EML 4905 Senior Design Project

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BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

In Situ Manufacturing of LTCC Based Optimized Heat Exchanger

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This B.S. thesis is written in partial fulfillment of the requirements in EML 4905. The contents represent the opinion of the authors and not the Department of Mechanical and Materials Engineering.

Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Michael Abbott, Sasha Philius, and Yonatan Rotenberg and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

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Abstract

A literature review was conducted on the different technologies needed to manufacture a monolithic, hermetically sealed micro-channel heat exchanger. Preliminary designs for the heat exchanger were created in SolidWorks to be optimized at a later date. Lunar and Martian regolith simulant was ball milled until an average particle size of 3 microns was obtained. A polyvinyl alcohol (PVA) solution of varying concentrations, was added as a binder to the refined powder and pellet pressed under 200 bars of pressure. A sintering study of the pellets was conducted for four different temperatures: 850°C, 950°C, 1050°C, and 1150°C. The crystallography of the pellets will be examined using a scanning electron microscope (SEM) and X-ray diffraction (XRD).

1. Introduction

New technologies need to be developed to support long range off-earth missions. One such crucial technology is a high efficiency heat exchanger. NASA funds the research into technologies that it deems worthy for two reasons: the first being that new technologies will be developed and the second reason is to progress the technology from being manufactured on earth to being manufactured in space. This would mean that Commercial-Off-The-Shelf (COTS) devices would be shipped off-earth in the short term whereas devices that are needed for the long term mission would be manufactured on site. This technological advancement would allow for Regolith, materials indigenous to the site, to be used in the fabrication of the device. The overarching goal for Lunar and Mars manufacturing is In Situ Resources Utilization (ISRU).

The heat exchanger that will be produced will address both of NASA's research goals. Two technologies will be developed in parallel from the same design, one on a timeline that is one step behind the other. The heat exchanger will be designed to conduct heat through vias, cylindrical passages filled with silver, which are connected to fins. These fins will be contained within a microchannel, through which a coolant will flow. The first goal will be to create a proof of concept combining technologies that are already mature. The stability, integrity, and the maximum allowable size of the microchannels must be determined before a design is optimized. The heat exchanger structure will be built using low temperature co-fired ceramic (LTCC) tape, DuPont 955 LTCC tape, as well as a fugitive material to fill the microchannels. There will also be an integrated temperature sensor inside the microchannel. We then need to test the scalability of the preliminary design.

Simultaneously, Lunar and Martian Regolith will be characterized. Once this is complete a process will be designed to turn the Regolith into an ink that can be used to make a tape and ink that can be fired according to NASA's specifications for in situ manufacturing. The fired Regolith must be a hermetic structure. This will show feasibility of a manufacturing transition path to Lunar/Mars based construction. From here on out the Regolith based heat exchanger will follow the last completed stage LTCC based heat exchange.

Once the proof of concept LTCC based heat exchanger is built, then the development of a 3D printed test structure will be started. The optimized design from the LTCC tape based heat exchanger will be optimized again since the restrictions for direct print additive manufacturing are different from tape based design.

There is further development for this project that will be completed after the conclusion of the senior design project. This project has the capacity to expand the implementation of heat exchangers by creating an industry for 3D printed or tape based LTCC heat exchangers.

1.1 Problem Statement

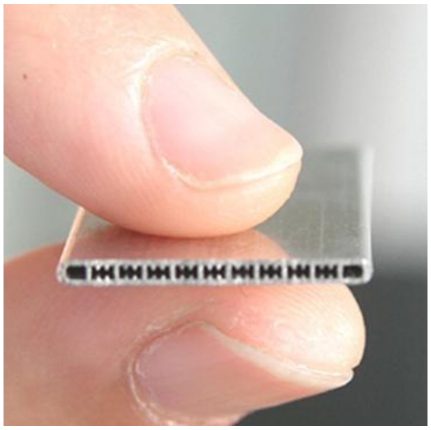

Figure 1 - Micro/Mini Channel Heat Exchanger

Demonstrate the ability to print micro channels for heat exchanger modules using 3D Printed Circuit Structures (PCS) from a digital file in high temperature ceramic materials with the long term goal to transition to regolith based materials.

1.2 Motivation

Figure 2 - Concept for 3D Printed Lunar Base

NASA requires methods for developing new technologies in support of remote, long range missions. A large portion of NASA space systems, satellites, and UAVs are composed of wiring and the related hardware, resulting in bulky structures. This project aims to provide a means to improve the functionality of these technologies while reducing the volume and weight through the use of 3D PCS. Mechanical structures and electronic modules will be manufactured in a monolithic fashion, merging structural and electronic functionality in a volumetrically efficient package.

In the short term, these technologies are manufactured on Earth to be transported to sites on the moon, satellites, or nearby space stations. For locations on Mars or farther, these modules would ideally be manufactured on site. The natural resources in these locations, primarily the indigenous soil known as regolith, will be utilized to produce these technologies. The long term goal is to produce a method for ISRU for both Lunar and Martian manufacturing.

1.3 Literature Survey

Due to the fact that the project is multifaceted, the design necessitated multiple aspects of independent literature search and review. With that, there are roughly three different topics that required investigation and understanding through the search of text. The first of these is the subject of materials engineering and more specifically with ceramics and ceramic substrate systems. The next area of investigation deal with transport phenomenon or more simply, fluid mechanics. Finally, the culmination of the two topics are utilized and the subject of heat transfer is applied. It is the combination of these three fields of engineering that will produce understanding and ultimately a finished product for this design project.

