Printing for and in Space: Novel Applications and Opportunities for Printing Technology on the Frontier

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Abstract

The history of printing has been defined by disruption, adaptation, and the continual evolution of specialized manufacturing systems. Printing is inherently multidisciplinary, uniting mechanical, chemical, and electronic systems to transform a pattern into a product, and the term "printer" has been adopted across science and engineering to describe machines that fabricate patterned materials. This broadening invites the graphic communication industry to extend its expertise into printed electronics. This paper reviews the shared heritage of the printing and electronics industries and reports work undertaken by Enova Concepts, with the NASA Jet Propulsion Laboratory and the University of Texas at San Antonio, to develop COLDFRONT, a printed materials set for electronics able to survive the harsh space environment. Candidate materials were screened with a structured selection framework; a custom-formulated dielectric, a silver nanoparticle conductor, and a barium titanate functional material were chosen and built on aerospace alloy substrates. Temperature-dependent thermomechanical models, correlated to experimental data at $R^2 = 0.94$, guided the design toward thermal-expansion compatibility. Specimens fabricated by inkjet and direct ink writing retained full adhesion and electrical function through fifteen thermal-shock cycles between −180 °C and +10 °C, with cross-hatch adhesion at the highest ASTM D3359 rating (5B), and the dielectric remained functional below −180 °C. The work shows the role that printing technology may play in realizing applications that shape the 21st century.

Introduction

Printing is among the oldest of the precision manufacturing arts, and it has always been defined less by the form of its mechanics than by a single capability: the controlled, repeatable transfer of a patterned colorant onto a substrate. From movable type through lithography, screen printing, and the digital press, that

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capability has reinvented itself, adapting each time to inks of new compositions and properties, upon new types of substrates, and in response to evolving expectations around volume, cost, and product type. This idea of printing as a continually evolving technology, defined not by its mechanism, materials, or product, leads one to ask: what is a printer?

The conventional answer—a machine designed to repeatably pattern a colorant onto a substrate in order to convey information—effectively captures the focus of the field of graphic communication. In the early 2010s the "3D printer" entered common parlance, following the expiration of foundational extrusion patents and the rise of the open-source RepRap and MakerBot communities [1]. The choice of the word "printer," rather than its technical name, fused deposition modeling, was meant to draw on the familiarity of the home-office printer and its ease of turning a digital file into a physical product. The broader engineering and scientific community has adopted this language, routinely describing the additive fabrication of everything from circuits to buildings [2] to biological tissue [3] as "printing." To reconcile the graphic communication industry's conventional definition with this broader use, we can simply update it to: a machine designed to repeatably pattern material onto a substrate to produce a product. The expansion is not novel to this paper, nor to the TAGA community; as early as 2012, William J. Ray of Nth Degree Technologies advanced a similar expanded definition of printing [4].

This paper takes that expanded definition seriously and argues that it represents a genuine opportunity for the graphic communication industry. The following section traces the long and frequently overlooked intersections of the printing and electronics industries, both in the biographies of the people who built the electrical age and in the processes they used. After doing so, this work examines the challenges of the civil-space environment that motivate new electronic manufacturing approaches, and then presents original work, carried out under a NASA Small Business Technology Transfer award, demonstrating a fully printed materials set engineered to survive the deep cold of the lunar surface.

Alignment Between Printing and Electronics Industries

The convergence of graphic printing and electronics manufacturing has given rise to the field of printed electronics. For those who have followed the field, or who understand how the competencies of the printing industry align with the needs of the electronics industry, it is the natural extension of a manufacturing discipline that has always defined itself by the controlled, repeatable deposition of a patterned material onto a substrate. This allows printing techniques to be carried over from colorant inks to functional materials. That transfer is not always without challenges: a colorant often needs only to satisfy visual and optical requirements, whereas a functional ink must also establish electrical continuity. Even so, the core competencies of registration, rheology control, and repeatable deposition

carry over readily, and it is on this foundation that printed electronics has steadily advanced [5], [6].

