ISBOE HERC-IGEM
Cellulosic 3D Printing of Modular Building Assemblies

MID YEAR REPORT
FISCAL PERIOD – JULY 1, 2021 - JUNE 30, 2022

SUMMARY OF PROGRESS
December 30, 2021

Prepared for:
HERC-IGEM – Idaho State Board of Education
Dr. TJ Bliss

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Dr. Damon Woods - Investigator

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Acronyms and Abbreviations

3D printing	Three-dimensional printing
AM	Additive manufacturing`
IDL	Integrated Design Lab
UI	University of Idaho

1. Introduction

The project objective is to identify the methodology, process, and materials necessary to three-dimensional cold print (3D print) building assemblies utilizing, to some maximum extent, wood products. Moving a significant portion of construction into a factory setting where labor and work is organized and executed more efficiently will have the following benefits: 1) increase the quality and energy efficiency of buildings; 2) lower overall construction costs; 3) provide appropriate compensation for a more skilled labor force and, 4) assist in mitigating the current construction skilled labor shortage challenge in Idaho.

Tasks for Year 3:

1) Identify private industry investors and solicit financial commitment from industry partners
2) Build a small-scale printer and print a two foot by two-foot by eight-inch wall section
3) Program a computer model for running printer.
4) Perform heat transfer and structural tests on a wall section.

Summary for Mid-Year 3:

Significant discovery was made on each of the four tasks identified as Year 3 deliverables. We have had significant interest from industry (wood products companies, resin company, and 3D printing companies). We have been unsuccessful in obtaining a provisional patent on the formulation and process.

Dr. McDonald has taken over as the project's PI due to Ken Baker retirement from UI.

We have secured a $3.97 million NSF grant "Developing a Circular Biobased Framework for Architecture, Engineering and Construction Through Additive Manufacturing" based on our work from this IGEM project.

U of I Mechanical Engineering (ME) has designed and built a first prototype printer and now modifying it to improve functionality for printing layers.

We have built a guarded hot plate for thermal testing of composites panel sections and the study is completed.

This has been an excellent discovery process for faculty and students. ME students Tais Mitchell and Conal Thie have competed their Master's theses on extruding the composites and thermal properties of printed composites. Environmental Science doctoral student, Berlinda Orji is documenting the flow and curing process of the resin-wood mix as part of her dissertation. ME master's student Robert Carne is documenting and modifying the 3D printer for improved functionality during the printing process. ME Ph.D student Anas Nawafleh is analyzing the flow behavior of the extruded composite material.

2. Summary of Project Accomplishments for the reporting period just completed

Research and identify the printing mix of wood/natural fibers, binders and adhesives.

Prepared by: Armando McDonald, Ph.D.

Mid-third year Report

Year 3, reporting Dr. McDonald staffing: 1 Ph.D. student in Environmental Science. 1 woman. Salary expenditures and student tuition in the McDonald lab have focused on supporting the research efforts of one Ph.D. student. Capital and operational expenses are in line with ongoing and projected research activities on wood-resin curing research. Appropriated funds will be expended by the end of year 3.

The third year research focused on the fabrication of large panels, the use of CO_2 for curing and optimization of CO_2 curing conditions. Wet wood (40 and 200 mesh) adhesive blends were pressed in 3" molds and cured in a pressure vessel containing 99% pure CO_2 for 24 hours and post cured in the oven at 60°C. Pressed sample discs of 400 mesh (Figure 1a) were cured in the presence of CO_2 between 30 mins to 24 h. Cross sections of the cured samples were analyzed to determine CO_2 penetration with time (Figure 1b). Bending properties of the cured samples were determined.

