Journal of Imaging Science and Technology® 69(2): 1–7, 2025.

Writing for the Future. What are the Options?

Barry M. Lunt, Felipe Riviera, Joshua Santos, Armando Carreon, Joshua Isaacson, and Matthew R. Linford
Brigham Young University, Provo, UT 84602
E-mail: luntb@byu.edu

Abstract. *An ideal archival storage system combines longevity, accessibility, low cost, high capacity, and human readability to ensure the persistence and future readability of stored data. At Archiving 2024 [B. M. Lunt, D. Kemp, M. R. Linford, and W. Chiang, "How long is long-term? An update," Archiving (2024)], the authors' research group presented a paper that summarized several efforts in this area, including magnetic tapes, optical disks, hard disk drives, solid-state drives, Project Silica (a Microsoft project), DNA, and projects C-PROM, Nano Libris, and Mil Chispa (the last three being the authors' research). Each storage option offers unique advantages in each of the desirable characteristics. This paper provides information on other efforts in this area, including the work by Cerabyte, Norsam Technologies, and Group 47 DOTS, and an update on the authors' projects C-PROM, Nano Libris, and Mil Chispa.*
Keywords: *preservation, longevity, cost, capacity, readability*

[DOI: 10.2352/J.ImagingSci.Technol.2025.69.2.020402]

1. INTRODUCTION

Each of the desirable characteristics (see Abstract) of an ideal archival storage system deserves some context in the area of archival storage. Longevity refers to the need for the system to preserve data for decades or even centuries without degradation. This includes not only the physical media's durability but also the ability to maintain the integrity of digital formats that may become obsolete over time [1].

Data stored in an archival system must remain accessible and readable over time. This is accessibility, which includes not only the physical ability to read storage media but also ensure that file formats do not become obsolete [2]. One of the best ways to ensure long-term accessibility is to store the data in human-readable formats. For the purpose of this research, human-readable means that the only instrument necessary for reading the data back is an appropriate magnifier.

Cost is always an issue, and proposed solutions that are not economically viable are not practical. At the same time, it is acknowledged that storing data for archival purposes is not a consumer-level issue and thus archival solutions would be more expensive than consumer-level solutions [3].

Capacity often goes hand in hand with cost. An archival solution that does not have high capacity (also meaning high density and scalability) would be unreasonably expensive for storing all the world's documents [4].

Received Nov. 15, 2024; accepted for publication Mar. 30, 2025; published online Apr. 30, 2025. Associate Editor: Rita Hofmann-Sievert.
1062-3701/2025/69(2)/020402/7/$25.00

2. LONG-TERM STORAGE EFFORTS

2.1 *Cerabyte*

Cerabyte [5] uses nanolayers of ceramic material on glass as the storage medium. Data is converted to a data matrix, which is then written onto the storage medium with ultra-short laser beam pulses together with off-the-shelf digital mirror devices, which ablates the ceramic nanolayer and enable writing up to 2 Mbits per pulse (Figure 1). This results in an overall write rate comparable to or faster than modern LTO tapes and hard disk drives (HDDs). For readback, a microscope optic, high-speed illumination, and an ultra-fast high-resolution image sensor work together to retrieve data at speeds matching or exceeding those of today's LTO tapes and HDDs. Unlike Nano Libris, which prioritizes nanoscale precision over speed, Cerabyte balances efficiency with long-term durability [6].

Given the nature of the storage medium of a ceramic nanolayer on glass, they expect the data to persist in the neighborhood of 5,000 years, but real-world validation requires extensive testing. Studies on ceramic durability in historical artifacts and semiconductor industries indicate that dense ceramic layers resist physical wear and oxidation over millennia, making Cerabyte's projections reasonable [7]. However, archival longevity also depends on readback technology survivability. Unlike human-readable solutions, Cerabyte requires a high-resolution imaging system and digital decoding algorithms for retrieval.