Printing and electronics share a surprisingly long-standing history. Michael Faraday, whose work on electromagnetic induction underpins essentially all modern electrical generation, received his earliest scientific education not at a university but at a London bookbinder's bench, reading the volumes he was apprenticed to bind [7]. Several of the defining processes of electronics were first printing processes: the planographic lithography invented by Alois Senefelder in 1796 reappeared a century and a half later as the photolithography at the heart of the semiconductor industry, when Jean Hoerni's planar process patterned silicon through a photographic mask and gave Robert Noyce the foundation for the first practical monolithic integrated circuit [8], [9], [10]. The printed circuit board itself was conceived by a printer, Paul Eisler, who reasoned in the 1930s that if images could be mass-printed onto paper, conductors could likewise be printed onto an insulating base [11]. Even the personal computer's entry into the office was mediated by the graphic arts, as Steve Jobs's exposure to calligraphy shaped the Macintosh's typography and helped launch the desktop-publishing revolution [12]. Seen against this lineage, the present convergence of printing and electronics is less a novelty than a homecoming.

This alignment has been demonstrated in practice over many decades, advanced incrementally by industrial and research laboratories, among them Xerox PARC, Heidelberg, BASF, and Konica Minolta, whose work on functional inks, thin-film devices, and roll-to-roll processing built the foundations of modern printed electronics [5], [6]. A concrete illustration from the graphic-arts literature is the work reported by past TAGA contributor William J. Ray and colleagues at Nth Degree Technologies, in which inorganic light-emitting diodes were manufactured not by conventional layer-by-layer fabrication but by dispersing micron-scale Indium Gallium Nitride micro-LED die into an ink binder and printing them across a large-area substrate to form a solid-state lighting device, an approach the authors explicitly offered as a high-speed, low-cost template for printing fabricated silicon and III–V semiconductors [4].

The printed electronics community is now institutionally organized. NextFlex, the United States Manufacturing USA institute for flexible hybrid electronics, was established in 2015 by the FlexTech Alliance through a proposal to the U.S. Manufacturing Innovation Institutes program, and is now a strategic technology community within the SEMI industry association. It coordinates a consortium of companies, universities, non-profits, and government partners and maintains public technology roadmaps developed by hundreds of subject-matter experts across many technical working groups, spanning application platforms such as integrated antenna arrays, human and asset monitoring, and soft wearable robotics, and manufacturing thrust areas such as materials, device integration and packaging, printed components and microfluidics, and standards, test, and

reliability [13]. These roadmaps document the current state of the art, identify prioritized technical gaps, and direct collaborative manufacturing investment. A parallel ecosystem of international organizations such as LOPEC, IDTechEx, TechBlick, and COLAE sustains the rapid exchange of results across the printing and electronics disciplines, and independent market analyses reinforce the trajectory, projecting sustained double-digit annual growth in roll-to-roll and printed-electronics manufacturing as displays, wearables, and conformal sensing scale up [14].

The field has also begun to demonstrate that printed electronics can serve demanding environments rather than only benign consumer ones. Work on printed electronics for extreme high-temperature service, for example, has shown that appropriately formulated and post-processed silver inks can maintain stable electrical behavior far beyond the ceiling of conventional screen-printable silver-flake systems, and that adhesion and dielectric stability are the limiting reliability factors under thermal stress [15]. The same trajectory is visible in recent industrial activity: in 2026 Inspira Technologies acquired the additively-manufactured-electronics platform formerly developed by Nano Dimension and announced its application to superconducting quantum computing, where additively printed three-dimensional interconnects are being developed to address signal-connectivity bottlenecks inside cryogenic dilution refrigerators [16]. That a printed-electronics platform is being directed at hardware operating near absolute zero underscores how far the demands now placed on additive fabrication extend beyond mild conditions, and it motivates the central question of this work: whether the same family of additive printing processes can be engineered to survive the deep cold of the lunar and deep-space environment, which is examined in the sections that follow.

Challenges in Civil Space

This section establishes a compelling use case for printed electronics. The renewed national effort to return to the Moon and to operate sustainably on its surface has surfaced a set of technology gaps that the established terrestrial electronics supply chain does not address. In July 2024 NASA's Space Technology Mission Directorate published its inaugural Civil Space Shortfall Ranking, an integrated prioritization of nearly two hundred technology shortfalls assembled from more than twelve hundred internal and external inputs. The single highest-ranked shortfall on that integrated list is the need to survive and operate through the lunar night, followed closely by surface power generation and high-performance onboard computing [17]. The challenges that follow are therefore not hypothetical; they are the gaps NASA itself has identified as most limiting, and each of them maps naturally onto a capability the printing industry can help provide.

