Development of a Monolithic Ceramic Electrostatic Ion Thruster for Interplanetary SmallSat Missions

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ABSTRACT
This paper describes the design, fabrication and evaluation of a novel electrostatic thruster which was designed for deep-space missions. The thruster design attempts to achieve high-I_sp, low-mass, low-volume, and long electrode lifetime by leveraging a novel materials system. The thruster uses the Low Temperature Co-Fired Ceramic (LTCC) materials system to realize a monolithic ceramic electrostatic RF ion thruster, or LTCC-ET. LTCC technology is analogous to PCB and entails laminating and co-firing layers of material containing conductive traces, vertical interconnects, and cavities. The design incorporates a propellant port, propellant manifold, plasma cavity, antenna, high-voltage electrodes. There are three major merits of using LTCC technology for the LTCC-ET. First, electrodes, which would typically be exposed to plasma in a conventional thruster, are embedded in durable ceramic, significantly increasing electrode lifetime. Second, the manufacturing process is scalable and low-cost; prototypes in single unit quantity cost ~$3500. Additionally the thruster is low mass (110 g), compact (72 mm X 72 mm X 8 mm), and can endure temperatures in excess of 900 C. Finally, the electrostatic thruster design renders the LTCC-ET capable of high I_sp. Three prototypes have been fabricated at the University of Arkansas and were evaluated at NASA’s Marshall Space Flight Center.

INTRODUCTION
The work described in this paper is of the first ever, to the knowledge of the authors, electrostatic ion thruster architecture based on Low Temperature Co-fired Ceramics (LTCC) manufacturing technology. It enables the parallel fabrication of all the requisite subsystems (internal ionization / plasma cavity, excitation electrodes, and accelerating electrodes) to produce a monolithically-integrated thruster. The successful development of a LTCC-manufactured propulsion system will revolutionize the area of SmallSats by providing a scalable low-cost, low-volume, and high-performance in-space propulsion system architecture. It will enable new capabilities in mobility for small-satellites, especially those at nanosatellite sizes; which are crucial to NASA’s goal of utilizing small-satellites for future planetary and deep-space missions. The system architecture could also allow for a new architecture of electric propulsion that can provide thrust vectoring and eliminate the need for a neutralizing spray.

The impetus for the LTCC electrostatic thruster (LTCC-ET) came from considering what features a propulsion system purpose-built for interplanetary CubeSats would contain. The ever growing capabilities of and technologies for CubeSats give rise to more and more ambitious mission concepts. This is evidenced by missions such as MarCo, launched on May 5, 2018, and the 13 CubeSats manifested on NASA’s Space Launch System (SLS) inaugural EM-1 flight. These missions demonstrate that CubeSat maturity is outgrowing low Earth orbit. Indeed, 12 of these 14 missions include some form of propulsion including: cold gas, water electrolysis, monopropellant, solid rockets, electrospray, and ion engines [1] [2] [3] [4] [5]. All of these propulsion systems are commercial solutions or custom solutions developed for each mission. The goal of the research described in this paper was present a generic alternative rather than a custom solution that
could address a wide range of interplanetary mission needs.

The primary focus of the work was on the thruster portion of such a propulsion system, not the propellant delivery or power handling. The authors see several key performance factors that need to be met to realize a generic solution for interplanetary CubeSats. First, the system would need to have significant delta-V. This led to an RF electrostatic ion propulsion architecture for its high I_{sp}. Second, limited sunlight and solar panel area constraints interplanetary CubeSats will face leads to a system that has low power needs. This led to a compact design using low-loss materials. Third, the system must be compact given the form-factor considerations of CubeSats. Fourth, the limited power and compact size will lead to low thrust. Therefore, this system would need to have a very long burn time in order to achieve significant delta-V. This led to embedding the electrodes in ceramic for maximum durability. Additionally, the durability afforded by the ceramic makes the thruster compatible with corrosive propellants such as solid subliming iodine, which is of significant interest due to its high propellant density [3]. A fifth factor was not a design goal but is a significant benefit is the scalability of system’s manufacturing process. This process enables batch fabrication of highly complex structures for relatively low cost. These considerations, in conjunction to the unique fabrication facilities at the University of Arkansas, lead to the adoption of the LTCC materials system and ultimately the LTCC-ET design.