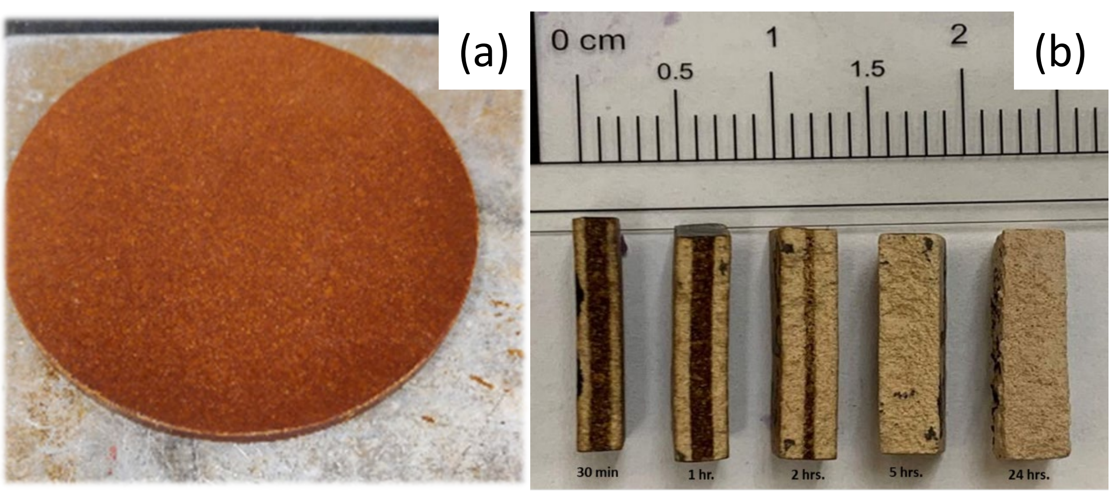


Figure 1: (a) Pressed 3-inch sample discs and (b) cross-sections of CO_2 cured samples at different times

Fabrication of large wood fiber-resin panels (5" x 5" and 10" x 10") were prepared (Figure 2) for thermal and usability testing at IDL and BSU laboratories. Future studies will focus on curing larger composite panels, modifying adhesive formulation for improved processability (extrusion) and overall property testing for CO_2 cured composites.

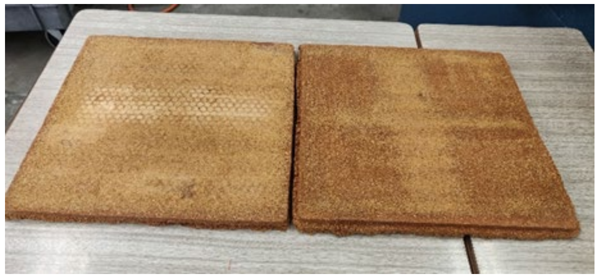


Figure 2: cured 10” x10” panels

Build a prototype printer.

Mid-Year Update Report, IGEM, Dec 2021 – University of Idaho Mechanical Engineering

Prepared by: Michael R. Maughan, Ph.D., PE and Tao Xing, Ph.D., PE

The UI Mechanical Engineering (ME) team has the responsibility of developing a 3D printing process and printer for depositing a wood waste composite mixture developed by researchers in the UI College of Natural Resources (CNR). The goal is to make bespoke small-scale composite structural building panels. UI ME is also responsible for thermal modeling and optimization of the 3D printed composite building panels.

In the first half of the 3rd year of the project the ME team has continued to make progress on the development and implementation of the 3D printer system. We developed a second nozzle and implemented changes to the hose system by using threaded fittings, which necessitated redesigning the nozzle and extruder die (Figure 3).

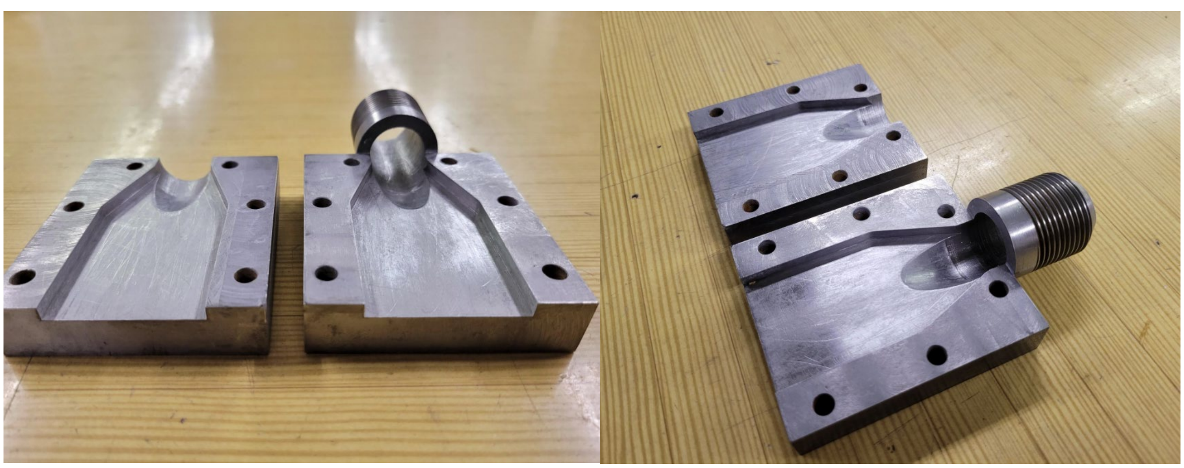


Figure 3: Printer nozzle with features for threaded hose connections.

