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Characterization of Low-Temperature, Co-Fired Ceramic-Manufactured Electrostatic Thruster—Closeout Report

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June 2019

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

CAD	computer-aided design
CAN	Cooperative Agreement Notice
DC	direct current
HiDEC	Hi-Density Electronics Center
LTCC	low-temperature, co-fired ceramic
LTCC-ET	low-temperature, co-fired ceramic electrostatic thruster
MSFC	Marshall Space Flight Center
NPT	National Pipe Thread
PCB	printed circuit board
RF	radio frequency
SMA	SubMiniature version A
TRL	Technology Readiness Level
UA	University of Arkansas

CHARACTERIZATION OF LOW-TEMPERATURE, CO-FIRED CERAMIC-MANUFACTURED ELECTROSTATIC THRUSTER—CLOSEOUT REPORT

TECHNICAL MEMORANDUM

1. PROJECT GOAL AND SUMMARY

The goal of the project was to evaluate prototypes of an experimental thruster developed by the University of Arkansas (UA), Fayetteville, AR. The design under evaluation is a radio frequency (RF) electrostatic thruster that was fabricated using the low-temperature, co-fired ceramic (LTCC) materials and fabrication process. This materials system is analogous to printed circuit board (PCB) technology with the most significant difference being that the laminate is replaced by a ceramic material and the copper layer is replaced by printed sinterable silver paste. LTCC designs are baked after fabrication and assembled to realize an entirely monolithic structure with internal conductors, vias, and cavities. In this process, the LTCC electrostatic thruster (LTCC-ET) that is the subject of the present work becomes a monolithic ceramic thruster capable of withstanding temperatures in excess of 500 ºC. The UA and NASA Marshall Space Flight Center (MSFC) jointly performed prototype testing on the LTCC-ET under a NASA Cooperative Agreement Notice (CAN) award. The LTCC-ET was tested at MSFC in May 2018 over a 1-week period. There were two goals for the test program:

(1) Testing to determine the operating parameters required to create plasma ignition in the test articles. This was explored by setting a propellant flowrate and increasing RF power until plasma ignition was observed. Testing was conducted with both argon and krypton.

(2) Investigate the thrust and specific impulse (I_{sp}) performance of the thruster as a function of propellant flowrate and grid voltage. This goal was not met during the project as technical challenges in maintaining stable plasma ignition arose due to stress and heating of the RF power feed.

In summary, a prototype thruster design (consisting of three packaged units) was fabricated by UA and tested for the first time under vacuum conditions at MSFC to experimentally determine basic performance metrics and functionality. It was found that the design was not sufficiently optimized or robust enough in its initial iteration to support a significant test campaign or characterization program. It was concluded that the propellant outlet channels must be reduced in size with the flowpaths adjusted to increase propellant residence time in the thruster, and that the RF connector must be replaced with a version capable of handling higher power throughput and heating. However, even in its unoptimized form, a plasma could be produced in the LTCC-ET, demonstrating the efficacy of the design approach. The design is especially compelling due to its low cost to manufacture and, more importantly, its scalability of size and power throughput. Low cost and scalability are also important in that additional functionalities, such as thrust vectoring and plume charge neutralization, can be integrated into future designs with minimal additional cost. This project has matured the LTCC-ET development Technology Readiness Level (TRL) from 1 to 2. The low-cost RF plasma source portion of the LTCC device was matured from TRL 2 to 4 through the demonstration of RF plasma ignition under vacuum conditions.

2. PROJECT DESCRIPTION

The LTCC manufacturing technology enables the parallel fabrication of all the requisite subsystems (internal ionization/plasma cavity, excitation electrodes, and accelerating electrodes) required to produce a monolithically-integrated electrostatic ion thruster. The successful development of an LTCC-manufactured propulsion system has the potential to revolutionize the use of SmallSats by providing a scalable low-cost, low-volume, high I_{sp} in-space propulsion system capability. High-performance propulsion on SmallSats can enable new capabilities in small satellite mobility, especially for CubeSats and nanosatellites. Mobility is crucial to NASA's goal of utilizing SmallSats for future planetary and deep-space missions. The LTCC manufacturing process could also allow for new electric propulsion designs that can provide thrust vectoring and eliminate the need for a separate beam neutralization component.

The impetus for the LTCC-ET arose from considering what features a propulsion system specifically designed 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 the 6U MarCO CubeSats, designed to serve as communications relays for a Mars flyby, and the 13 CubeSats manifested on NASA's Space Launch System inaugural Exploration Mission-1 flight. These missions demonstrate that CubeSats are maturing and their capabilities are expanding far beyond 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.[1–5] All of these propulsion systems are commercial or custom solutions developed and tailored for each mission. The goal of the research described in this Technical Memorandum was to present a generic alternative propulsion system, rather than a custom solution, that was capable of addressing a wide range of interplanetary mission needs.