The first of these topics is as mentioned the subject of materials science and engineering. In this field of engineering, the expertise and knowledge found in text can further facilitate understanding of substrate technology. Within these technologies understanding sintering, mechanical properties, interaction with other materials and methods for producing substrates is investigated [8] and [11]. The concepts of ink and sheet fabrication are also expanded upon and understood as to use them both to produce laminated and fired structures for the finished product [3].

The next field investigated is that of fluid mechanics and its association with fluid behavior within channels of the heat exchanger. The design will incorporate moving liquids past a metallic object. Each of these aspects of the channel add to the flow characteristics of the medium and there effect are important to recognize. Understanding geometrical considerations plays a large role in the behavior of the fluid [17]. Geometry coupled with dimensions plays an even larger role and has a direct impact on the profile, its laminar or turbulent nature which is based on Reynolds number as well as the channels associated pressure drops [10].

Finally, incorporating the two prior disciplines, the field of heat transfer is investigated. The first aspect of this is associated with the materials science in that the medium used for the ceramic must act as an insulator to efficiently transfer heat in an expected way. Next, the heat must be conducted through metallic medium which will be embedded into the design. Finally, this heat is extracted from the system via convection from the surface of fins within the heat exchanger and to the liquid medium flowing through it [17].

A complete literature survey will address these issues as well as shed light on additional, possibly more important ones. Through the use of experience gained from the discipline of engineering as a whole, a final device of quality concept and design can be built.

2. Project Formulation

2.1 Overview

As actual regolith is difficult to obtain, the project will be using a simulant for both lunar and Martian regolith [18]. The simulants are made of natural components found on Earth with only a slight variance between it and the actual material. Once obtained, the regolith had to be refined to achieve the appropriate particle size needed for sintering studies [2]. In order to ensure an easy to duplicate process, ball milling was used to reduce the particle sizes. Using alumina balls, several batches of refined regolith powder were made from solutions of raw regolith simulant and distilled water. Once the water had evaporated, the refined powder was ready for pellet pressing.

Following the process indicated in [4], 2011, several batches of regolith and an organic binder, polyvinyl alcohol (PVA), were created. Different concentrations of PVA were used, ranging from 1% to 5% solutions. A hydraulic, hand-operated pellet press was used to produce ½ in. pellets under varying loads. A sintering study was conducted by firing the different pellet configurations at four different temperatures: 850°C, 950°C , 1050°C, and 1150°C. The final step in characterizing the regolith will be to use a scanning electron microscope (SEM) and X-Ray diffraction (XRD) to evaluate the crystallography of the different samples.

Running parallel to the material characterization of the regolith will be the design optimization of the micro heat exchanger. DuPont's 951 LTCC tape will be used as a baseline and several different configurations of the heat exchanger will be created using CAD software. A hybrid optimizer, consisting of gradient and evolutionary based algorithms, will be used to generate the optimum design for manufacturing. The heat exchanger must be optimized for the final step will be to produce a regolith-based ink for additive manufacturing. This ink, as well as a silver paste and fugitive materials, will be used to create the micro-heat exchanger.

2.2 Project Objectives

There are two primary objectives to be achieved: (1) manufacturing a monolithically 3D printed micro heat exchanger and (2) show feasibility of ISRU for lunar and Martian manufacturing. Meeting these two objectives will support NASA's desire to build structures and devices independent of location while reducing the amount of resources normally needed.

In an effort to produce a purely 3D printed structure, design optimization will be integral for developing the micro-heat exchanger. The complex microchannel structures needed will be based Murray's law [9]. The fins will be composed entirely of silver due to the naturally high thermal conductivity of the metal. Fugitive materials capable of decomposing in oxygen will completely burn out in vacuum conditions and will allow porous structures to be easily fabricated. Additionally, a micro-dispensing system will be utilized to improve the additive manufacturing process. nScrypt micro-dispensing technology allows better control over the start and stop of material flow while enabling high speed printing [12].

Ultimately, a process must be created that demonstrates the feasibility of regolith-based 3D additive manufacturing. Ideally, a hermetic regolith structure will be produced to further demonstrate applicability for structures capable of supporting gas/fluidic processes. The final product will also display the potential for manufacturing structures of any size, independent of form or function.

2.3 Design Specifications

The heat exchanger will use one of three materials. The choice of material will depend on the manufacturing location. They are DuPont 951, lunar regolith, and Martian regolith. This design specification is mainly created to keep the cost as low as possible. Along the same lines, maximum performance is desired. There are two performance factors that need to be taken into account, the amount of heat transfer and the power required to pump the working fluid. The design that will be chosen will maximize the amount of heat transfer while simultaneously minimizing the pressure drop across the micro channel and the power required to pump the working fluid.