Low Temperature Co-fired Ceramics (LTCC) is a manufacturing technology analogous to PCB technology but uses ceramic structural layers instead of glass-epoxy laminates [6] [7]. Designs are created by stacking individual layers of soft ceramic-polymer thick films called ‘green tape’. Each layer can have patterned geometries and vias (vertical interconnects), much like PCBs, which are then filled with electrically conductive pastes (i.e. silver particles). Once each layer is completed, they are stacked together and subjected to high pressures ranging from 2000 – 4000 psi to laminate the layers together. The entire stack is then cofired at 850 – 1000 °C to fuse all the layers together and burn off the polymer binders. The value of using LTCC technology is that it is extremely durable, can operate at very high temperatures, mechanical and voltage leakage doesn’t occur until ~450°C, and has a very low dielectric loss tangent (0.001 at 10 GHz) [6]. Additionally, designs using this manufacturing process are scalable in complexity. That is, they can have a wide range of complexity without significantly increasing cost. This is similar to PCB fabrication technology where the cost for three conductors on a layer is the same as for a thousand. The most significant cost driver is the number of unique layers, not the complexity they contain. This feature is important to the LTCC-ET because device complexity is scalable. The typical applications for LTCC technology are packaging for high power electronics or extremely high frequency devices (>10 GHz). This technology was selected for the thruster design due to its manufacturing (parallel and scalable), mechanical (durability of ceramics in plasma environment), and electrical (insulator and low RF losses).

**RF ELECTROSTATIC ION THRUSTER**

Although the operating principle of an electrostatic thruster is straightforward, the actual device can be quite complex [8]. There are three primary elements. First, a cavity contains a plasma consisting of a positively ionized propellant. Propellant is fed into the cavity and plasma ignited through RF excitation or arc discharge. Second, there is a screen electrode which is perforated with holes to allow propellant to leak out of the cavity. Third, there is an accelerating electrode outside of the screen electrode which is charged to a high DC voltage. As ionized gas leaks out of the cavity and past the screen electrodes, the electric field from the accelerating electrode applies a force on the ions and accelerates them out of the system to provide thrust. A secondary device called a neutralizing spray is typically included in propulsion systems to spray electrons on the exhaust propellant to keep the spacecraft charge neutral. The Isp is directly related to the voltage of the accelerating electrode and the thrust is directly related to this voltage as well as to the mass flowrate of propellant. The power of the system is directly related to the product of mass flowrate and accelerating voltage.

**LTCC-ET PROTOTYPE FABRICATION**

An opportunity arose in the summer of 2015 that afforded the taking first steps in developing the LTCC-ET. The author’s research group (Roddy, Huang) hosted an NSF Research Experience for Undergraduates student for 10 weeks and this program provided a small amount of funding to support a project. These resources were used to build the LTCC-ET prototypes over that summer. The design concept had already been conceived but no significant design work had been done. For this reason, the specific design was quickly assembled to contain all the functional elements of an electrostatic RF ion thruster including: propellant inlet ports, propellant distribution manifold, RF antenna, plasma cavity, screen and accelerating electrodes, RF and high voltage connections, propellant discharge orifices, and overall structure and size. The primary goal of the manufacturing effort was to prove a monolithic ion thruster could be built using LTCC and

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to develop design guidelines for future iterations. The biggest challenge was to design a plasma cavity structure that would not collapse during the high-pressure lamination process. The embedded electrodes were relatively easy to design. Due to time constraints, none of the functional elements were able to be optimized through design, simulation, and calculation before manufacturing took place. These efforts resulted in 4 prototype thrusters, one of which shattered during high-temperature processing due to internal stresses. The manufacturing experiment was very successful as it led to the creation of 3 functional prototypes which were the largest and most complex LTCC devices ever built at the University of Arkansas.

The LTCC-ET thruster’s design was based on the work by Goebels and Katz in their book on electric propulsion [8]. The thruster is composed of two distinct stages, each composed of numerous green tape sheets. The first stage of the thruster is the plasma cavity. This stage has a gas distribution manifold, a RF patch antenna, a plasma cavity, and a screen electrode. A plasma cavity must be a conductive cage and in the thruster it is defined by a via post-wall around its perimeter, the antenna on the bottom, and the screen electrode on the top. The post-wall is not a contiguous conductive wall but rather a wall made of vertical grounded conductors that are spaced close enough so that they can effectively contain electromagnetic energy at the frequency of operation, in this case, 915 MHz (although the cutoff frequency of this cavity would be in excess of 10 GHz). The post wall, antenna, and screen electrode are all embedded in the ceramic to form a monolithic structure. The screen electrode is virtually identical to the antenna but has propellant outlet orifices and is held at a positive DC potential during operation. The cavity and gas distribution manifold is created by numerous interdigitated cavities or voids that are punched into the green tape. The arrangement shape and size of these voids was selected to try and maximize the open internal volume of the plasma cavity while still maintaining structural integrity to prevent collapse during manufacturing. The second stage of the thruster is the accelerating stage. This is composed of propellant outlet orifices and an accelerating electrode. The orifices are simply holes in the green tape. The electrode is again virtually identical to the antenna and screen electrode but is held at a negative DC potential during operation.