2.2 *Norsam Technologies*

Norsam Technologies [8] is a company that is focused on providing archival storage solutions in non-standard formats. Their products serve organizations in microscopy, semiconductor manufacturing, metrology, materials science, and research. Their data storage services are often used for the storage of religious documents or texts for very prolonged periods. Their technology uses focused-ion beam (FIB) tools to write at resolutions down to about 500 nm. They have shown the ability to create either analog or digital marks on thin metals and ceramics among other materials.

Given the nature of the writing tool (FIB) and the materials it writes on (metals and ceramics), it is estimated that such writings will last a very long time (at least hundreds of years) and that their scalability is limited by the number of FIBs they have to write with. Figure 2 is a good example of what they are able to produce. The characteristics of the Norsam technology are summarized in Table I. The authors of this paper were not able to find a standard format or substrate for their data storage.

Table I. A comparison of several characteristics of the storage technologies included in this paper.

Technology	Longevity (years)	Accessibility	Human readability	Read/Write speed	Cost/GB	Capacity/Scalability
HDDs	3–5	Online	No	Very high	Very low	Very high
SSDs—Mil Chispa	1,000?	Online	No	Very high	Very low	Very high
Optical disks (ODs)	10–20 (normal); 1000 (M-DISC)	Online or Nearline	No	Medium	Low	Average; limited by capacity of ODs
Magnetic tape	10–30	Online or Nearline	No	Very high	Very low	Very high
Project Silica	100,000	Nearline	No	High	Medium	Very high
DNA	100,000	Nearline	No	Very low	Low	Very high
Cerabyte	5,000	Nearline	No	High	Medium	Very high
Norsam Technologies	1,000	Service	Yes	Low	Medium	Limited by FIB writing
Nano Libris—FIB	1,000	Service	Yes	Very low	Medium	Limited by FIB writing
Nano Libris—FED tips	1,000	Service	Yes	Very high	Medium	Limited by number of FED tips

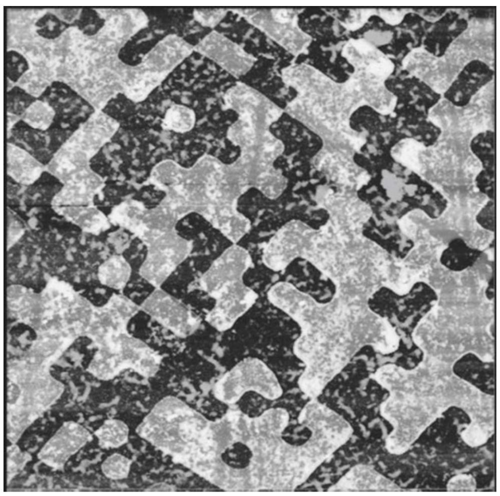

Figure 1. An SEM image of the recorded data layer of the Cerabyte recording medium (from https://www.cerabyte.com/press-kit).

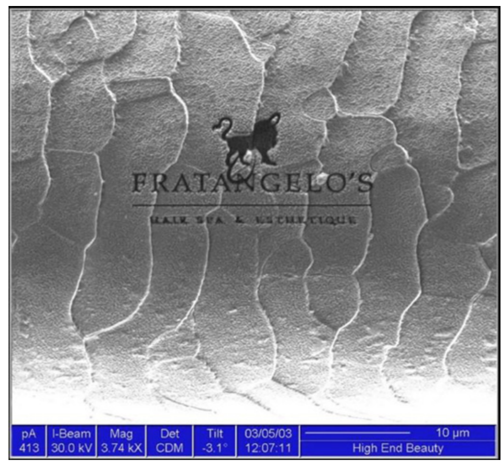

Figure 2. Norsam Technologies inscribed a hair-styling salon's logo on a human hair. Note that the scale of the entire image is about 20 × 10 μm (from their website at https://norsam.com/services/artifacts-and-inscriptions/).

