparing students to transform society.

**Philosophy:** Exploration; new ideas directed towards engineering applications; high risk research at the boundaries of engineering and science

**Focus:** Experimental and theoretical fluid and thermal physics, with capillarity as an important effect; spanning fundamental discovery to technology development.

2 The Numbers

Numbers are important in academia as a measure of productivity even though these are an incomplete picture of teaching, scholarship, and service. Nevertheless, during the last year there have been:

- 6 journal publications
- 4 conference proceedings
- 4 professional poster presentations
- 1 PhD students successfully finishing
- 3 dissertation committees; 2 MS, 1 PhD from Canada
- 5 proposals; 1 funded, 2 pending

$\approx 80$ citations

- 14 h-index (cumulative)
- 22 i10-index (cumulative)
3 People

During the past year, the MnIT group included 3 PhD students, 1 undergraduate student, 1 post-doc, and 1 research professor.

Ezequiel Médici, Assistant Research Professor *Percolation in Porous Media*

Ezequiel is now an Assistant Research Professor at Michigan Tech, which is a soft-money position. He currently leads the modeling efforts on two projects sponsored by NASA and DOE. In addition, he manages the Michigan Tech Atmospheric Shock Facility located in Hancock. During the academic year he has been teaching graduate courses in fuel cells and continuum mechanics. Ezequiel is also serving as a mentor/advisor for Karrar Alofari and Shahriar Alam. He applied for one of our faculty positions last year and was the leading candidate from the ETF area.

Kishan Bellur, Post-doc *Phase Change and Cryogenic Fluids*

Kishan Bellur finished his PhD last summer and is supported as a post-doc on the new NASA funded project that is using data from a space station experiment (from RPI) to answer some fundamental thermodynamic questions regarding evaporation and condensation. In reality, Kishan is the Principal Investigator on this project even though I am listed as such. During the Spring semester Kishan taught MEEM 3210 Introductory Fluid Mechanics and Heat Transfer as a Distinguished Teaching Faculty Fellow. Currently, he is finalizing journal manuscripts on the cryogenic hydrogen and methane studies. Two manuscripts will be submitted within the next week or two.

In September, Kishan will move to the University of Michigan and will work with Prof. Bill Schultz in Mechanical Engineering. He will still be employed by Michigan Tech to work on the NASA phase-change project. The purpose of moving Kishan downstate is for him to be immersed in a culture and research environment unique from Michigan Tech.

Karrar Alofari, Ph.D. *Percolation Fuel Cell Electrodes, Multiphase Flow in Porous Media*

Karrar Alofari was originally a student of Prof. Reza Yassar, who left Michigan Tech. Karrar approached me to see if I would serve as his advisor. Karrar is a unique student in that the US government funds a program in Iraq to send promising students to the United States for study. He is working on extending our percolation tests to fuel cell electrodes, which are only 5 to 10 nanometers thick. He has also worked with Ezequiel to adapt a 100-year old model of liquid displacement in porous media for application to fuel cells. Karrar has, with Udit Sharma, been studying energy storage using phase-change materials. My intent is for both of them to learn this topic on their own and then build a network model for predicting storage capacity and rate of energy transfer in a wide range of materials. Karrar is scheduled to finish by next May.
Udit Sharma, Ph.D.  *Energy Storage with Phase Change Materials*

Udit Sharma began his PhD program in August 2017. He has passed his qualifying exam last fall and is working towards his PhD proposal defense this coming academic year. He has worked on a variety of projects, but none of these were suitable for a PhD dissertation. He is interested in heat transfer and porous media. A promising dissertation topic is with thermal energy storage using phase change materials. He and Karrar are studying this topic with the goal to build a network model for predicting storage capacity and rate of energy transfer in a wide range of materials. Udit will be the Lead TA for MEEM 2911 - ME Practice 2 this coming academic year. He plans to get married in November.

Wonyoung Choi, CWRU

This is the third summer that Wonyoung has worked in the MnIT Lab. She is the daughter of Prof. C.K. Choi in our department and is pursuing her BS in mechanical engineering at Case Western Reserve University. This summer she is working on thermal modeling in ANSYS/Fluent with Kishan.