Prototype fabrication was conducted at the LTCC lab at UA’s Hi-Density Electronics Center (HiDEC) in the summer of 2015. Four prototypes were fabricated in the pursuit of a successful fabrication process. The first prototype cracked after it was fired and was used to test soldering methods for attaching RF and high voltage connectors. The LTCC-ET contains seven distinct layers of green tape. There are multiple sheets of each layer. There are also 4 distinct metallization layers. Additionally, every layer contains the same layout of vertical interconnects (this creates the via post-wall through the entire device), but only a single metallized sheet per layer. The sequential stack-up is as follows. Layer 1 contains an accelerating electrode, discharge orifices for propellant, and an interconnect via to make connection to layer 2. There were six 10 mil thick instances of Layer 1, the topmost of which contained the screen-printing for the accelerating electrode. Best results were obtained when the accelerating electrode was screen-printed and fired after the co-fire process. There was a single 10 mil thick instance of Layer 2 containing the screen electrode and propellant discharge orifices. The screen electrode also serves as an RF ground for the ionization chamber. These seven layers were laminated to form a subassembly. Layers 3-5 form a structure comprised of the ionization chamber and a propellant gas manifold. Each layer has different cavities built into them which, when stacked together, form an interconnected cavity but all have the same post-wall vias. The cavities consist of interdigitated channels. There were two sets of Layer 3 composed of four 10 mil sheets of green tape. These were each laminated to realize two Layer 3 subassemblies. The same was true of Layers 4 and 5; two subassemblies of each Layer composed of 4 sheets of 10 mil green tape. The stack-up of these six subassemblies forms the plasma cavity and propellant manifold. Layer 6 was composed of a single layer of 5 mil thick green tape and contained the via post-wall and propellant inlet channels. This layer served to isolate the antenna from direct exposure to the RF plasma. Layer 7 contains the propellant inlets, the RF patch antenna, an RF ground, the via post-wall, and an additional interconnect via to make electrical connection to the antenna. The Layer 7 stackup was composed of six 10 mil layers of green tape. The topmost layer contained the antenna and the bottommost layer contained RF ground and the RF interconnect via solder pad. Layers 6 and 7 were laminated to form the final subassembly. All subassemblies were then aligned and laminated to form the final device stack. The structure was then co-fired. All prototypes were manufactured using DuPont 9k7 LTCC Green Tape. Figure 1 shows a negative of the cavities in the LTCC-ET for better visualization of the shape and distribution of voids which make up the internals of the thruster. Figure 2 shows the seven unique layers and the electrodes silk-screening as well as the circuit diagram of the thruster. Figure 3 shows photographs of the LTCC-ET during fabrication. Figure 4 shows the arrangement of the via post-wall, RF
antenna, and screen electrode which forms the plasma cavity.

The final fabrication process can be broken down into nine steps. First, all sheets and layers were punched out using a CNC punching tool to create cavities, orifices, and vias. Second, all via holes were filled with DuPont LL601 silver paste. Third, the internal metallized layers (Layer 2 and Layer 7 topside) were screen printed with DuPont LL612 silver conductor paste to form the screen electrode and antenna, respectively. Fourth, all subassembly stack-ups were laminated at 3000 psi. Fifth, the eight subassemblies were stacked together and laminated at 2500 psi. It was critical to the design of the device that the two instances of Layer 3, 4 and 5 had a 90 degree rotation between each of them. Sixth, the laminated stack-up was co-fired at 900°C for 18 hours. Seventh, the accelerating electrode and ground plane conductors were screen-printed on Layers 1 and 7, respectively, using DuPont 6277 silver / palladium paste. Eighth, the final conductors were cured and sintered at 850°C for 1 hour.