2.4 Constraints and Other Considerations

2.4.1 Materials and Cost Considerations

The process of creating the heat exchanger must be designed to be streamlined and as energy efficient as possible. Therefore, one of the main design objectives of this project is to create an in SITU manufacturing process. This is due to the immense cost of shipping anything off earth. As a result, readily available materials such as local soil will be used for as large a percentage of the mass of the heat exchanger as possible. Additionally, since energy is scarce in such sites, the actual manufacturing process must be as energy efficient as possible. As much of the materials processing as possible will be accomplished by outfitting devices that are already available. With this in mind, milling of the lunar soil will be powered by bicycles outfitted with a gearing system to ensure the proper rotational speed. The previously mentioned consideration applies to a lunar manufacturing process. The power requirements here on earth are different, so the method of manufacturing the heat exchanger will be different. The main goal is to have a defined process that can be implemented anywhere, with some variation depending on the local constraints.

2.4.2 Performance Considerations

Heat pipes used in consumer electronics are capable of removing a heat flux of 150 $\frac{W}{cm^2}$ [5]. Since this project is a proof of concept, a minimum goal of $\frac{2}{3}$ of the heat flux capacity of a heat pipe will be imposed. Therefore, we will impose a minimum constraint of 100 $\frac{W}{cm^2}$ for the heat exchanger. Additionally, a maximum pressure drop of 50 Pascal will be imposed for a 5 mm by 15 mm space. This is to assure the structural integrity of the heat exchanger.

3. Design Alternatives

3.1 Overview of Materials Conceptual Designs Developed

Due to the nature of this project, it is essential to understand that there are two parallel process's occurring. The first is that a ceramic characterization and manufacturing must be established. The next is that a heat exchanger must be designed, developed, and tested. Ultimately these goals are intertwined, but it is still important to acknowledge there fundamental differences in nature in regards to design and engineering.

With that, we will begin to investigate the designs available for ceramic characterization and manufacturing. LTCC, or low temperature co-fired ceramics is a technology that is already very established. One of the more common tapes used is what is known as DuPont 951 green tape; which is an LTCC material. They have been proven to be capable of producing packages made by combining ceramics, glasses, and metals. These materials have had a considerable amount of success specifically in the electronics industry, but we wish to extend this use into the mechanical field. They can also be said to be cost effective, have a range of environmental performance, highly reliable, and be produced rather quickly [8]. The next vehicle to be used for manufacturing of the device will be lunar and Martian soil simulant. These simulants have been produced by a NASA funded company, Orbitec and have properties very similar to Moon and Martian dust. These materials are essentially ceramic and glass mixtures, which ultimately makes them great candidates for LTCC application [18], but first sheets of these materials must be made in order to properly develop them.

3.1.1 Materials Design Alternatives 1, 2, and 3

As mentioned previously, this project will investigate a wide range of materials for applicability to the overall goal of developing a micro device using LTCC (ceramic/glass) substrate systems. With that, the materials to be used for LTCC development are the DuPont 951 series of green tape, a tape formulated in house based on the Lunar Regolith, and finally another tape formulated in house based on the Martial Simulant.

The first of these materials has already been developed and is well established. It is also the product of a company's hard work its exact formulation is kept proprietary to preserve the companies rights over the product. With that, the tape is a great baseline for understanding how to make the heat exchanger and ultimately a guide as to how the development of our in house tapes progresses. The next material(s) that will be explored is/are the Lunar and Martian based Simulants. These materials are an obvious choice once the components of the nonhomogeneous mixtures are examined. Both materials have very similar compositions and ultimately, they share a tremendous amount of material compositions with that of traditional and developed LTCC. Both materials have high proportions of the ceramics: alumina, silica, and a smaller portion of titania as well the important compositions of the glass's which are what ultimately reduce the firing temperature of the medium.

For the lunar simulant, although the purpose is to develop a tape we initially already know that making a monolithic structure is a possibility as it has been investigated priori. From [2] it has been shown that simulants can be sintered and hermetically sealed at lower temperatures than the melting temperature of the individual constituents; this is an important component of developing a tape. These tests were done with simply pressing the powder and showed promising results. Tests conducted within house have also shown that sintering is greatly aided by the addition of a binder, which will ultimately be used to produce a tape.

3.2 Overview of Exchanger Conceptual Designs Developed

The next subject of investigation will be that of the heat exchanger design using LTCC. It has already thoroughly been proven that LTCC is a great candidate for fluid networks in Micro-devices. This has been shown in many cases [15] and in [9], but the exact design of said device is still to be determined. The evolution of the designs have started originally with just simple micro channels being built out of LTCC for micro reactors, etc [9]. Later the addition of heat transfer mechanisms were added in the form of pins [1]. It is now an expectation for this to progress and a new technology to be established as the main driver in the overall heat transfer. This would be the main application and purpose behind introducing fined devices for heat exchange. Further, all applications will use a similar set up of a surface plate where the electronic (heat generating device) is located, which then connect to through hole vias of conducting material and finally connect to a structure for the convective heat transfer process to occur.

3.2.1 Design Alternative 1, 2, and 3

The first design introduced is that produced by Hari Adluru using pinned structures for the convection heat transfer mechanism [1]. This design was a starting point in regards to the established nature of vias or pin type structures with traditional LTCC applications, however it was determined to not be a truly suitable candidate due to its relatively small surface area and ability to transfer heat. This design evolved and is now being investigated with the use of fins as opposed to pins. This is an important evolution because fins can act as channel walls and more importantly provide a significantly larger surface area for the heat convection process to take place.