The first and most directly relevant challenge is the extreme thermal environment. Global mapping of the lunar surface by the Diviner Lunar Radiometer Experiment aboard the Lunar Reconnaissance Orbiter shows equatorial daytime maxima approaching 390 to 400 K (well above 120 °C) and falling to roughly 95 K, near −178 °C, just before lunar dawn, while permanently shadowed polar cold traps remain colder still, approaching −250 °C [18]. A single lunar day–night cycle therefore subjects surface hardware to a temperature swing of roughly 300 °C, repeated every twenty-nine Earth days. For electronics, the destructive consequence of such cycling is not temperature alone but the differential expansion and contraction of dissimilar bonded materials: when a conductor, a dielectric, and a substrate possess mismatched coefficients of thermal expansion, repeated cycling drives interfacial stress, cracking, and delamination that conventional rigid assemblies are not designed to tolerate. Designing a materials set whose thermal expansion is deliberately matched across the printed stack is consequently the central materials problem, and it is the one this work addresses. The second challenge is ionizing radiation. Beyond the protection of Earth's magnetosphere, crews and hardware are exposed to galactic cosmic rays and to episodic solar particle events, and radiation is widely characterized as the foremost risk to human health on missions beyond low Earth orbit, with documented potential to elevate the risks of carcinogenesis and of cardiovascular and central-nervous-system effects [19]. Mitigation strategies span passive shielding, including the use of local regolith, and active approaches, but the monitoring problem, knowing the dose a crew or a system is actually accumulating, distributed across a habitat or a vehicle, invites large-area, conformal, low-mass dosimetry of exactly the kind that printed sensors are suited to provide. Printable radiation detection is thus a second point at which additive printing intersects a ranked civil-space need.

The third challenge is isolation from terrestrial resources. Every kilogram of finished hardware bound for the lunar surface must first be lifted out of Earth's gravity well, and the cost of doing so, although falling dramatically, remains substantial: NASA analysis places the Space Shuttle's delivery cost at approximately $54,500 per kilogram to low Earth orbit, against roughly $2,720 per kilogram for the Falcon 9, itself about a twenty-fold reduction, with later reusable and heavy-lift vehicles projected to drive the figure lower still [20]. Even at these reduced rates, mass and volume to the surface are precious, lead times are long, and emplaced hardware cannot easily be repaired or replaced from Earth. This logistical reality places a premium on manufacturing approaches that are additive rather than subtractive, that are mass- and volume-efficient, that can draw on locally available feedstocks where possible, and that can ultimately be performed in situ. NASA's In-Space Manufacturing initiative, led from Marshall Space Flight Center, pursues exactly this capability: on-demand production of mechanical and electrical components during transit and on-surface operations, including recent infrastructure dedicated to printed electronics, recycling, and the extraction of materials from lunar and Martian regolith [21]. Additive printing

methods, being inherently low-waste, digitally defined, and compact, align closely with these in-space-manufacturing goals and with the broader objective of supply-chain independence for off-world operations.

Taken together, these three challenges, surviving extreme temperature, detecting ionizing radiation, and manufacturing in isolation from terrestrial resources, define three corresponding opportunities for printing technology: cold-survivable printed electronics, large-area printable radiation detection, and in-space additive manufacturing. The distinctive advantage printing brings to the second and third of these is reach over area: the same roll-to-roll and direct-write methods that pattern meter-scale graphics can blanket a habitat or vehicle surface with conformal, low-mass sensing far more economically than discrete assembled devices. The remainder of this paper concentrates on the first opportunity, the development of a cold-survivable printed-electronics materials set and process, which both responds to the highest-ranked civil-space shortfall and exercises precisely the ink-formulation, deposition, and characterization competencies that the printing industry already possesses.