Shahriar Alam, Ph.D.

Shahriar was in the MS coursework only program and was recruited into the PhD program by Ezequiel in January. He is currently running a parametric study on the catalyst layer model in support of the 3M/DOE project. This work may expand into a dissertation.
4 Activities

This section highlights the major research, teaching, and service activities for the last year.

Water Management in Fuel Cell Catalyst Layers (3M/DOE)

This project is funded by the Department of Energy with 3M as the lead. We, along with Tufts University, are subcontractors to 3M. Funding for Michigan Tech is $650k for three years. We are a year and half into a three year project and making good progress.

Our goal is to predict the behavior of water in thin catalyst layers with a range of polymer chemistries. The research at Michigan Tech includes modeling, characterization experiments, and small fuel cell testing. The principal investigators are myself, Prof. Kazuya Tajiri, and Dr. Medici. Catalyst layers are the electrodes of a fuel cell (or battery). These electrodes are extremely thin, less than 10 nanometers thick, and are porous to allow oxygen or hydrogen to diffuse through. Electrode flooding from the water produced by the reaction leads to rapid degradation. Hence the interest by the Department of Energy.

We are extending our network model of the porous transport layers (PTL) in fuel cells to the catalyst layers. PTL’s sit between the gas flow channels and the catalyst layer. The graphic below illustrates the modeling approach. Three separate, but connected networks are used for the catalyst layer. The “solid-phase” network is for electrical and thermal transport. The “pore-phase” network is for oxygen and water transport. And the third network is the “ionomer phase” for proton and water transport. It is the ionomer phase network that is the new addition and where the most interest lies. The multi-network model has been primarily developed and coded by Ezequiel. The multi-network model is only of the cathode catalyst layer. To simulate the entire fuel cell, our multi-network model has integrated into a fuel cell model developed in commercial software by Tufts University (now by UC Davis). Significant progress has been made. This project ends in December. The results and the model architecture opens the door to future research opportunities.
**Water Extraction from Gypsum Deposits on Mars (NASA)**

We are in the second year of a three year grant to investigate hydraulic mining of gypsum deposits on Mars for the purpose of recovering water. The project was the idea of Prof. Paul van Susante, though for bureaucratic reasons I am the PI. Other principal investigators include Prof. Tim Eiseli in Chemical Engineering and Dr. Medici. Honeybee Robotics in Pasadena is a subcontractor.

We have made substantial progress in both hardware and modeling. We have acquired gypsum samples from quarries in Michigan and Iowa. A senior design team was sponsored to develop a calcining unit to extract water from disaggregated gypsum. Their unit was awarded first place in the Michigan Tech Undergraduate Symposium. Michael Foetisch is working on this project as part of his PhD in Physics with his primary advisor, Tim Eisele, in Chemical Engineering. Ezequiel, Paul, and I are on his committee. There is a lot of interest from NASA in this project and Paul has been invited to speak at more than a half-dozen events in both the US and Europe.