Within the concept of using fins, there are many directions one can take. A tremendous amount of work has been produced on micro channel heat exchanger with straight tubing, however, as of late the introduction into winding and ultimately denser (in terms of surface area to overall size) designs have come into play [13]. The latter of the finned devices seems to be the more appropriate path to follow, however technology must prove itself in that making such geometrically complex structures can be a reality.

3.3 Feasibility Assessment

There are essentially two main issues that are to be considered when determining the feasibility of this manufacturing process coupled with the production of the device. The first is whether or not the simulant will make a good materials for the substrate. It has already been hinted at that there is a very good chance the simulant and ultimately the actual lunar soil will be a good match due to their constituent components being so similar to established LTCC materials. The other issue comes from current technologies ability to produce finned structures. This is a new area of research and involves evacuated materials that burn out in the process of firing. The questions relating to this will be answered by June of 2014 as an initial test device has been constructed and will be tested.

3.4 Proposed Design

The initial proposed design is a simple 7 channel straight tube exchanger with conducting fins that run the length of the channels. The conduction and convection portions of the device will be approximately 12.32mm long, 5mm wide, with channels that are .5x.5mm. It is expected to evacuate 5-10W/cm^2 and is simply a benchmark. The outside ceramic frame will be 20.32mm long and 6mm wide. This is the initial proposed design, but as the technology develops and other configurations feasibility are proven the design will inevitably change. This device will be made with LTCC DuPont 951 tape first and proven. Once this is established the manufacturing process will turn itself over to the Lunar and Martian simulant tapes and proven using both substrates.

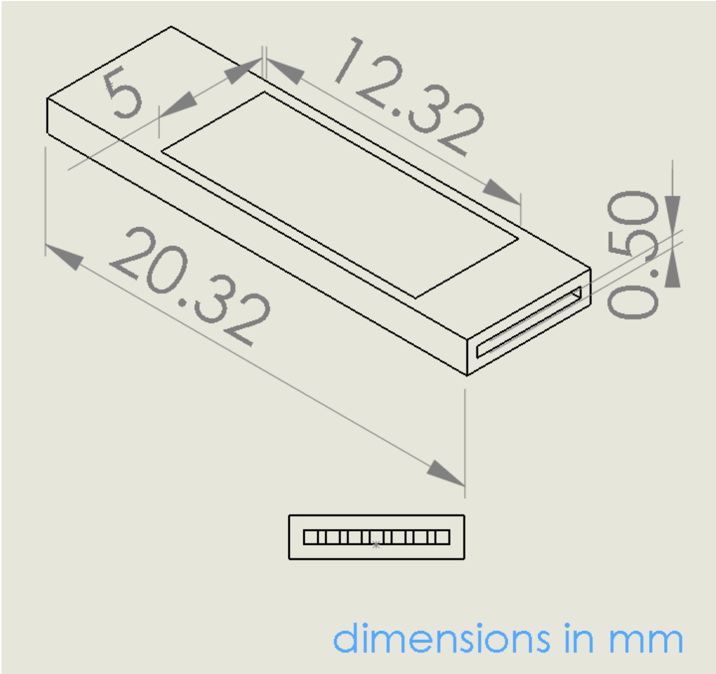

Figure 3 - Initial Design of Heat Exchanger

3.5 Discussion

It is important to note some very key aspects of this design. The first is the expected evolution of this device. To start off with straight tubed configurations is the most appropriate method as the manufacturing methods have yet to be proven. However, once they are and their abilities develop, it is only natural to assume that more complex and denser structures will be proposed, designed, and produced. At last, a winding structure with a very large surface area in relation to the overall package size is to be expected.

Also, a large portion of the project is to produce an optimized device with respect to pressure losses and the amount of pump work to be done as well as maximizing the overall heat transfer of the device. It is incredibly important to mention that within this, there will be an initial population of twenty or so devices for the determining parameter optimization functions. After this is done and the optimization is performed on the device, it is highly likely the device will look and behave completely differently than the one initially designed.

4. Project Management

4.1 Timeline

The following is a graphical breakdown of the tasks and timeline for the project.