2.3 *Project Silica*

Project Silica (Microsoft) [9] was discussed in our paper from Archiving 2024. Their technology stores data on glass with femtosecond laser etched lines that can be decoded and read digitally. This has been a great step forward for long-term storage because the data is said to cause a permanent change to the glass and the data can be stored at high density (about 7 TB in a glass platter about 4 in^2). One of the issues, however, with this emerging technology is that the data must undergo error correction [10] since it is still stored digitally, which means that files can become corrupted by bit errors. Additionally, the very complicated readback technology has to survive along with the glass. All of the decoding, light readers, and the machine learning algorithms that they use must still be in service for the data to persist and be accessible in the future.

2.4 *Group 47 DOTS*

Group 47's Digital Optical Technology System (DOTS) [11] offers a long-term data preservation solution by recording information onto metal alloy tapes in a human-readable format. This method ensures data stability for over a century without reliance on controlled environments, as the medium is resistant to extreme temperatures and environmental factors. The technology has progressed beyond the prototype stage, with successful laboratory demonstrations, including a contract with the CIA to build a laboratory prototype proving the DOTS technology. The projected density would be about 1.2 TB on an LTO-type cartridge or about 54 such cartridges to store the contents of the US Library of Congress.

2.5 *Folio Photonics*

Folio Photonics [12] has pioneered an enterprise-scale optical storage solution utilizing multi-layer disk technology. By leveraging advancements in materials science, their approach enables dynamic multi-layer read/write capabilities, significantly enhancing data density and access speeds. This innovation positions their technology as a cost-effective alternative for active archival storage, with medium costs projected at $3 per TB and a roadmap

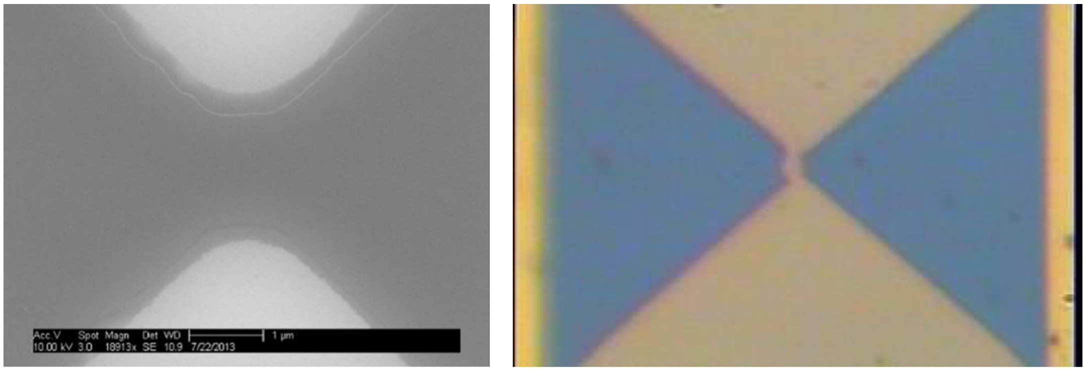

Figure 3. Intact carbon fuse on the left; blown fuse on the right. These fuses can eventually be made incredibly small, similar to the scale of today's flash memory cells.

aiming for less than $1 per TB. As of early 2023, Folio Photonics showcased this technology at CES 2023, indicating a transition from development to commercial availability. It is not human-readable technology. They project a capacity of 1 TB for an individual disk, and when packaged in 10-disk caddies, the capacity would be about 10 TB or about one-sixth the contents of the US Library of Congress.

2.6 *Piql*

Piql [13] specializes in ultra-secure, long-term data storage solutions by writing digital data onto high-resolution photosensitive films in binary. This film medium is designed to last for centuries, offering resilience against technological obsolescence and environmental degradation. Each Piql film comes with human-readable instructions that can be accessed with even just a magnifying glass, for decoding the digital files to further protect it from technological obsolescence. Piql's services are commercially available, providing clients with a unique approach to data archiving that emphasizes longevity and security. The medium is a 35-mm film known as piqlFilm, with each reel being 950 m in length with a capacity of 120 GB per reel. This would be approximately 1/60th the contents of the US Library of Congress on each reel.