The primary focus of the work was on the thruster portion of such a propulsion system, as opposed to the propellant storage and delivery system or power generation and conditioning. The authors see several key performance factors that need to be met to realize a generic solution for interplanetary CubeSats:

(1) The system would need to have a high I_{sp} so as to be capable of imparting significant ΔV to the spacecraft. This led to an RF electrostatic ion propulsion architecture.

(2) The limited sunlight and solar panel area constraints interplanetary CubeSats face lead to a system that has low power requirements with compact, low-loss power transmission pathways.

(3) The system must be compact to integrate within the limited mass and volume envelope of CubeSats. A consequence of the limited power and compact size is a low thrust level. At low thrust, this system must operate over a long time to impart significant ΔV to the spacecraft. The electrodes were embedded in the 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 storage density.[3] A significant benefit of the manufacturing process is its scalability. The LTCC process enables batch fabrication of highly complex structures for relatively low cost. These considerations, in conjunction with the unique fabrication facilities and capabilities at UA, lead to the adoption of the LTCC materials system and, ultimately, the LTCC-ET design.

The use of LTCC in manufacturing is analogous to PCB fabrication, except that LTCCs use ceramic structural layers instead of glass-epoxy laminates.[6,7] Designs are created by stacking individual thick film layers of soft ceramic-polymer called 'GreenTape' (DuPont™ LTCC GreenTape™ 9K7). 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 all layers are completed, they are stacked together and subjected to high pressures ranging from 2,000 to 4,000 psi to laminate the layers together. The entire stack is then co-fired at 850 to 1000 °C to fuse all the layers and burn off the polymer binders. The value of using LTCC technology is that it is extremely durable, can operate at very high temperatures, has a very low dielectric loss tangent (0.001 at 10 GHz), and does not exhibit mechanical and voltage leakage until ~450 °C.[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). In the present work, LTCC technology was selected for the thruster design due to ease of manufacturing (parallel and scalable), mechanical properties (durability of ceramics in plasma environment), and electrical properties (insulator and low RF losses).

2.1 Radio Frequency 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: a cavity, a screen electrode, and an accelerating electrode. Propellant is fed into the cavity and a plasma is produced through the application of direct current (DC) or RF power. The screen electrode is perforated with holes to allow propellant to emerge from the cavity and it is at a potential to draw ions out of the cavity while repelling electrons. The accelerating electrode downstream of the screen electrode is held at a high DC voltage to accelerate the ions as they enter the gap between the screen and accelerating electrodes. A secondary device called a neutralizer is typically included in propulsion systems in the downstream region. This device injects electrons into the positively-charged exhaust beam, allowing the spacecraft to remain charge neutral. The I_{sp} of such a device is directly related to the square root of the applied voltage divided by the molecular mass of the propellant $\left(\sqrt{V / M}\right)$, while the thrust directly scales with this quantity times the propellant flowrate. If the thruster is operating in the space-charge limited regime, the thrust per unit area simply scales with the square of the applied voltage divided by the electrode spacing $\left([V / \Delta x]^2\right)$.

2.2 Low-Temperature, Co-Fired Ceramic Extrostatic Thruster Prototype Fabrication

An opportunity arose in the summer of 2015 that started the development of the LTCC-ET. The research group at UA hosted a National Science Foundation Research Experience for undergraduate students over a period of 10 weeks. Limited financial resources of that program were used in the fabrication of LTCC-ET prototypes. At the time of that effort, the concept had already been conceived but no significant design work had been performed. Due to time constraints, none of the functional elements were optimized through design, simulation, and calculation before manufacturing took place. Instead, the primary goal of the effort was to demonstrate that a monolithic ion thruster could be fabricated using LTCC, with an additional goal of developing 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 specific design was quickly assembled, containing all the functional elements of an electrostatic RF ion thruster including propellant inlet ports, a propellant distribution manifold, RF antenna, plasma cavity, screen and accelerating electrodes, RF and high-voltage connections, propellant discharge orifices, and overall supporting structure. The embedded electrodes for all the interactions with the plasma were relatively easy to incorporate into the LTCC structure. These efforts resulted in the fabrication of four prototype thrusters, one of which shattered during high-temperature processing due to internal stresses. The manufacturing experiment was successful as it led to the creation of three functional prototypes representing the largest and most complex LTCC devices ever fabricated at UA.