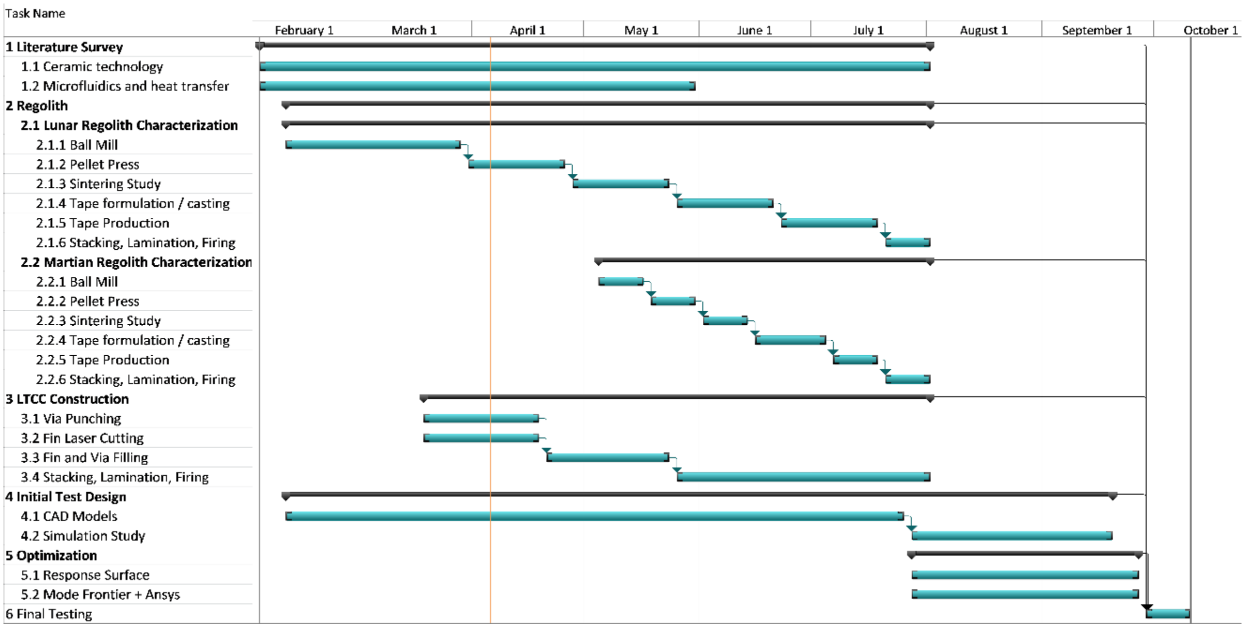

Figure 4: Gantt Chart

The timeline for this project is parallel in nature since it is not a project that has an inception of a single device that can be constructed from start to finish with one specific goal in mind. Due to the parallel nature of this design, there will be three separate timelines that will at times coincide and/or be dependent upon one another. Initially, the first timeline that will be considered is that of the regolith characterization. This timeline after certain goals have been achieved will become one with LTCC fabrication of a finned and channel device. Finally, this LTCC and Regolith ceramic device will be incorporated into the parallel process of an optimized heat exchanger design.

Initially, the development of the Regolith substrate will be of upmost importance to the project. This will start with materials characterization of the regolith through particle size analysis. After completion of this, a sintering study will be performed as to understand that correlation of particle size and the particles ability to sinter with one another at lower and lower temperatures. Once this part of the study has been completed the next step will be to determine the mechanical nature of the sintered product through the use of a three point bend test. The next step in the regolith process is the production of a casting ink to be used in producing sheets of ceramic tape. This is accomplished by determining appropriate inks mixtures with organics, solvents, and other materials. The final aspect of the regolith process is actually producing sheets of tape that are ultimately to be stacked fired and laminated. At this point, the LTCC and regolith processes combine and become one.

Once these processes combine, an initial design of the heat exchanger is produced as a test mule for the creation of the heat exchanger with both substrates. First, via formation is established. Since this is a technology that already exists it will not necessarily be an aspect of design but more an aspect of incorporation. Next, fin formation for the heat exchanger will be investigated. They will be designed with stability in mind due to the fact that skewness and warping occur in the firing process which must be eliminated. Finally, fugitive materials will be investigated for the purpose of designing channels that will appear during the firing process due to organic burn off.

Once these processes have been successfully completed both substrate demonstrators will be tested for hermeticity and troubleshooting will occur if problems are realized.

The other process which will occur in parallel to the steps of regolith and LTCC tape casting production is that of heat exchanger optimization. In order for this to transpire, an initial population of designs based on designs from other institutions as well as intuition are created. From these designs a response surface is created to streamline the process. After this the design variables are determined and with the implementation of multiple algorithms, such as Genetic Algorithm, Differential Evolution, Predator/Prey, etc. the optimized variables, such as channel size, fin spacing, etc. are determined and an optimal design is produced. Finally, this design is built and tested with both substrates resulting in the finalization of the project.

4.2 Breakdown of Work into Specific Tasks

The entire project can easily be broken down into a few tasks that apply to the entire project or repeat themselves for each choice of material. A Literature review for the entire project is the first task. It encompasses a ceramic technology literature review, microfluidics literature review, and heat transfer literature review. During the previous task, a parallel task of the creation of computer aided designs and computational fluid dynamics modeling of the heat exchanger designs are created and conducted. This is essential initial information for the project. The next step is the material characterization task that can be broken down into a few subtasks. They are ball milling, pellet pressing, sintering, and tape production. Similarly, the manufacturing process can also be broken down into subtasks. They are via punching, fin laser cutting, stacking, fin and via filling, lamination, and firing. At this point, the design will then be tested. Now that proof of concept has been completed, the optimization process will commence. This process has subtasks. A parametric computer aided design of the heat exchange must be created, an optimization algorithm must be run, and new heat exchangers need to be created.

4.3 Organization of Work

The project is projected to be completed by the middle of October. Many of the tasks overlap each other due to the nature of the project. The first task, literature survey, will span most of the project. The creation of the heat exchangers takes a lot of time due to the nature of the project so it needs to be started as soon as possible. The project requires a heat exchanger to be created from three different materials. The laboratory tasks have been broken down so that each manufacturing technology can be learned from one material base and implemented in the other two material bases. Material characterization is therefore started with lunar regolith. Once the lunar regolith is most of the way through its characterization, Martian regolith characterization is started. The Martian regolith characterization process is expected to run on a much shorter timeframe since the entire team will know how to use all the machinery and how the experiment should run. The same is true for the construction process. It will be started with DuPont's 951 green tape, then moved to lunar regolith, and then Martian regolith. Extra time has been left for delays due to learning how to use the machinery. Simultaneous to the laboratory work, computer models of the heat exchanger will be created. These models will be used for an optimization process that will commence once the first prototypes for each heat exchanger are created. The final task will be to choose a design from the Pareto front of design options, build it, and test it.