<table>
<thead>
<tr>
<th>Low mass, low power, non-mechanical excavation of gypsum and other evaporites for water production on Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PI:</strong> Jeffrey Allen, Michigan Technological University (MTU)</td>
</tr>
<tr>
<td><strong>Co-Investigators:</strong></td>
</tr>
<tr>
<td>Timothy Eisele (MTU)</td>
</tr>
<tr>
<td>Paul van Susante (MTU)</td>
</tr>
<tr>
<td>Ezequiel Medici (MTU)</td>
</tr>
<tr>
<td>Kris Zacny, Honeybee Robotics (HBR)</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Research Objectives</th>
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<tr>
<td>The objective is to demonstrate an innovative process for extraction of water from hard extraterrestrial soils. The process involves ‘dissaggregating’ material with a water jet to form slurry, and pumping the slurry into water extraction system. This innovation eliminates the hardest problem in mining: comminution, which involves heavy equipment, significant energies, forces, and tooling impractical for sustained extraterrestrial ISRU. Research is focused on TRL 1-2 processes for excavation of minerals and extraction of water at 0.8 kg/hr. At the conclusion of the project the innovative technology will be at TRL 3-4.</td>
</tr>
</tbody>
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<tr>
<th>Approach</th>
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<tbody>
<tr>
<td><strong>Concept:</strong> create slurry in-situ and transfer to water extraction cycle</td>
</tr>
<tr>
<td><strong>Research:</strong></td>
</tr>
<tr>
<td>• dissolution, disaggregation, separation and precipitation requirements in relevant environment</td>
</tr>
<tr>
<td>• environment constraints – sealing and heat/water losses in mineral deposits and relevant environment</td>
</tr>
<tr>
<td>• System integration – size, power required to achieve 0.8 kg/hr water production</td>
</tr>
<tr>
<td>• Brassboard feasibility testing</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Potential Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>• reduction in power requirements as compared to mechanical excavation</td>
</tr>
<tr>
<td>• improved reliability as compared to mechanical excavation</td>
</tr>
<tr>
<td>• Simple, scalable extraction process</td>
</tr>
<tr>
<td>• capability to handle a wide range of mineral deposits and contaminants; extract water from multiple locations</td>
</tr>
<tr>
<td>• reduced need for resupply – no tooling or replacement components required</td>
</tr>
<tr>
<td>• absence of dust dispersion/generation during excavation</td>
</tr>
</tbody>
</table>
Fundamental Study of Evaporation & Condensation

Last October, Kishan Bellur and I submitted a proposal to NASA to study fundamental thermodynamics of evaporation and condensation. The proposal was for accessing the Physical Sciences Informatics (PSI) database. Of particular interest is the data collected by the Constrained Vapor Bubble (CVB) experiment conducted on the International Space Station. Profs. Wayner and Plawsky from Rensselaer Polytechnic Institute (RPI) were the principle investigators for this experiment. The graphic illustrates the experiment setup, which is a closed quartz cuvette containing only n-pentane. Heat is applied at one end and extracted at the other end. That heat is transferred from end-to-end by evaporation and condensation. Kishan’s proposal is to use the CVB data and his modeling work from his dissertation to more closely study kinetic phenomena of phase change.

Kishan’s proposal was well-written with a great idea to use the CVB data for a new purpose. He leveraged his dissertation research on evaporation of liquid hydrogen for the proposed work. In May 2018 we were informed that NASA had selected Kishan’s proposal for funding at $200k for two years, which is primarily to support Kishan as a post-doc. We did not receive any funding until December 2018. Since then, Kishan has been sorting through the database and developing image processing tools to extract information from the space station videos.

Kishan’s outstanding efforts in this field has resulted in wide recognition to him, myself and to Michigan Tech as evident by the invitation to serve on a review panel for the Department of Energy’s “Advanced Research Projects Agency - Energy (ARPA-E)”, which is the DOE version of DARPA and the invitation to speak at the Gordon Research Conference on Micro and Nanoscale Phase Change Heat Transfer February in Italy.

Associate Chair, Director of Undergraduate Studies

Last fall I began to serve as the Associate Chair, Director of Undergraduate Studies for the Department. I anticipated that this position would impact some of my research activities, notably publishing and proposal, since I also would have a full teaching load. Part of my responsibility is chairing the Curriculum Committee. In addition to the regular curriculum housekeeping duties, I charged the committee with assessment of MEEM core courses with respect to the new ABET Student Outcomes. ABET is our accrediting agency and last year began a change student outcome requirements for undergraduate engineering degree programs. Originally there were 10 outcomes, now there are 7. This task was challenging due to the vagueness of the new outcomes. In order to assess our courses, we also had to develop a consistent interpretation of these new Student Outcomes. I am proud of the committee members’ effort and anticipate that the interpretation document will serve other departments in the college. This coming year, technical electives will be evaluated against the new Student Outcomes and the committee will begin reviewing curriculum assessment tools. One of my responsibilities as Associate Chair is to review enterprise student’s project briefs. Students who wish to participate in Enterprise instead of Senior Capstone Design must petition me for approval to waive capstone design. They provide short project description that is supposed to outline the design aspects of their project as well as a timeline. The current template provided to the students generates confusion and a general perception that this approval
process is merely bureaucratic process with no real value. My goal is to emphasize the technical communications nature of the petition by providing a new template and instructions. While this effort is directed only towards MEEM students, the director of the Enterprise program supports the initiative.