Cold-Survivable Printed Electronics: The COLDFRONT Materials Set

The objective of this work was to determine whether additively manufactured electronics could be engineered to survive and operate through the deep cold of the lunar environment, and to do so using the deposition, formulation, and characterization competencies native to the printing industry. The effort, carried out by Enova Concepts in collaboration with the University of Texas at San Antonio and the NASA Jet Propulsion Laboratory under a NASA Small Business Technology Transfer (STTR) award, advanced the concept from basic principles toward an experimental proof of concept, in the language of technology maturation, from Technology Readiness Level (TRL) 1 to TRL 2–3. The program was organized around three objectives: to establish a fundamental understanding of cold survivability and the associated failure modes; to develop and validate predictive multiphysics models of the printed material stack; and to engineer and experimentally demonstrate a candidate materials set, designated COLDFRONT.

Experimental Methods

Materials selection. Candidate materials were screened against the lunar thermal environment using a structured, one-hundred-point evaluation framework weighted across four criteria: space heritage (25 points), multi-environment performance (30 points), additive-manufacturing process compatibility (25 points), and supply-chain readiness (20 points). Fifteen candidate materials were evaluated across the three functional roles required of a printed electronic stack: an insulating/dielectric layer, a conductive layer, and a multifunctional layer for sensing or actuation. The framework was deliberately demanding, and a large majority of candidates were disqualified on environmental-performance grounds

alone, failing to span the required temperature range or to meet radiation-tolerance, outgassing, or stability thresholds.

Materials set. The selection identified a complementary set. A printable dielectric, the custom-formulated COLDFRONT insulator, was chosen for its broad thermal stability and its compatibility with multiple additive-deposition methods, and serves to isolate the active electronics from the alloy substrate while contributing to thermal-expansion matching across the stack. Silver, supplied as a commercially available nanoparticle ink (Novacentrix JS102A) with established space-relevant performance and a mature supply chain, was selected as the conductor for interconnects and power. The barium titanate ($BaTiO_3$) family of lead-free ferroelectric perovskites, supplied as an ink formulated by US Nano, Ltd., was selected for the multifunctional layer, which can be used for sensing and actuation functions in electronics. The printed stack was built on aerospace alloy substrates, principally titanium alloy Ti-6Al-4V and aluminum alloy Al 6061.

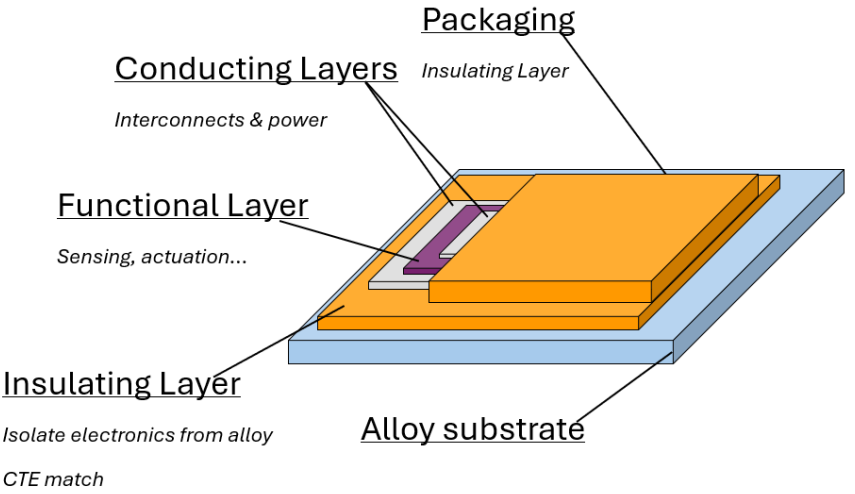


Figure 1. The COLDFRONT printed stack: alloy substrate, custom-formulated COLDFRONT insulating layer (electrical isolation and thermal-expansion matching), silver conducting layers for interconnects and power, a barium titanate functional layer for sensing or actuation, and packaging.

Thermomechanical modeling. Because the dominant failure mode under thermal cycling arises from strain created by differences in coefficient of thermal expansion, a predictive modeling capability was developed to guide materials engineering before fabrication. Temperature-dependent property models, covering coefficient of thermal expansion, elastic modulus, and related properties, were constructed from NIST, NASA, and peer-reviewed datasets spanning roughly −260 °C to +160 °C and fitted with physics-based relations. These property models fed a thermomechanical stress analysis implemented in a Python framework using classical laminate theory for the multilayer stack [22], extended

with a Stoney-type treatment for curved geometries [23], and wrapped in a Monte Carlo procedure for uncertainty quantification. The models were used to predict coefficient-of-thermal-expansion mismatch and interfacial stress at representative lunar temperatures and to identify the stack configurations least prone to thermally driven failure.