4.4 Breakdown of Responsibilities among Team Members

Responsibilities for this project were broken down into the following categories. There was one individual who assumed the role of manager and coordinator of the project who delegated work to the other two members of the group.

Table 1 - Tasks

Tasks	Michael	Sasha	Yonatan
Literature Review	X	X	X
Project Coordination	X		
Computer Aided Design of Heat Exchanger	X		
Thermo Fluid Simulations	X		
Ball Milling of Lunar Regolith	X		
Ball Milling of Martian Regolith	X	X	X
Pellet Pressing of Lunar Regolith	X	X	
Pellet Pressing of Martian Regolith	X	X	X
Sintering Study of Lunar Regolith	X	X	
Sintering Study of Martian Regolith	X	X	X
XRD Analysis of Lunar Regolith	X	X	X
XRD Analysis of Martian Regolith	X	X	X
SEM Analysis of Lunar Regolith	X		
SEM Analysis of Martian Regolith	X		
Initial Build of DuPont 951 Based Heat Exchanger	X	X	X
Initial Build of Lunar Regolith Based Heat Exchanger	X	X	X
Initial Build of Martian Regolith Based Heat Exchanger	X	X	X
Optimization of Heat Exchanger Design	X	X	X
Final Build of DuPont 951 Based Heat Exchanger	X	X	X
Final Build of Lunar Regolith Based Heat Exchanger	X	X	X
Final Build of Martian Regolith Based Heat Exchanger	X	X	X

4.5 Patent/Copyright Application

The technology discovered in this project will be patented when the heat exchanger concept has been successfully proven.

4.6 Commercialization of the Final Product

The end result of this project is not a commercially saleable device. Further research must be completed before it will be commercially viable.

5. Engineering Design and Analysis

5.1 Stress Analysis

A three-point bending test will be conducted to analyze the stress-strain behavior of the regolith-based ceramic once the material characterization is completed. In this test, a simply supported beam made of regolith will be bent until fracture occurs. The stress at this fracture is the maximum stress and is known as the Modulus of Rupture.

5.2 Material Selection

Two primary materials will be used in the construction of the micro-heat exchanger. The majority of the device will be composed of regolith-based ceramic. This will be achieved by creating a regolith-based ink to be used in an additive manufacturing machine. Regolith is an essential component of this project as it will enable in situ manufacturing of devices for future NASA missions. The fins within the heat exchanger will be made entirely of silver paste. Silver has the highest thermal conductivity of any element and is ideal for creating improving the heat transfer properties of this device. The micro channels needed for the heat exchanger will be produced using a fugitive material, namely polyethylene carbonate [8] that will be burned out in the sintering process, leaving open channels for fluids to flow through.

5.3 Deflection Analysis

Deflection analysis will not be conducted as the heat exchanger is only experiencing thermal expansion. The thermal expansion itself will be very small as it occurs mainly in the silver fins within the device.

5.4 Component Design/Selection

To optimize the efficiency of the micro heat exchanger, multipassage micro-channels will be incorporated into the design [14]. This increases the heat transfer power while keeping the pressure drop relatively low. Residence time is also increased due to the large number of right angle turns that lengthen the channel passes.

5.5 Simulation Study

Finite-volume method (FVM) will be used to study the thermal properties of the micro-heat exchanger.

5.6 Cost Analysis

The majority of the costs for this project came from the man hours needed to research, operate machinery, run simulations, and analysis the data. An average of $32/hour was factored into the costs based on the median national wage for junior mechanical engineers [16]. Table 1 depicts the breakdown of costs as accumulated so far.

Table 2 - Cost analysis of project at 25% benchmark

Cost Analysis – 25% Completed		
Task	**Hours**	**Cost ($)**
Lunar Regolith Simulant (1 kg)	–	30.00
Martian Regolith Simulant (1 kg)	–	25.00
DuPont 951 LTCC GreenTape™	–	????
Ball Milling	20	640.00
Pellet Pressing	20	640.00
Sintering Study	5	160.00
SEM Analysis	4	128.00
XRD Analysis	4	128.00
Research/Literature Review	35	1120.00
Project Organization	20	640.00
Initial Build	6	192.00
Modeling (SolidWorks Modeling)	15	480.00
Total	**129**	**$4183.00**

5.7 Discussion

Analysis of the micro-heat exchanger will be composed mainly of simulation studies and stress analysis to evaluate the behavior of the materials under a given load. Thermal properties may play a much more important role than mechanical due to the nature and function of the structure.

6. Prototype Construction

6.1 Description of Prototype

The prototype device is shown in figure 3 of chapter 3. This device is what all the substrates will be plat formed off of for operational ability and will act as a development platform. The initial prototype design will constitute that of a straight pipe finned heat exchanger with a conducting plate to be attached to the heat generating device. It will be made of DuPont 951, Lunar Simulant, and Martian Simulant independently.