The LTCC-ET thruster design was based on the work of Goebel and Katz.[8] The thruster is composed of two distinct stages, each composed of numerous GreenTape sheets. The first stage of the thruster is the plasma cavity. This stage has a gas distribution manifold, an RF patch antenna, a plasma cavity, and a screen electrode. The plasma cavity must be a conductive cage and in the thruster it is defined around its perimeter by a via post-wall, at the bottom by the RF antenna, and at the top by the screen electrode. The post-wall is not a contiguous conductive wall but rather a wall 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 so as to be part of the monolithic structure after high-temperature processing. The screen electrode is virtually identical in size to the antenna, but it has propellant outlet orifices and is held at a fixed DC potential during operation. A positive or negative DC potential could be employed to accelerate negative or positive ions, respectively. The cavity and gas distribution manifold are created by numerous interdigitated cavities or voids that are punched into the GreenTape. The arrangement, shape, and size of these voids were designed in an attempt to maximize the open internal volume of the plasma cavity while still maintaining structural integrity to prevent collapse during manufacturing and high-temperature, high-pressure processing. 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 GreenTape. The electrode is again virtually identical to the antenna and screen electrode but is held at a negative DC potential relative to the screen electrode during operation.

Prototype fabrication was conducted in 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 the scrap pieces of this unit were used to test soldering methods for attaching RF and high-voltage connectors.

All prototypes were manufactured using DuPont's LTCC GreenTape 9K7. The LTCC-ET contains seven distinct layers of GreenTape and there are multiple sheets comprising each layer. There are also four distinct metallization layers. Additionally, every layer contains the same layout of vertical interconnects, creating the via post-wall through the entire device. The sequential stackup is as follows:

Layer 1 contains an accelerating electrode, discharge orifices for propellant, and an interconnect via to make a 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. The seven sheets of the first two layers were laminated to form a subassembly. Layers 3–5 form the ionization chamber and a propellant gas manifold structure. 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 GreenTape. 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 four sheets of 10-mil GreenTape. The stackup of these six subassemblies forms the plasma cavity and propellant manifold. Layer 6 was composed of a single layer of 5-mil-thick GreenTape and contained the via post-wall and propellant inlet channels. This layer served to electrically insulate 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 for the electrical connection to the antenna. The layer 7 stackup was composed of six 10-mil layers of GreenTape. The topmost layer contained the antenna and the bottommost layer contained an 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.

Figure 1 shows a negative of the cavities in the LTCC-ET for better visualization of the shape and distribution of voids which comprise the internals of the thruster. Figure 2 shows the seven unique layers and the electrode silk-screenings, as well as a circuit diagram of the thruster. Figure 3 shows photographs of the LTCC-ET during fabrication while figure 4 shows the arrangement of the via post-wall, RF antenna, and screen electrode which forms the plasma cavity.