Fabrication. Printed test structures were produced by two complementary additive methods: drop-on-demand inkjet printing and direct ink writing. Inks were tuned so that their rheology fell within the operating window of the chosen deposition method, and the deposited films were subjected to a surface-activation pre-treatment by plasma and a subsequent thermal post-processing step to develop adhesion and final film properties. A custom, low-cost direct-ink-writing apparatus was constructed in-house to demonstrate materials deposition and to support rapid iteration. The direct ink writing method cannot achieve high resolution features without significant development but is suitable for large area coating of materials with millimeter-sized features.

Characterization and testing. Printed specimens were evaluated against the lunar duty cycle and against aerospace quality standards. Cold survivability was assessed by direct liquid-nitrogen thermal-shock cycling between approximately −180 °C and +10 °C, with transition and soak times varied to construct a deliberately aggressive screening regime. Adhesion was quantified by the ASTM D3359 cross-hatch tape test [24]. Dielectric behavior, permittivity and loss tangent, was measured in situ as a function of temperature down to below −180 °C. Film microstructure was examined by scanning electron microscopy, ink rheology by rotational viscometry, and electrical behavior with a microelectronics probe station.

Results

Materials selection. The scoring framework produced a clear ranking within each functional role. The material central to the COLDFRONT insulator scored 92 of 100, the silver nanoparticle conductor 90 of 100, and the chosen barium titanate functional material 61 of 100, with the lower functional-layer score reflecting the genuine difficulty of maintaining ferroelectric response across the full lunar temperature span. Approximately eighty percent of the evaluated candidates were eliminated primarily on environmental-performance grounds, underscoring how restrictive the lunar thermal and space environment is for conventional electronic materials.

Thermomechanical models. The temperature-dependent property and stress models achieved strong agreement with experimental reference data, with a correlation of $R^2 = 0.94$ across the modeled temperature range. The models reproduced the coefficient-of-thermal-expansion behavior of the alloy substrates,

the COLDFRONT materials, and standard electronic materials, and quantified the expansion mismatch at representative lunar temperatures.

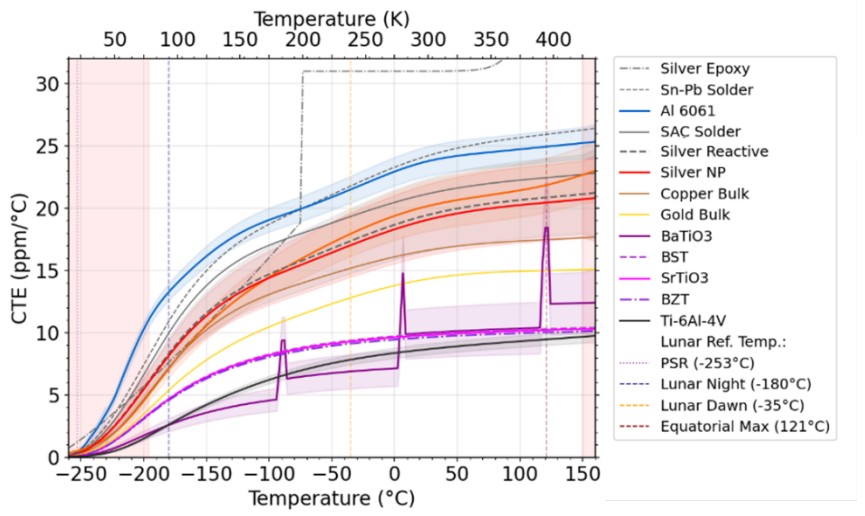


Figure 2. Modeled coefficient of thermal expansion versus temperature (−260 °C to +160 °C) for alloy substrates, COLDFRONT materials, and standard electronic materials, correlated against experimental data ($R^2 = 0.94$).