6.2 Parts List

Due to the devices relatively simple nature, the parts list is for all intents and purposes an incredibly short one. To make the device in its entirety, only an LTCC substrate and a conducting medium are needed. The LTCC substrates will be made from the DuPont tape, the Lunar Simulant, and Martian Simulant and the conducting materials will be silver. A fugitive material will be incorporated into the design for channel formation and will most likely be graphite paper. Further, for the substrates associated with the Lunar and Martian simulants, it will also be necessary to incorporate a binder which will most likely be Poly Vinyl Alcohol (PVA).

6.3 Construction

Construction will take place in much the same way for all three substrates. For the simulants, construction will begin with materials processing. This starts with ball milling the material to an appropriate size. Once this has occurred, mixing the materials and producing the tape follows. After this has been successfully accomplished all three tapes will have the exact same construction. The individual layers will be determined using CAD software and set up to be punched or laser cut. Once the layers have been cut and punched they will be filled with either the conducting material or the fugitive material that will burn off in the firing process. From this point, the individual layers are stacked and laminated under pressure to start the sintering process. After this step is completed, the final step of construction is to simply fire the stacked and laminated structure in a furnace at approximately 850^o Celsius to promote sintering.

7. Testing and Evaluation

7.1 Initial Design

7.1.1 Computer Aided Design and Computational Fluid Dynamics

Initially a couple of tradeoff designs for the heat exchanger are drawn up. The tradeoff design may be the shape and length of the fins or the height of the microchannel. They are each modeled in a computer aided design program. These designs are then meshed for finite volume analysis and evaluated in a computational fluid dynamics program. The device that exhibits the best results will be chosen as the initial heat exchanger build.

7.2 Design & Description of Experiments

Raw material is generally not suitable for a streamlined manufacturing process. Therefore, a process for the manufacturing of the material for the construction of the heat exchanger is detailed below.

7.2.1 Fineness of Grind

The Regolith samples will go through a ball milling process wherein the average particle size must drop to five mills. There are four parameters that will be analyzed in the lab; the rotational speed of container, the size and amount of the milling media, the amount of time to run the mill, and the type of milling process (dry or wet). U.S. Stoneware's Jar, Ball and Pebble Milling Theory and Practice manual specifies the critical rotational speed and the recommended rotational speed range based on the critical speed. The critical rotational speed is $Nc = \frac{76.6}{\sqrt{D}}[RPM]$ where D is the inside diameter of the mill in feet. They state that the speed should range from 35% to 115% of Nc. Additionally, they state that most mills run at 60% to 65% of Nc for dry milling and 2 to 5 RPM faster for wet milling. Our mill was run at 105 RPM due to these considerations. Wet and dry milling were also run side by side. We found that the dry milling was not successful so wet milling was chosen. It is good to not that distilled water should be used for wet milling. At this point large and small zirconium cylinders were used as the milling media for a side by side wet milling process. Throughout this process at even intervals samples were taken and measured for maximum and minimum particle size. This will produce a time versus particle size graph so that a recommended milling time can be created. The measurement of the particle size was measured using a fineness of grind gauge while the material was wet.

Results for Lunar Regolith

We found that at twenty hours of milling, the average particle size was between three and five micrometers (one to two mills).

7.2.2 Pellet Press and Sintering Study

After the material is ground down to the desires size, a pellet must be created from the material so that a sintering study may be conducted. A hydraulic press will be used to compress a die and containing cylinder to create a pellet of the material. Polyvinyl alcohol (PVA) was added in as a binder so that the material would hold properly. The binder should be mixed into the material using a pestle and mortar. Stearic Acid is used as a lubricant so that the pellet can be removed. The amount of pressure to be used is 1 – 3.5 Tons. Once the pellet is created it will be fired in a furnace. The temperature will be ramped up. The fired pellet will then be analyzed using a scanning electron microscope (SEM) and using x-ray diffraction (XRD). We will rerun the sintering study and find out what temperature to ramp up the furnace to so that we may find at what temperature sintering takes place.

7.2.3 Tape Production

Tape formulation needs to be produced.

7.2.4 Via Punching and Fin Cutting

For Via punching, green tape will be used and placed in the punching machine. The machine will be given a schematic for the location and size of the Vias. It will then punch through the tape in an optimized route. For fin cutting, a sacrificial material tape will be used. The tape will be placed in a laser cutting machine, where the machine has been given the schematic for where the fins will be located. It will then cut through the tape.

7.2.5 Fin and Via Filling

After all the tape layers have been created, they will be stacked on top of each other. The via section in one stack and the fin section in another stack. The holes will be filled with a silver paste.

7.2.6 Stacking, Lamination, Firing

Now that the fins and vias have been filled, they will be stacked on top of each other. They will go through the lamination process and then placed in the furnace. The furnace temperature will then be ramped up to the temperature found in the sintering study.

7.3 Improvement of the Design

Once a completed heat exchanger is produced using each of the three materials then an optimization process will be started. Each prototype will be tested for heat flux capacity and pressure drop. These values will be used to verify the computer model. Now the optimization process will be started. Design parameters will then be defined for the heat exchanger. The computer model will altered so that the heat exchanger will depend on these parameters. Sobols quasi random sequence algorithm will be used to create random points though our design space such that a response surface can be created. New heat exchangers will be created based on the design parameters defined by Sobols algorithm. They will be tested. A response surface will be created using different methods. They will be analyzed for error and the best response surface will be chosen. Population and then gradient based algorithms will be used to create a Pareto front. A new set of heat exchangers will be created from this Pareto front. A new set of response surfaces will be created from all the experimental data, and the optimization process will be run again. The end result is to have a couple trade off designs that can be used.