Chair, Undergraduate Workstream Committee

At last year’s department retreat, Bill Predebon challenged the faculty and staff to begin incorporating elements of digital mechanical engineering (as part of the “Fourth Industrial Revolution”) into the curriculum. I became chair of the Undergraduate Workstream committee. A core group of faculty spent last year studying “digital engineering”, surveying industry and other degree programs, and identifying key skills and knowledge that are necessary for undergraduate mechanical engineering students. That work will continue at this year’s retreat and I anticipate during the coming academic year the committee will focus on strategies for implementation.

MEEM 2911 - ME Practice 2

A significant effort and time commitment was devoted to finalizing the development of MEEM2911 for which I serve as course coordinator. This is the second practice-based course in the undergraduate curriculum. It integrates elements of statics, dynamics, thermodynamics, manufacturing, fluid mechanics, controls, and technical communication during two engineering design challenges. Students are required to apply engineering science to practical systems during which they learn instrumentation and sensors, data analysis and technical communication. There is heavy emphasis on building competency in Matlab. During the last year, I have worked with other faculty and graduate students to identify and implement improvements to hardware, software, assignments, instructional materials, and weekly GTA instructions. The course now has a complete set of technical articles (book) for student instruction.

MEEM 3201 - Introduction to Fluid Mechanics & Heat Transfer

MEEM 3201 is a required 4-credit course covering topics in fluid mechanics and heat transfer related to internal flow. I was responsible for developing the course three years ago and am currently the course coordinator. In the Spring semester, Kishan taught this course as a Distinguished Doctoral Teaching Fellow.

MEEM 5211 - Advanced Thermodynamics

During the fall semester I taught a new graduate course on Advanced Thermodynamics (MEEM 5211), which had not been taught previously. I developed the course from scratch. It included elements of classical, statistical, and non-equilibrium thermodynamics. The course will be taught alternating years and is now a 6000-level course and a new 5000-level Intermediate Thermodynamics course is being developed.

MEEM 4230 - Compressible Flow

This course has been traditionally taught by Prof. Tajiri who was on sabbatical last year. I agreed to teach the course in the Spring semester knowing that it was a one-off; I likely would not get to teach it again (and before I agreed to become the Associate Chair). There were 40 students in the
class, the largest enrollment ever. It was a fun course to teach in spite of the development work required.

**University Service**

During the last year I served as a mentor for junior MEEM faculty (Bigham, Masoud). I was also the MEEM representative for the College of Engineering Promotion and Tenure Committee, which reviews and makes recommendations regarding promotion from Assistant-to-Associate and Associate-to-Full Professor.

**Professional Service**

One of the advantages of holding the Calder Chair is the recognition by the external community. This recognition has opened doors earlier than would have occurred otherwise, and the open doors are more hospitable. One such example is the opportunity to serve as a reviewer for the Advanced Research Projects Agency – Energy (ARPA-E). Another example is the request to serve as an external committee member for PhD Defenses. This year I served in this capacity for Ali Malekin, Mechanical Engineering, Simon Frasier University, British Columbia.

## 5 Planned Initiatives

**Education**

1. When developing MEEM2911 - ME Practice 2, I had thought that it would take five years to finish the course development. We are entering the sixth year and the course is in relatively good shape. This August I am updating the technical articles and developing a new module for the first week. The new module will require students to calibrate a load cell, then use the load cell and calibration during weeks 2 through 5. I will continue to serve as course coordinator for the upcoming academic year and I will update and revise the individual and group exercises. Another major activity will be to replace the existing cranes with a new system that will likely include a combination of hydraulic and pneumatic actuators, keeping the same learning objectives. My goal is that by next year the course is ready to turn over to a new coordinator.

2. During the next year I will charge the Curriculum Committee to review, and revise if needed, our current curriculum assessment tools in light of the changes to ABET evaluation criteria.

3. The department retreat at the end of August will include more discussion regarding integration of digital engineering into the undergraduate curriculum. I will be working with the Undergraduate Workstream Committee to develop strategies for implementing what comes out of the retreat discussions.