Using the modified system, we demonstrated the first successful extrusion in connection with the 3D printer bed, which is shown in Figure 4. This process identified a problem in the system that needed to be addressed – heat generated by extruding the mix and causing to prematurely cure the resin. The solution was to design a counterflow heat exchanger around the extruder barrel (Figure 5). The cooling effect was confirmed with the infrared camera and proved very effective.

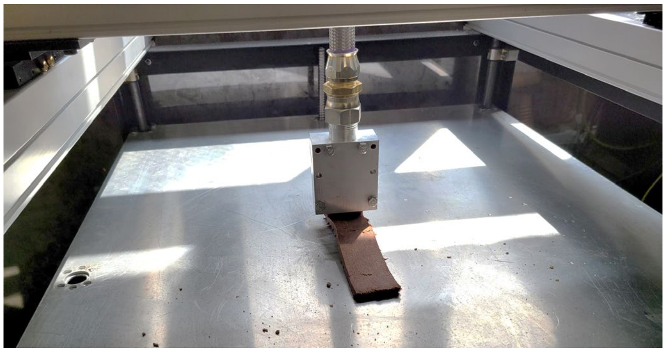


Figure 4: First successful "print" to the 3D printer bed.

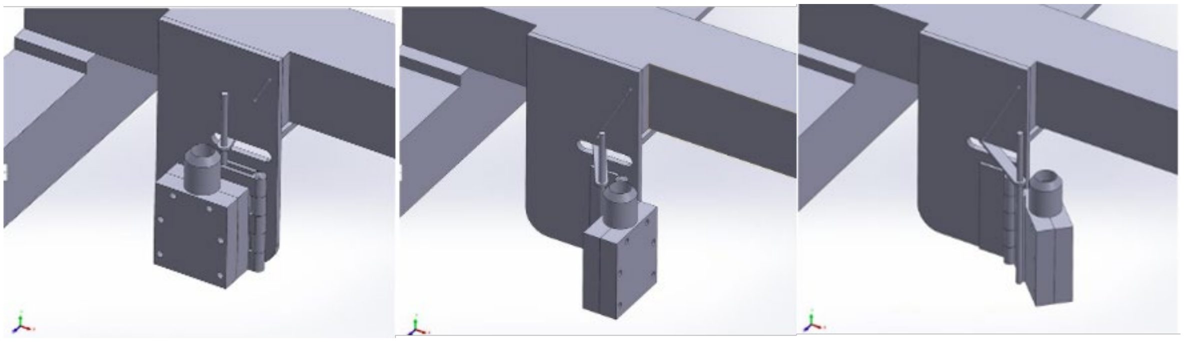


Figure 5: Design for rotating print head.

Extrusion simulation

The team has employed a computational fluid dynamics (CFD) model on the ANSYS Multiphysics platform to simulate the extrusion process, which reveals pressure, velocity, and temperature distribution during the printing process. The information is critical to optimize the mixing process and reduce the heat generated through parametric studies, including the die design, the screw extruder design, and the screw rotational speed. The first simulation was conducted for the capillary extrusion process shown in Figure 6a. Solution verification on three systematically refined meshes achieved monotonic convergence, which indicated the results are independent of mesh resolution. Then solution on the finest mesh was validated using experimental data by comparing the load data at the plunger, as shown in Figure 6b. The second simulation for the single screw extrusion process is in progress to study the pressure and velocity distribution, as shown in Figure 6c. This information will help to understand the effectiveness of the single screw extruder on mixing the wood and resin. Future work involves using the discrete element method (DEM) to model the wood fibers during the extrusion process.