Printable insulator and process refinement. A printable formulation of the COLDFRONT insulator was developed whose rheology could be matched to the operating windows of several deposition methods, allowing the same material family to be deposited by inkjet for fine features and by direct ink writing or other higher-viscosity methods for thicker dielectric layers. Process refinement then proceeded in a deliberate order of surface pre-treatment, deposition parameters, substrate conditioning, and layer strategy, and demonstrated that the plasma surface pre-treatment markedly improved film uniformity and the statistical repeatability of the deposited features relative to untreated controls.

Cold survival. The central result of the program is that the printed COLDFRONT stack survived repeated, aggressive cold cycling with its mechanical and electrical integrity intact. Across fifteen thermal-shock cycles between −180 °C and +10 °C, printed specimens retained full adhesion and full electrical functionality, with adhesion graded at ASTM D3359 Class 5B, the highest rating, corresponding to no removal of material, both before and after exposure. In-situ measurements confirmed that the dielectric remained functional down to below −180 °C, demonstrating operation, not merely survival, at lunar-night temperatures. Some failure modes were observed wherein samples would not exhibit signs of damage after the first cycle of exposure, but show highly variable damage (i.e. an

undamaged patch next to a severely damaged patch) after repeated exposures. While there is further testing to be done, we believe that this is due to water vapor condensation on the surface which subsequently expands. This can be overcome by encapsulation using our COLDFRONT insulator and is also less of a risk in space due to the vacuum environment.

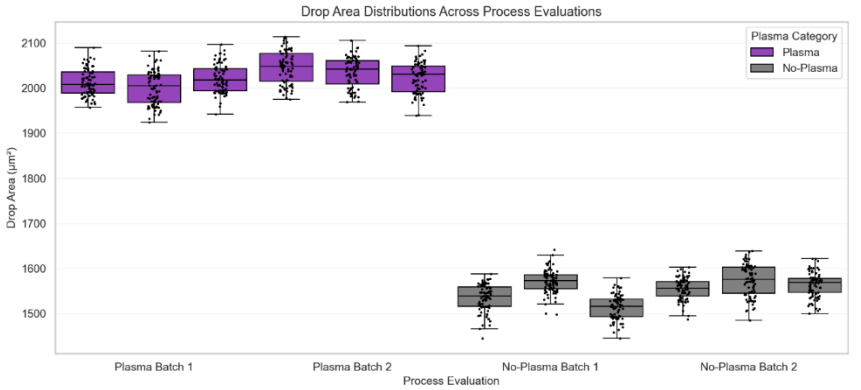


Figure 3. Effect of plasma surface pre-treatment on deposited-feature uniformity and repeatability, comparing treated and untreated specimens.

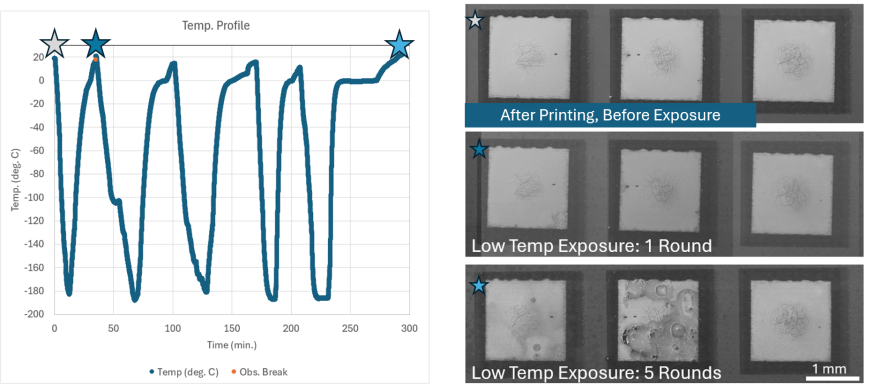


Figure 4. Representative liquid-nitrogen thermal-shock temperature profile and scanning-electron-microscope images of printed insulator and silver features before and after five cycle cold exposure.

Direct ink writing and adhesion. Direct ink writing on the custom apparatus produced printed features on the alloy substrates, and cross-hatch adhesion testing to ASTM D3359 returned a Class 5B result, confirming that the low-cost deposition route is capable of aerospace-relevant adhesion quality.