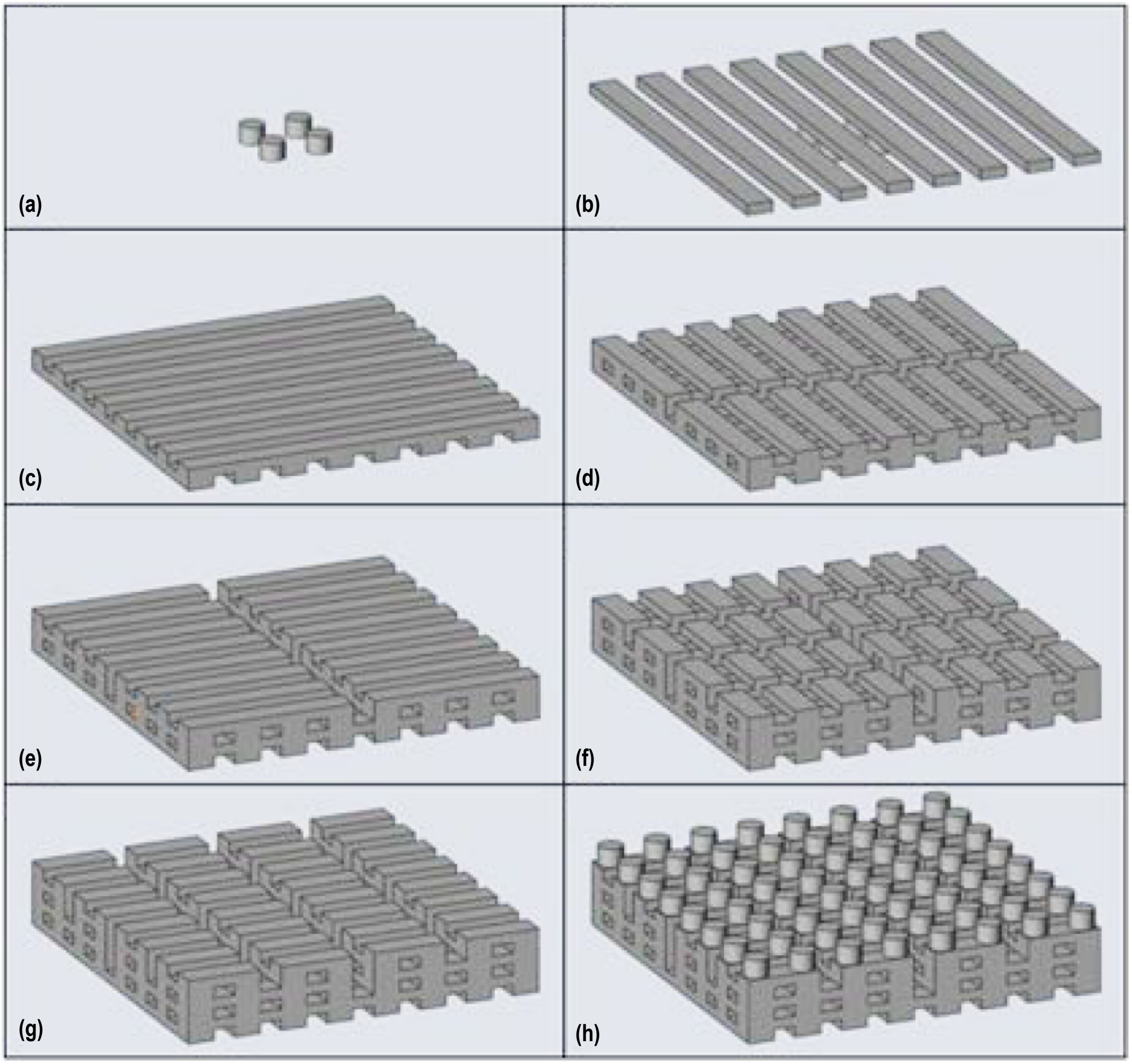


Figure 1. Negative-space, layer-by-layer CAD model showing the internal cavities in the LTCC-ET that form the propellant manifold, plasma generation cavity, and propellant outlet ports: (a) Propellant inlet ports, (b) first copy of layer 5, (c) second copy of layer 5 (rotated 90º), (d) first copy of layer 4, (e) second copy of layer 4 (rotated 90º), (f) first copy of layer 3, (g) second copy of layer 3 (rotated 90º), and (h) propellant outlet ports.