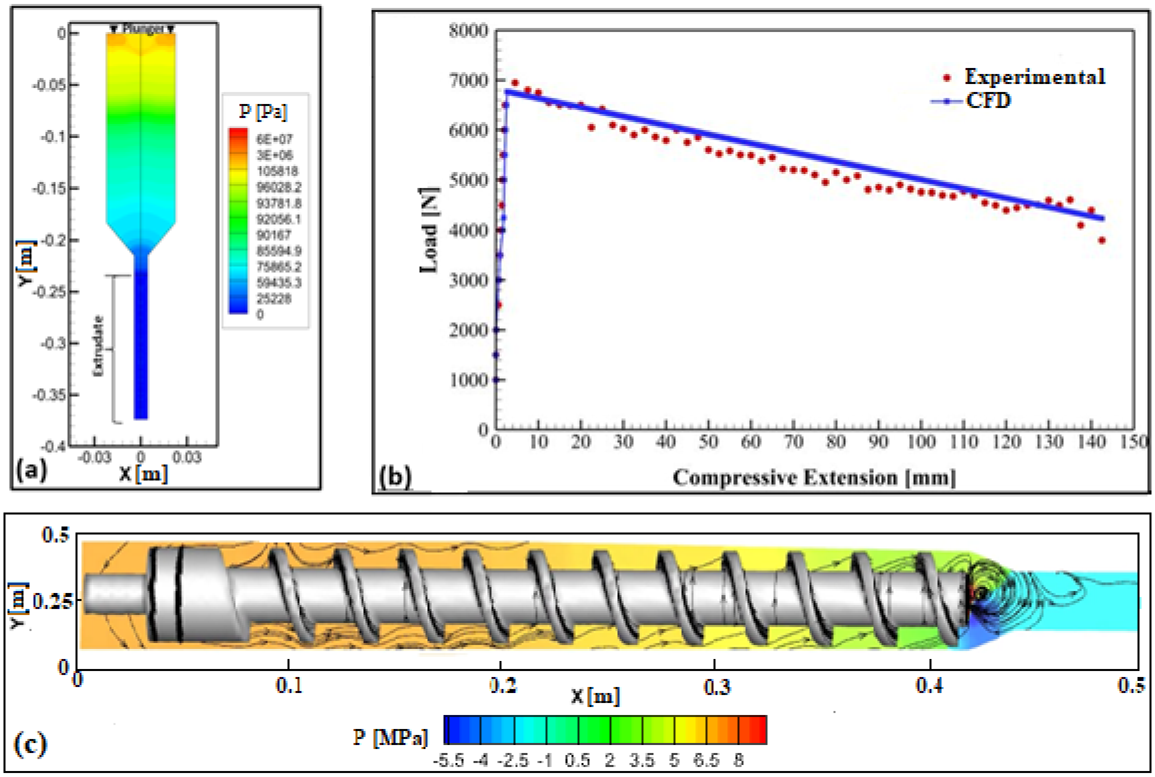


Figure 6: CFD simulations: (a) Contour of pressure for the capillary extrusion, (b) Comparison between CFD and experiment, and (c) contour of pressure with streamlines for screw extrusion.

One UI ME graduate student completed his master's thesis and has graduated. He is now employed at the Micron Company in Boise, Idaho. The project remains staffed by two other graduate students. Robert Carne is pursuing an M.S. degree and is planning to graduate in May 2022 and Anas Nawafleh is pursuing a Ph.D. and will graduate in 2023.

External funding - Project participant, Dr. Maughan, is PI on funding to continue this project provided by the NSF. The $3.97 million grant will engage researchers at the University of Idaho and at Auburn University to continue the project developing cost-effect bio-based housing solutions.

Develop guarded hot plate for thermal testing

Prepared by: Damon Woods, Ph.D, P.E., Ralph Budwig, Ph.D, P.E.

Staff: William (Bob) Basham

Graduate Students: Tais Mitchell

The University of Idaho's Integrated Design Lab team continued work on characterizing the thermal properties of the 3D-printed wood composite. The team finished the development process for the guarded hot plate apparatus that was designed according to ASTM standard C177. The team made several improvements to the apparatus including a refined power measurement system, an improved plate-sample contact design, and automating the apparatus to run thermal experiments unsupervised. The verification process found that the apparatus achieved an accuracy of around 8%, which is a slightly higher uncertainty compared to other commercially available instruments, but this device was built for a tenth of the cost.