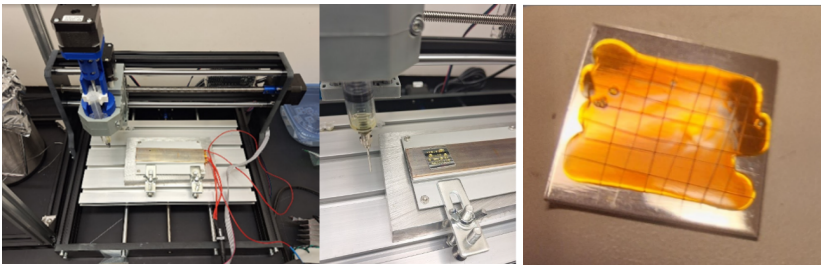


Figure 5. Custom direct-ink-writing apparatus and ASTM D3359 cross-hatch adhesion result (Class 5B, no removal).

Taken together, these results advanced the COLDFRONT concept from first principles to a demonstrated proof of concept (TRL 2–3): a deliberately expansion-matched, fully printed materials set that retains adhesion and electrical function through repeated lunar-magnitude thermal shock, produced entirely with printing methods.

Discussion

The results reported here support three principal conclusions. First, a printed electronic stack can be deliberately engineered for thermal-expansion compatibility, and doing so allows it to withstand thermal cycling of lunar magnitude: the COLDFRONT stack retained both adhesion and electrical function through repeated shock between −180 °C and +10 °C. Second, the COLDFRONT insulator can be formulated for printability across more than one deposition method while remaining mechanically robust through multi-cycle cold shock and achieving the highest grade of the ASTM D3359 adhesion test. Third, a plasma surface pre-treatment measurably improves both film uniformity and the statistical repeatability of the deposited features.

The broader implication relates to the earlier sections of this work. The competencies exercised throughout this development effort (materials selection, ink formulation and rheology control, multilayer deposition, metrology, and durability testing) are precisely the competencies of the printing industry, applied to a functional rather than a graphic purpose. That the demanding requirements of a lunar mission can be approached with this toolbox, and that low-cost deposition hardware built in-house can produce aerospace-relevant adhesion quality, suggests that the barrier to entry for printing companies and graphic communication programs is lower than it might appear. The interest in printing technology now coming from the wider engineering and scientific community is, in this light, an invitation.

Several open questions remain. Achieving a critical dielectric thickness reliably by inkjet, as opposed to higher-throughput or higher-viscosity methods, remains

a practical challenge for the insulating layer. Durability beyond the cycles demonstrated here must be established against the hundreds of cycles a long-duration surface mission would impose, and the most directly transferable benefits may in fact be terrestrial: avionics, arctic and polar systems, and low-temperature electronics such as the support circuitry for quantum devices all share the cold-survivability problem that this work addresses.

Conclusion and Future Work

This work set out to determine whether the methods of the printing industry could produce electronics capable of surviving the lunar thermal environment, and it answered that question affirmatively at the proof-of-concept level. A complementary materials set, comprising the custom-formulated COLDFRONT insulator, a silver nanoparticle conductor (Novacentrix JS102A), and a barium titanate functional material (formulated by US Nano, Ltd.) on aerospace alloy substrates, was selected against a structured environmental-performance framework, modeled for thermal-expansion compatibility with strong agreement to experimental data, fabricated by inkjet and direct ink writing, and demonstrated to retain adhesion and electrical function through repeated cold-shock cycling to −180 °C. In the language of technology maturation, the concept advanced from basic principles to a demonstrated proof of concept.

Future work proceeds along three lines. The first is the fabrication of functional sensor demonstrators, among them a printed radiation detector and a printed pressure sensor, that move the materials set from coupons toward devices. The second is the development of new printing capability, including non-planar direct ink writing for conformal deposition onto curved structures and progress toward in-situ processing compatible with in-space manufacturing. The third is durability: extending thermal-cycle testing toward the several-hundred-cycle target representative of a long-duration surface mission, supported by cycle-fatigue modeling. In parallel, the materials set is being matured toward a product in cooperation with a commercialization partner, and the authors are actively seeking industrial and institutional collaborators to advance these and other novel applications of printing technology.

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