![Figure 1: CAD visualization of how the internal cavities in the LTCC-ET add up to form a propellant manifold, plasma cavity, and propellant outlet ports. A) Start with propellant inlet ports B) Add the first Layer 5 C) Add the second Layer 5 D) Add the first Layer 4 E) Add the second Layer 4 F) Add the first Layer 3 G) Add the second Layer 3 H) Add the propellant outlet ports](image1)

![Figure 2: CAD models of the seven unique layers in the LTCC-ET showing vias and silkscreen conductors. A) Layer 1, propellant outlet ports and accelerating electrodes. B) Layer 2, propellant outlet ports and screen electrodes. C) Layer 3, small cavities. D) Layer 4, medium cavities. E) Layer 5, large cavities. F) Layer 6 propellant inlet port and RF antenna. G) Layer 7, propellant inlet port and ground plane. H) Electrical schematic of the LTCC-ET showing the plasma cavity, RF antenna, screen voltage, $V_s$, and accelerating voltage, $V_a$.](image2)
The final device measures 2.75” on each edge, is 340 mils thick, weighs ~110 g, and has a volume of ~45 mL. However, this could be reduced with design optimization. The LTCC thruster was not only the thickest device ever fabricated at the HiDEC labs, but was also the first to incorporate internal cavities. The design posed two unique challenges. First was the challenge of how to incorporate a plasma cavity without having the device collapse under the extreme pressure of the lamination process. This was achieved by adding additional sheets to Layers 1, 2, 6, and 7. Functionally speaking, they did not need to have multiple sheets but eight sheets were incorporated to add structural integrity. Also, the interdigitated cavity design allowed for ‘pillars’ of LTCC material to exist in the cavity to help prevent collapse. The second challenge was to minimize the thermal stresses in the device. Excess thermal stress was identified as the reason why the first prototype failed. For this reason, post-fire metallization was used to reduce thermal coefficient of expansion mismatch between the external conductors and the ceramic stack during firing. The fabrication process has been documented and will be used as design guidelines for successful manufacturing of future devices.

THRUSTER TESTING

The LTCC-ET had to be packaged for testing before further evaluation. A custom package was designed and built to serve several key functions. First, the package provided a way to mechanically attach test articles to test fixtures. This structure was made of machined 6061-T6 aluminum and was a clam-shell design where the ceramic was sandwiched between two halves that were bolted together. The contact surfaces between the ceramic and aluminum were padded by Grafoil® high-temperature graphite gasket material. The package also provided support for RF, high-voltage, and propellant connectors. Second, a propellant injection port provided a means to plumb test articles with gas. This port was also machined out of 6061-T6 aluminum. It sealed to the back of the ceramic thruster body with a custom laser-cut, 30 mil thick, buna-N rubber gasket. The port mounted to the main structure and was threaded to accept a ¼” NPT to compression connector. Third, there was Teflon plug in the front of the thruster that blocks the four center propellant outlet orifices to help increase the chamber pressure. This feature was added because the propellant injector delivers fuel straight into the plasma chamber which has propellant outlet orifices directly in front of the injectors. This is a design flaw that was not considered initially as the prototypes were designed for a manufacturing experiment, not designed for test. Without this feature, propellant would simply flow at supersonic velocities (in vacuum) through the thruster and not build up enough pressure to light a plasma. The Teflon plug was sized so that the distance between it and the end of the injector was 0.005”. Fourth, the test articles had...
electrical connectors. The RF antenna was connected with an SMA connector and the screen and accelerating electrodes used MHV connectors. Figure 5 shows photographs of a packaged test article.

The goal of testing the LTCC-ET was threefold. The first goal was to determine the power requirements to ignite a plasma as a function of propellant flowrate. The second goal was to measure thrust as a function of accelerating voltage. The third goal was to determine if it was possible to accelerate electrons and positive ions in an alternating fashion. This was the most interesting testing goal due to its significant implications. The fact that the sides of the plasma cavity are insulated from the plasma by a layer of ceramic give them more durability. However, this fact also means that as positive ions are accelerated out of the thruster there is negative charge buildup as the electrons in the plasma have no path to ground. This could lead to ‘poisoning’ the plasma by making it too negative. Eventually the plasma would extinguish if negative charge cannot be discharged. This can be avoided by periodically switching the polarity of screen and accelerating electrodes to expel electrons instead of positive ions. These goals were not met during testing due to issues with the test articles.