After completing the apparatus (Figure 7a), the team tested the wood composites for thermal conductivity. The purpose of these tests was to verify the preliminary thermal testing results completed in year 2. The results from the tests gave very consistent results between the two testing methods that were within 2% (Figure 7b).

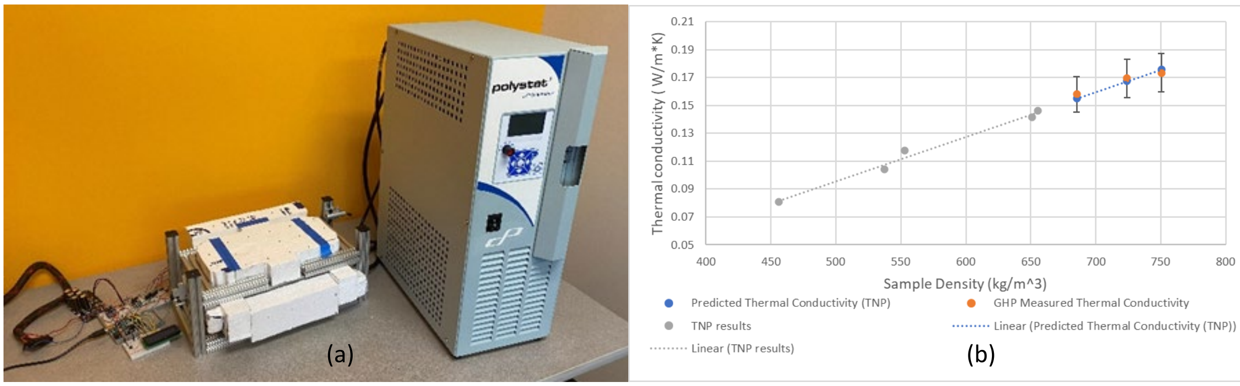


Figure 7: (a) Guarded hot plate apparatus for thermal conductivity measurements and (b) comparison of the guarded hot plate and transient needle probe results

These results are encouraging because it shows that the transient needle probe method can reliably estimate the thermal conductivity in the wood samples. This is a benefit for the overall project because the thermal experiments can be done relatively quickly and can be performed on larger and more complex shapes fabricated using the prototype 3D-printer. Thermal testing using the transient needle probe will continue with testing variations in the binding resin, particle size, binder content, and additional additives for the wood composite.

Tais Mitchell successfully graduated with a M.S. in ME with a thesis titled "Thermal Characterization of Printable Wood Composite and Life Cycle Assessment of a Novel Wood-Based 3D-Printed Exterior Wall".

Constructability Analysis

R. Casey Cline, Boise State University, Department of Construction Management
Kirsten A. Davis, Boise State University, Department of Construction Management
J. Ty Morrison, Boise State University, Department of Construction Management

The Boise State University Construction Management (BSU CM) research team has been working on publications related to the constructability analysis for the project. We have been delayed in our ability to work on the project in more depth due to a five-month delay in the BSU subcontract.

Progress in Publications:

We have submitted abstracts to two conferences thus far; both have been accepted.

- 2022 American Society for Engineering Education (ASEE) Zone IV Conference
- 2022 American Society for Engineering Education (ASEE) Annual Conference and Expo

One will be developed further as a poster presentation and the other will be developed into a paper and presentation. Both focus on a framework for teaching constructability analysis for new construction product design to students.

We also are in progress on an additional abstract/poster for a third conference.

- 58th Annual Associated Schools of Construction International Conference

This work will focus on construction management coordination issues during the development of new construction products.

Future Plans:

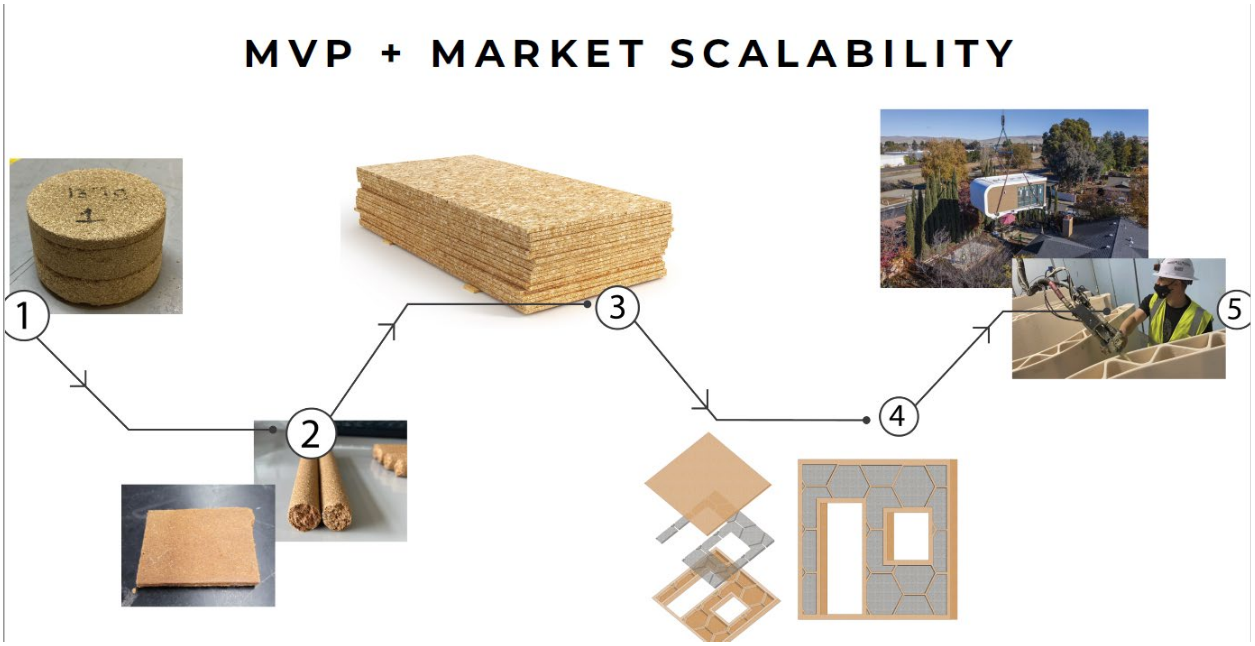
We will begin experimenting with small sections of the 3D printed substrate that were recently received to help ensure that the panels will meet our constructability priorities. Samples of 3D printed material will also allow us to determine how panels can be connected together to create a wall or other part of a structure, as well as whether those connections actually work. Aspects such as durability of the panels and suitability for finishes will also be explored over the next several months.

3. Summary of Budget Expenditures

Salaries:	$ 59,236.73
Temp Help	$ 7,824.70
Fringe	$ 11,090.65
Travel	$ 1,515.30
Operating	$ 9,564.34
BSU Sub	$ 00
Tuition	$ 28,789.00
TOTAL	**$118,020.72**

4. Demonstration of economic development/impact

- Patents, copyrights
  - We have not been successful in obtaining a provisional patent for the cold-setting process.
- Technology licenses signed
  - None at this time
- Private sector engagement
  - PI Armando McDonald and Investigator Michael Maughan have had conversations and instigated NDAs with Boise Cascade and Massivit 3D Printing on additive manufacturing of wood composites regarding the path to commercialization.
- Jobs created
  - None outside the universities at this time.
- External funding
  - We were awarded an NSF Track 2 grant (Michael Maughan PI) titled "Developing a Circular Biobased Framework for Architecture, Engineering and Construction Through Additive Manufacturing" for $3.97 million. Under this proposal we will expand our current research to use bio-based resins for our panel prints and explore the architectural resiliency expressions of materials in design applications.
- Other pertinent information
  - We are working on printing a panel. We have made a hardboard panel and we believe this will be competitive with current products. The goal under this grant is to get to image #4 below. We are currently working on #3.



5. Numbers of Faculty and Student Participation

There are nine faculty participating in the grant, six from the U of I and three with BSU. There were five Research Associates working on the grant in year three.

6. Description of Future Plans for Project Continuation or Expansion

Four key outcomes were expected in year 3 of the three-year grant:

1. The print mix for cold setting print will be identified. Completed.
2. The printer specifications and printer will be further defined as a product that could scale up for manufacturing large-scale panels. Completed
3. Business/industry partners will be engaged, and private investment will be solicited. We are currently in discussions with Boise Cascade and Massivit 3D Printing.
4. The thermal characteristics of printed panels will be assessed. Completed.

7. Commercialization Revenue

None to date.