8. Design Considerations

8.1 Assembly and Disassembly

Once the heat exchanger has been printed, laminated, and fired, no assembly will be required due to the nature of the design; it will be a single, monolithic structure.

8.2 Environmental Impact

There is exists a possibility, in the far future, if the manufacturing process is successful and is used globally, that soil erosion may become an issue [7]. On lunar and Martian locations this should not be an issue but on Earth, there may be a risk involved with large amounts of soil harvesting used for ceramics manufacturing. This would lead to desertification of the surrounding areas, decrease in agricultural productivity, and loss of the nutrient rich top soil where the harvesting is being conducted. Further literature studies will be needed to gauge the possibility and severity of such a scenario.

8.3 Risk Assessment

The only risks involved with this design lie in the operation of the machines used to process the regolith. It is possible that a negligent operator may put themselves or others at risk but the final product itself will be completely safe.

9. Conclusion

Test model characteristics have been determined and simulation data has been generated. Heat flow in and out of the microchannels, velocity of the medium, and temperature of the device (in steady state conditions) have all been considered. CAD models, created in SolidWorks, have also been made for different aspects of the project. The ceramic device as well as mediums for both conduction and convection have been modeled. Additionally, material characterization of the lunar regolith has been successfully completed. An average particle size of 3 microns has been obtained after 20 hours of ball milling. This size should be sufficient for sintering the regolith.

The next steps for this project centers on 3D printing. Specifically, Ceramic and metallic inks must be developed, with the goal of creating regolith based ink. The CAD drawings must then be coupled to the nScrypt printing system to manufacture the heat exchanger. Further literature review on both ceramics engineering and optimization methods will be conducted to move the project towards completion.

10. References

1. Adluru, H. (2004). *Design and Analysis of Micro-Channel Heat Exchanger Embedded in Low Temperature Co-Fired Ceramic (LTCC).* Miami, Florida.
2. Allen, C. C., Graf, J. C., & McKay, D. S. (1994). Sintering bricks on the moon. *Engineering, Construction, and Operations in Space IV, ASME*, 1220-1229.
3. Bansal, N. (2012). *Ceramics and Composites Processing Methods.* Hoboken: Wiley.
4. Ekka, P. (2011). *Effect of binders and plasticisers on alumina processing.* National Institute of Technology Rourkela.
5. enertron-inc. (2001, 12 4). *Heat Pipe Selection.* Retrieved from http://www.enertron-inc.com/: http://www.enertron-inc.com/enertron-resources/pdf/how-to-select-a-heat-pipe.pdf
6. Favis-Mortlock, D. (2005, February). *On-site effects of soil erosion*. Retrieved from Soil Erosion Site: www.soilerosion.net
7. Ferraro, P., & Hanggodo, S. (2010). *The benefits of polyalkylene carbonate binders (QPAC) for low temperature glass frit or powdered glass in low temperature processed thick film applications.* New Castle: Empower Materials.
8. Fred Barlow, A. E. (2007). *Ceramic Interconnect Technology Handbook.* Boca Raton, Florida: CRC Press.
9. Gongora-Rubio, M. R., de Novais Schianti, J., Gomez, H. C., & da Costa Teves, A. (2013). LTCC-3D coaxial flow focusing microfluidic reactor for mico and nanoparticle fabrication and production scale-out. *Journal of Microelectronics and Electronic Packaging, Vol. 10*, 102-108.
10. Kandlikar. (2006). *Heat Transfer and Fluid Flow in Minichannels and Microchannels.* Waltham: Elsevier.
11. Kingery, B. U. (1976). *Introduction to Ceramics.* New York: Wiley.
12. Li, B., Clark, P. A., & Church, K. H. (2007). Robust direct-write dispensing tool and solutions for micro/meso-scale manufacturing and packaging. *International Manufacturing Scient and Engineering Conference.* Atlanta: ASME.
13. Lingai Luo, Y. F. (2007). Heat exchanger: From micro- to multi-sclae design optimization. *Interanational Journal of Energy Research*, 1266-1274.
14. Luo, L., Fan, Y., & Tondeur, D. (2007). Heat exchanger: From micro- to multi-scale design optimization. *International Journal of Energy Research, Vol 31*, 1266-1274.
15. Marcio Rodrigues da Cunha, M. R.-R. (2009). Fabrication and Testing of an LTCC Microfluidic Serial Dilution Device. *Jounral of Microelectronics and Electronic Packaging*, 108-113.
16. *Mechanical Engineers*. (2014, April 6). Retrieved from Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook, 2014-15 Edition: http://www.bls.gov/ooh/architecture-and-engineering/mechanical-engineers.htm
17. Ohadi, M. (2013). *Next Generation Microchannel Heat Exchangers.* College Park: Springer.
18. Orbitec. (2006, Decemeber 12). *Characterization summary of JSC-1AF lunar mare regolith simulant.* Retrieved from Orbitec: http://www.orbitec.com/store/JSC-1AF_Characterization.pdf