Testing was conducted at the High-Power Plasma Propulsion and Diagnostics Laboratory at NASA’s Marshall Space Flight Center (MSFC) in Huntsville, Alabama in June 2018. A cooperative agreement partnership was established with MSFC because there are no facilities with sufficiently large vacuum chambers at the University of Arkansas to test electric propulsion systems. Additionally, MSFC lent their expertise to help plan and conduct testing activities. The testing activities were limited to only one week of work due to time and funding constraints. A work plan was established to try and achieve the testing goals. The plan was to first attempt to ignite a plasma in the thruster. This was done in an ad-hoc manner until nominal setpoints could be established to reliably ignite and maintain a plasma. The next part of the plan was to integrate the thruster on the thrust stand and instrument with thermocouples and Langmuir probes. Finally, conduct the characterization experiments. Unfortunately, the testing did not progress past the first step of determining nominal setpoints during the week of testing. While a plasma was successfully ignited, it was not reliably stay lit for reasons to be discussed.

Testing was conducted with argon gas as a propellant. This was selected for its relative ease in forming a plasma. A photograph of a test article setup for ad-hoc testing in the facilities at MSFC as well as the vacuum chamber and RF equipment is shown in Figure 6. The propellant was flowed to the device at a given flowrate and the power increased up to the maximum power rating of the RF system, 50 watts. This process was
repeated for ever increasing propellant flowrate until a plasma was ignited. No ignition was achieved at argon flowrates of 1, 3, 10, and 33 sccm. Ignition was repeatably achieved with an argon flowrate of 95 sccm and an input power of 22 W. Ignition would be maintained for 20 – 60 seconds before the plasma went out. The extinguishing of the plasma was determined to be due to inefficient RF power delivery to the test article. The RF load (antenna) was well matched to 50 ohm when there was no plasma. Upon ignition, the RF load seen by the power supply changed and led to less power being delivered to the test article. This issue was exacerbated by heating of the entire test setup. Once inefficiencies were sufficiently encroached on the setup the plasma extinguished as it no longer was receiving enough power to sustain itself. Increasing the propellant flowrate to 400 of sccm marginally reduced the input power needed for ignition. Plasma was ignited, if only briefly, for each of the three test articles that were brought for testing. All of them suffered the same issues of impedance mismatch, inefficient RF power delivery, and excessive heating. After initial ad-hoc testing each, every test article stopped working entirely and exhibited open circuit behavior when observed with a vector network analyzer. Every test article suffered desoldering of their SMA connectors, further confirming that excessive heating was causing damage. The test articles were repaired and retested with similar results as before. A photograph of a test article with a plasma being created is shown in Figure 7.

![Figure 7: Photograph of the Test Article 1 of the LTCC-ET prototype generating an argon plasma.](image)

**FUTURE WORK**

The LTCC-ET shows promise but still needs further development to realize something that can be characterized as a thruster. There are three major issues that must be addressed before new test articles can be fabricated. First, the antenna matching needs to be improved. The antenna needs to be modeled to ensure good impedance matching at the operating frequency, in this case 915 MHz in the ISM band. Most importantly the antenna needs to be matched when plasma is being created. The presence of plasma changes the electrical characteristics of the antenna and these must be considered in the design. If matching cannot be achieved, then a matching network must be created for efficient and reliable operation. Second, cavity pressure must be increased by decreasing the propellant outlet orifice size and number. The ideal pressure can be obtained by examining the Paschen’s curve for the selected propellant and taking into account the antenna / screen electrode spacing, and electric displacement caused by the presence of ceramic in the plasma cavity [9]. The pressure of the cavity can then be calculated as a function of orifice size via CFD or other means. The proper orifice size and number can be determined by matching the design to the desired cavity pressure. Third, the thruster structure should be improved. The primary improvement would be to increase the operating temperature of the RF and high voltage connectors for higher reliability. This can be achieved by using higher temperature solder and larger connectors which are better at dissipating heat.

**CONCLUSIONS**

In conclusion, the authors have realized functional prototypes of the LTCC-ET. The test articles were successfully fabricated and demonstrated that the LTCC materials system could be a viable way of creating an electric thruster. The primary benefit of this is that designs can add significant complexity while not increasing cost in a commensurate way. The ultimate application of this technology would be to create an entirely monolithic thruster that has multiple quadrants whose accelerating grids could be controlled independently to realize a solid state thruster that can electrically thrust vector with no moving mechanical parts or actuators. Additionally, regions could be build in to accelerate negative ions / electrons and thereby have an electric thruster that does not require a neutralizing spray. These two technological possibilities make the LTCC-ET design concept well suited to interplanetary SmallSat missions as due to low volume, long-lifetime, and high $I_{sp}$ properties.

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