4. The combined fluid mechanics and heat transfer course (MEEM 3201) was developed as an “internal flow” course focused on pipe and duct flows with and without heat transfer. The intent was to integrate fluid mechanics and heat transfer. In practice we use two separate textbooks in the class and most faculty treat this as 7 weeks of fluid dynamics and 7 weeks of heat transfer, which defeats the original intent. I plan to work with Prof. Choi to prepare a new textbook on internal flow specifically for this course. I anticipate that this will be a three-year effort.
Research

1. I will continue pursuing collaborative opportunities in fuel cell and electrolyzer research. Currently, there is interest from several US and German companies for possible research. There is also strong potential to leverage ongoing collaborations with Canadian universities, NIST and PSI in Switzerland. We have significant momentum in this technology field so it is a priority to sustain that momentum. I plan to involve in this effort Dr. Médici, Prof. Tajiri, Prof. Jon Pharaoh from Queen’s University (Ontario), and potentially Peter Berg from the University of British Columbia.

2. Work will continue on the NASA funded project to extract water from gypsum via hydraulic mining. Dr. Médici and Profs. van Susante and Eisele are leading the technical efforts. We are working with NASA to plan a workshop with other researchers in this field, likely in the November timeframe.

3. Work will continue on the new NASA PSI grant with Kishan. His relocation to the University of Michigan will help to build a collaborative effort on phase change with Prof. Bill Schultz. One potential, interesting area of collaboration is on evaporation from the Great Lakes, which could leverage our new wave tank.

4. Research on fundamental thermodynamics of phase change has been supported by NSF and NASA. In June I submitted a NASA proposal with Profs. Choi and Ponta as well as professors from Purdue and Case Western Reserve University that would be a radical departure from traditional computational modeling of cryogenic phase change. We also have a proposal pending with NSF examining fundamental physics a evaporating liquid layers. This latter proposal is with Prof. Jim Hermanson of the University of Washington and Dr. Aneet Narendranath (MEEM).

5. Prof. Bigham and I have been awarded an ARPA-E proposal to study high-temperature (2000 °F), high pressure (80 bar, 1200 psi) ceramic heat exchangers fabricated using additive manufacturing (3D printing). The proposed budget was $4M, but is currently being negotiated around the $2.2M. The contract should be in place by the start of the fall semester.

6. Modeling and characterization of heat and mass transport in thin porous layers is now an area of technical expertise and international recognition. This was the result of work on automotive fuel cells for the last ten years. This year I plan to pursue opportunities in other technologies that leverage the fuel cell work. One such potential is the paper and pulp industry and in particular paper drying.

7. Transport, transfer, and management of liquid hydrogen has recently seen an increase in interest by funding agencies. DOE has identified liquid hydrogen, transported in trucks, as the most cost effective means for supplying fueling stations. These stations would be used for fuel cell fleet vehicles, heavy trucking, passenger vehicles. NASA is also interested in this topic, though for other technologies. We have a unique opportunity to bridge these research fields.

8. I plan to hire two post-docs this next year. We are looking to hire one post-doc with Prof. Choi to pursue opportunities in advanced manufacturing that integrate near-field optics, phase change, and catalyst layers as described below. This is an effort to establish a new research direction described in initiative 9. We interviewed a promising candidate in February, but
did not extend an offer. A second post-doc will be hired to support the ARPA-E project with Prof. Bigham.

9. Automotive fuel cells have made great advances during the last ten years and are now primed for mass manufacturing. Scaling up manufacturing from a couple of thousand vehicles per year to hundreds of thousands is an incredible challenge. New manufacturing approaches are needed. Quality control and assurance is an untapped area requiring advances. The smallest pinhole in a membrane can result in an entire automotive fuel cell stack being rejected. New inspection diagnostics (optical and acoustic) are needed for roll-to-roll manufacturing. Machine learning coupled to advanced manufacturing is an opportunity for which Michigan Tech is uniquely qualified.

**Professional Service**

1. I have started to work with the new NSF director of the Thermal Transport Processes program, Prof. Ying Sun, to coordinate fundamental heat transfer research interests between NSF, NASA, and DOE. I am not sure how this initiative will develop.