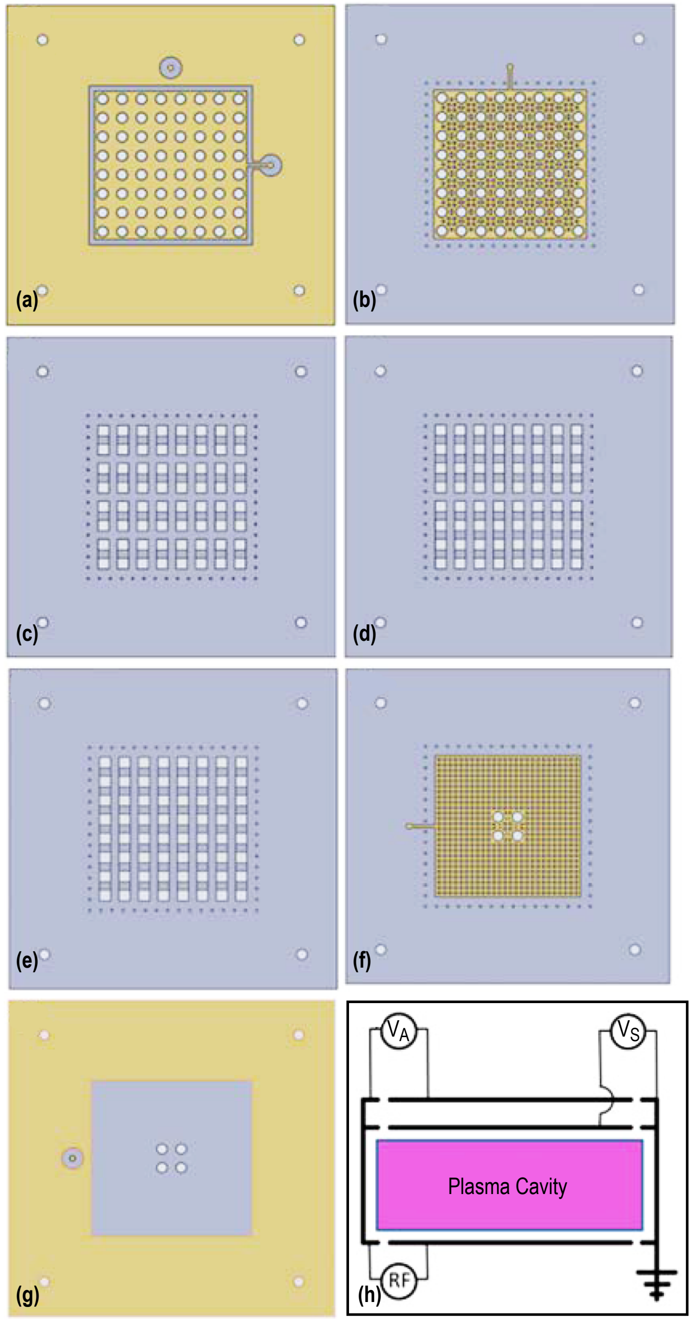


Figure 2. CAD renderings of the seven unique layers in the LTCC-ET showing vias and silkscreen-printed conductors: (a) Layer 1, propellant outlet ports and accelerating electrode, (b) layer 2, propellant outlet ports and screen electrodes, (c) layer 3, small cavities, (d) layer 4, medium cavities, (e) layer 5, large cavities, (f) layer 6, propellant inlet port and RF antenna (g) layer 7, propellant inlet port and ground plane, and (h) electrical schematic of the LTCC-ET showing the plasma cavity, RF antenna, screen voltage, V_s, and accelerating voltage, V_A (outer conducter on left and right of frame are electrically connected and grounded).

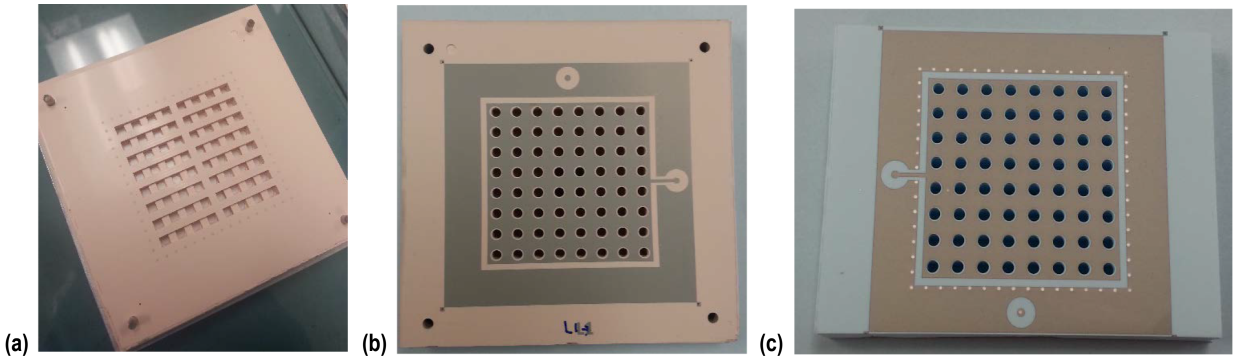


Figure 3. LTCC-ET during fabrication: (a) Partially completed thruster stack showing internal cavities, (b) fully laminated device before co-firing of the ceramic, and (c) fully complete device after co-firing.

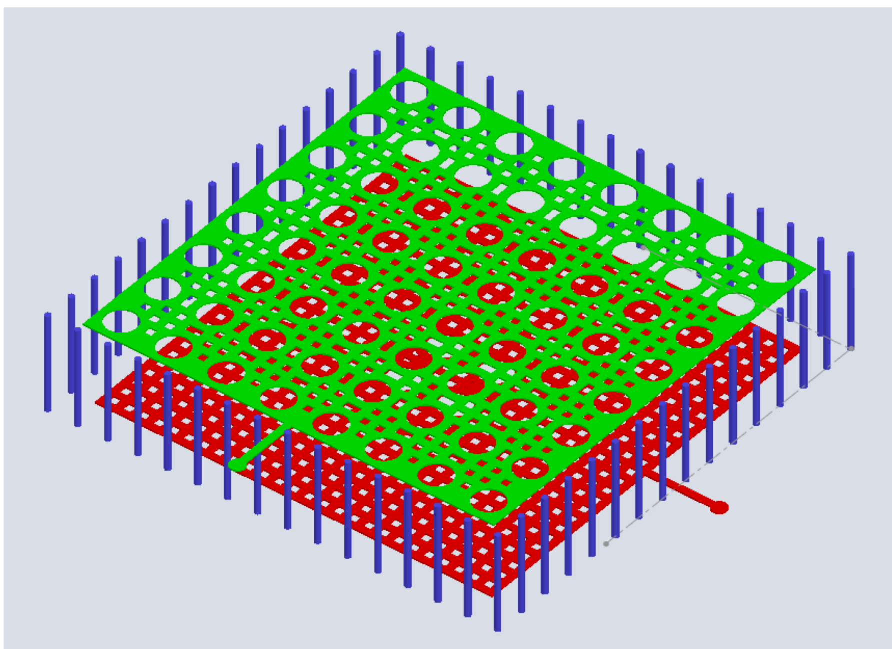


Figure 4. CAD model of the plasma cavity with ceramic removed and color added for visual clarity. The red structure is the RF antenna, the green structure is the screen electrode, and the blue structures comprise the via post-wall.

The final fabrication process can be separated into the following steps:

(1) The hole patterns in all sheets and layers were punched using a CNC punching tool to create cavities, orifices, and vias.

(2) All via holes were filled with DuPont LL601 silver paste.

(3) The internal metallized layers (layers 2 and 7 topside) were screen-printed with DuPont LL612 silver conductor paste to form the screen electrode and antenna, respectively.

(4) All subassembly stackups were laminated at 3,000 psi.

(5) The eight subassemblies were stacked together and laminated at 2,500 psi. It was critical to the design of the device that the two instances of layers 3, 4, and 5 had a 90 degree rotation between each of them.

(6) The laminated stackup was co-fired at 900 ºC for 18 hours.

(7) The accelerating electrode and ground plane conductors were screen-printed on layers 1 and 7, respectively, using DuPont 6277 silver/palladium paste.

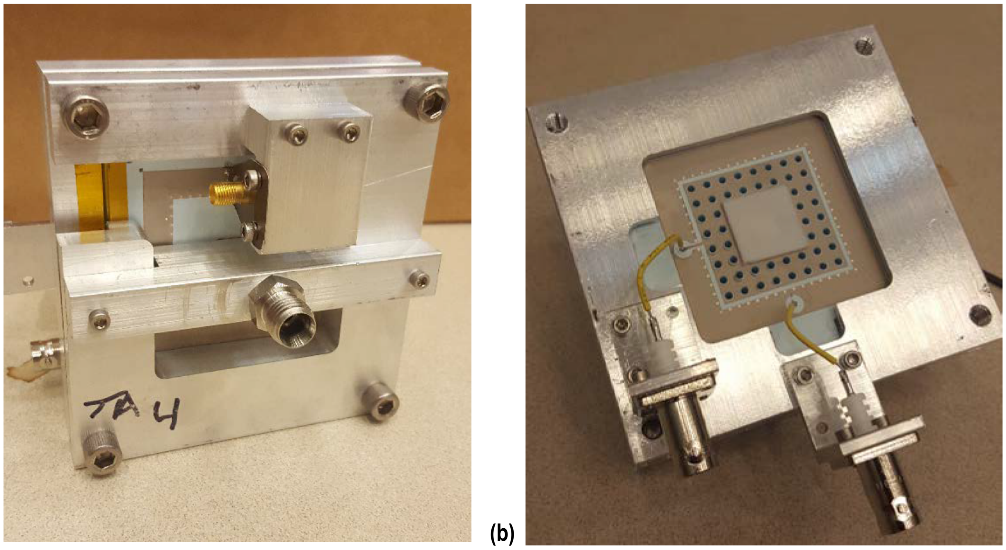
(8) The final conductors were cured and sintered at 850 ºC for 1 hour.

The final device measures 2.75 inches on each edge. It is 340 mils thick, masses ~110 g, and has a volume of ~45 mL. It is thought that the size and mass could be reduced in the design optimization process. The LTCC thruster was not only the thickest device ever fabricated at the HiDEC labs, but it was also the first to incorporate internal cavities.

The LTCC-ET design posed two unique challenges. First was the challenge to incorporate a plasma cavity in the design without having the device collapse under the extreme pressure of the lamination process. This was achieved by including additional sheets in layers 1, 2, 6, and 7. Functionally speaking, these layers did not require multiple sheets, but eight sheets were incorporated during assembly to add structural integrity. Also, the interdigitated cavity design shown in figure 1 allowed for 'pillars' of LTCC material to exist in the cavity to provide added support and prevent collapse. The second challenge was to minimize the thermal stresses in the device. Excess thermal stress was identified as the reason for the fracture during the assembly of the first prototype. For this reason, post-fire metallization was used to reduce the 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.

2.3 Thruster Testing

The LTCC-ET had to be mounted in a 4-inch by 3.8-inch planar cross-section test fixture (see fig. 5) to permit further evaluation. A custom fixture serving several key functions was designed and fabricated. The fixture provided a way to mechanically attach the test articles to



(a) (b)

Figure 5. LTCC-ET mounted in the test fixture: (a) The back of the test article showing the SMA RF connector and the propellant inlet fitting and (b) the front of the test article showing the two MHV connectors for the screen and accelerating electrodes and the teflon plug in the center of the device blocking a 4×4 grid of holes.