2. I will be participating in a NASA workshop in October to help define future NASA research opportunities in microgravity fluid physics.

**Other**

1. Per Bill’s request I plan to apply for Fellow status in ASME and Associate Fellow status in AIAA this year. These honors will bring additional recognition to the department and the university.
6 Expenditures & Budget for Next Year

2018-2019 Expenditures

The plan this year was to provide interim support for graduate students and post-docs during lapses in research funding.

<table>
<thead>
<tr>
<th>Category</th>
<th>FY18-19</th>
<th>FY19-20</th>
<th>FY20-21</th>
<th>FY21-22</th>
<th>FY22-23</th>
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<tbody>
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<td>Start of Year New Funds</td>
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<td>20.0</td>
<td>30.0</td>
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<td>Postdoc</td>
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<td>Research Engineer</td>
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<td>Student Development &amp; Travel</td>
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<td>Equipment</td>
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<td>Fostering International Collaboration</td>
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<td>New Initiative Development</td>
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<td>Year-End Balance</td>
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<td>18.6</td>
<td>20.2</td>
<td>-23.0</td>
</tr>
</tbody>
</table>

Post-Doc Support

A portion of the funds were used to support Kishan as a Post-doc while we waited for the new NASA PSI grant to be finalized. These funds were repaid from the NASA grant. In February, I used a portion of the funds to support Kishan’s travel to the Gordon Research Conference (GRC) in Italy and to present at the associated Gordan Research Seminar (GRS). The GRS is for students and post-docs to present their research and occurs the weekend before the GRC.

Student Development & Student Travel

A portion of the funds were used to support undergraduate student salary, $713 as of July 1, for Wonyoung Choi. Her work is primarily supporting Kishan’s modeling effort on the NASA PSI grant. She is also helping researchers in other departments with contact angle measurements.

Equipment: Optics

Optical components (optical rails and slides) were purchased to revamp the contact angle measurement apparatus in the MnIT Lab.

Graduate Student Support

Udit Sharma was partially supported using Calder funds in the Fall 2018 semester. His was also supported on overhead return (cost share) associated with the NASA Gypsum grant. In the spring semester he was supported as a GTA in MEEM 2911 - ME Practice 2.
Travel

I used a portion of the funds, $3.2k, to support my travel to two conferences where I was an invited speaker. The first was the Gordon Research Conference on Phase Change Heat Transfer in Italy. The second was the ASME Summer Heat Transfer Conference held in Seattle last month (funds for registration and airfare were allocated in May).

New Initiative Development

A portion of funds, $1.1k, was used to explore the capability of the new Titan S-TEM (state-of-the-art electron microscope) to image catalyst layers at sub-nanometer resolution. The results are promising and I plan to follow up this work in the fall.

Tax

In order to offset a budget shortfall resulting from institutional initiatives, Michigan Tech has imposed a “Designated Fund Administration Fee” (tax), which resulted in $369 being transferred out of the account.

2019-2020 Budget

My plan for the coming year is to use a portion of the funds to support Kishan’s visit to the University of Michigan. The NASA PSI grant is not sufficient to fully support his Post-doc salary and there are some service fees associated with his access to UM computing facilities and office space. The 3M/DOE grant will end in December and the NASA Gypsum grant will undergo a continuation review that traditionally holds up funding for several months. I plan to use funds to bridge any support gaps for graduate students. I am also planning to use a portion of the funds for equipment purchases to support research initiative 9 once a post-doc has been hired.

7 Thank You!

I have been able to sustain my research activities in addition to the service commitment to the new curriculum and as Associate Chair. This is due in large part to the generous funding you have provided. I can keep students supported and maintain professional presence through funding gaps and cycles. Because of this I am in a position to transition my research program to larger, collaborative projects that will bring an increased awareness of Michigan Tech by the national and international community. Your generous support has been essential.

In addition to funding stability, your sponsorship and my association with your good name has opened up doors for international collaborative opportunities. We (myself, my students, the department and Michigan Tech) are gaining a worldwide reputation for excellence.

I cannot thank you enough for your generous support.