larger structures, such as a table or thrust stand. The structure was machined from 6061-T6 aluminum and consisted of a clam-shell design where the ceramic apparatus was sandwiched between the two halves that were bolted together. The contact surfaces between the ceramic and aluminum were padded by GRAFOIL® high-temperature graphite gasket material. The fixture provided support for RF, high-voltage, and propellant connectors. The propellant injection port feeding the test article with gas was also machined from 6061-T6 aluminum. This connection was sealed at the back of the ceramic thruster body with a custom laser-cut, 30-mil-thick, buna-N rubber gasket. The gas port was a threaded ¼-inch National Pipe Thread (NPT) connection, which was connected to a flexible gas line by a male-to-male ¼-inch NPT to ¼-inch Swagelok® compression fitting. A square teflon™ plug installed on the front side of the thruster in the middle of the grid blocks the center outlet orifices, increasing the chamber pressure by ensuring the injected neutral gas could not freestream through the device. This plug was added when a visual inspection resulted in the realization that there was a straight-line path from the propellant injection holes through the plasma chamber and out of the thruster. Since the LTCC-ET was initially a manufacturing experiment, this aspect of test operation was not considered in the design phase. Future designs will have these free-streaming exit paths blocked by the internal structure of the device, without the need for an additional plug. The teflon plug was sized so that the distance between it and the end of the injector was 0.005 inch. The test fixtures contained the electrical connectors for the LTCC-ET. The RF antenna was connected with an SubMiniature version A (SMA) connector and the screen and accelerating electrodes used miniature high-voltage connectors.

In this project there were three LTCC-ET testing goals. The first was to determine the RF power required to ignite a plasma in the device as a function of propellant flowrate. The second was to measure thrust as a function of applied accelerating voltage. The third was to determine if it was possible to accelerate electrons and positive ions in an alternating fashion by modulating the applied voltage between positive and negative. This was the most interesting testing goal due to its potential to remove a neutralizing cathode from the thruster design. In addition, while the plasma cavity sidewalls are insulated from the plasma by a layer of ceramic, giving them more durability, this insulation removes any possible path to circuit common for the electrons, permitting negative charge to accumulate on the sidewalls as positive ions are accelerated out of the thruster. This could lead to 'poisoning' the plasma by making it too negative. Eventually, the plasma may self-extinguish as the accumulated negative charge screens the applied RF fields. During the present effort, goal 1 was met. Goals 2 and 3 were not attempted as issues with the RF connection to the antenna arose during testing.

Testing was conducted in June 2018 at the Propulsion Research and Development Laboratory at MSFC, Huntsville, Alabama. This testing was performed under a NASA CAN contract (NNM17AA15A). The use of the facilities at MSFC were required because there are no sufficiently large vacuum chamber facilities at UA that would be suitable for testing electric propulsion systems. Additionally, MSFC personnel have significant expertise in the planning and conduction of electric propulsion testing activities. The testing activities at MSFC were limited to 1 week due to time and funding constraints. While not all tasks were accomplished (or attempted), the initial work plan is given here for completeness. Step one of the plan was to ignite the RF plasma in the thruster. Since this type of device had never been operated in the past, this was accomplished in an ad hoc manner until nominal setpoints could be established to reliably ignite and maintain a plasma. While a plasma was successfully ignited several times, it was unreliable and would extinguish for reasons to be discussed. Had the plasma demonstrated reliable ignition, the next step was to integrate the thruster on the thrust stand and instrument it with thermocouples and a Langmuir probe in the thruster plume. Once instrumented, a matrix of varying parameters (inlet gas flowrate, RF input power, acceleration grid voltage) would have been devised and systematically tested. Finally, if all that had been completed, the voltage on the grids would have been modulated to attempt electron extraction from the device.

Hardware used for ignition testing consisted of a signal generator, an RF amplifier, an isolator, a bi-directional coupler, two spectrum analyzers, and the test article. During ignition testing, the accelerating and screen electrodes were grounded to remove any issues that might arise from floating, electrically-conductive surfaces. Testing was conducted with argon gas as a propellant, selected for its traditional relative ease in breaking down at RF frequencies. Photographs of the test facilities at MSFC and a test article set up for ad hoc ignition testing are shown in figure 6. The propellant to the device was provided at a controlled flowrate. The initial flowrate was low, and when a plasma would not form up to the maximum RF power of the system (50 W), the flowrate was increased to a new value and the RF power was again ramped up to the maximum value. This process was repeated until a plasma was ignited. No ignition was achieved for argon flowrates of 1, 3, 10, and 33 sccm. Ignition was repeatably achieved at an argon flowrate of 95 sccm and an input power of 22 W. The plasma was maintained for 20–60 s before it would self-extinguish. 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 a 50 Ω impedance at 985 MHz when there was no plasma. However, upon ignition, the RF load presented to the amplifier changed, resulting in significantly less power being delivered to the test article. This issue was exacerbated as the entire test setup would heat during operation. Eventually, the plasma extinguished as it was no longer

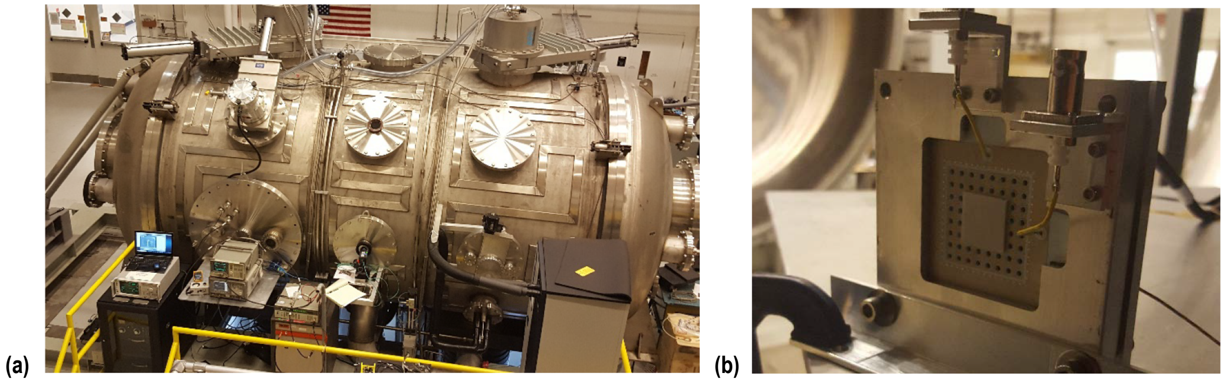


Figure 6. Vacuum chamber at MSFC: (a) 9-ft-diameter, large vacuum chamber used for testing and (b) test article installed for plasma ignition testing—the screen and accelerating electrodes were grounded (grounding wires not shown).

receiving enough power to sustain the discharge. Increasing the propellant flowrate to 400 sccm marginally reduced the input power needed for ignition. A plasma was ignited—if only briefly—in all three of the 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 test article stopped working entirely, with the RF antenna exhibiting open circuit behavior when measured using a vector network analyzer. Visual inspection revealed that the heating caused the SMA connectors to desolder, disconnecting the RF antenna from the amplifier. The test articles could be resoldered and would operate briefly, but they would again suffer the same desoldering issue after a brief period of operation. A photograph of one test article with an RF plasma in it is shown in figure 7.

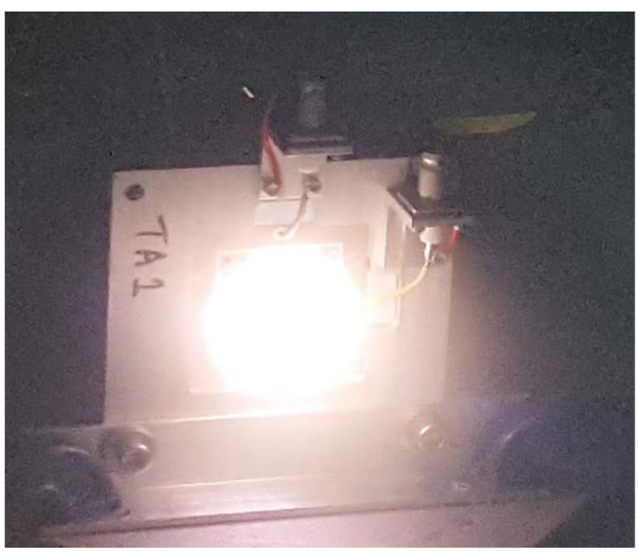


Figure 7. Test article 1 of the LTCC-ET prototype with an RF-driven argon plasma.

3. FUTURE WORK AND CHALLENGES

The LTCC-ET exhibits promise but still requires further development before it becomes something that can be rigorously tested. There are major issues that must be addressed before new test articles can be fabricated. The antenna matching needs to be improved. The antenna should be modeled to ensure good impedance matching at the operating frequency, which in the present case was designed to be 915 MHz (placing it in the industrial, scientific, and medical radio band). Most importantly, the antenna needs to be matched when a plasma is present to reduce reflected power owing to impedance mismatches in the system.

If matching cannot be achieved, then a matching network should be implemented to promote more efficient and reliable operation. The cavity pressure must be increased by decreasing the propellant outlet orifice size and number, and by designing the cavity so there are no exits for freestreaming gas entering the thruster. The ideal pressure can be estimated by examining a Paschen curve for RF breakdown of a selected propellant, taking into account both the spacing between the RF antenna and the screen electrode 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 computational fluid dynamics or other means. The proper orifice size and number of openings can be determined by matching the design to the desired cavity pressure. Finally, the thruster structure should be improved. The primary improvement would be to design the system so the RF and high-voltage connectors will remain reliably connected even at higher temperatures. This can be achieved by redesigning the connection points to reduce insertion losses and improve heat dissipation. A mechanical connection, as opposed to a soldered joint, may be more useful and robust in this instance.

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