3. BYU RESEARCH EFFORTS

3.1 *C-PROM*

This technology was developed at the Brigham Young University (BYU) several years ago (patented in 2013), and it uses a carbon-based material for the cell that stores each bit (Figure 3). The carbon-based material solves dendrite-related reliability problems of early (1970s) PROMs, and is projected to store data for 1000 years. Because the cell that stores each bit is very scalable using today's IC manufacturing processes, the future density is very high although today's prototypes are only capable of storing 8 MB.

3.2 *Nano Libris*

Nano Libris is our solution to long-term storage that is human-readable, of high density, accessible, and eventually inexpensive. As its name implies, Nano Libris is just that, writing really small books on a unique type of half-inch tape for the purpose of data storage. Writing at the nanoscale can be done with FIB, electron beam (E-beam), or 3D printing with two-photon polymerization (TPP) on metal-coated Mylar (polyethylene terephthalate [PET]) or Kapton® (polyimide) tape. The FIB, E-beam, and TPP writing technologies each allows for nanoscale precision due to their unique ability to manipulate matter at extremely small dimensions. The FIB writing achieves this by directing a finely focused beam of ions, typically gallium, which can physically mill and modify material surfaces at the sub-micron scale, enabling highly precise and controlled patterning. Similarly, E-beam writing uses a narrow electron beam to achieve nanometer resolution, ideal for creating extremely small and detailed structures on various surfaces. In contrast, TPP writing uses a high-intensity laser to polymerize photosensitive materials within a targeted nanoscale resolution, allowing for intricate structuring. The TPP option is still very much in the preliminary stages of research while FIB and E-beam writing are being developed. Together, these technologies have the potential to allow Nano Libris to achieve the fine detail and density required for storing data at the nanoscale, making them highly suited for durable and compact data storage solutions on materials like metal-coated Mylar or Kapton tape.

Mylar and Kapton tapes were selected for their durability in archival applications. Mylar tape has been used for decades in data storage due to its resistance to heat, humidity, and mechanical stress, withstanding temperatures from −73° to 150°C [14]. Kapton tape offers even greater thermal resistance, making it ideal for long-term data preservation.

The use of chrome as a thin-film metal-coating solution is rather appealing due to its properties. Thin chromium films are very adhesive, a property that has significant appeal because if we wanted data to last a long time, we need the material to stay adhered in place, especially because of the flexible film state of half-inch tape. Other materials might flake off or rub off, unable to flex with the tape. Chrome is also a very hard element, resistant to corrosion and tarnishing, which also proves its application for long-term

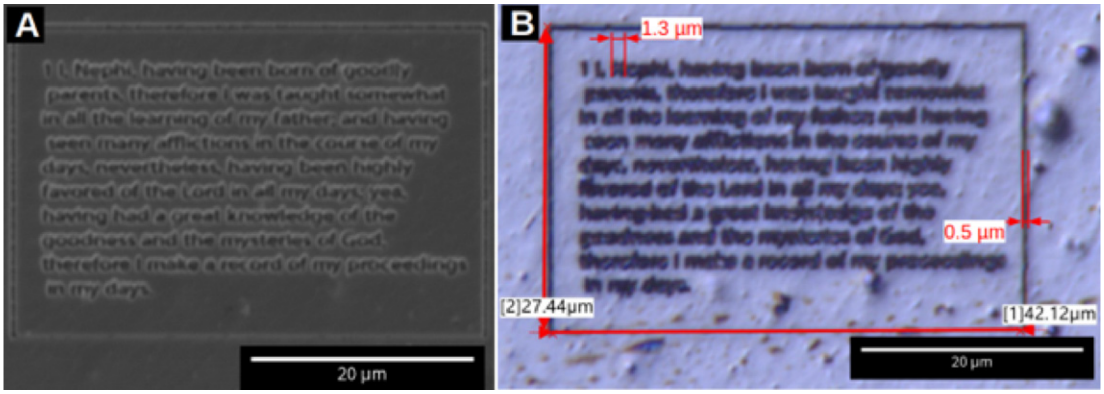

Figure 4. (A) Ion micrograph of an FIB-patterned 27 μm × 42 μm text box onto a 15 nm thick Cr layer on Mylar. (B) Optical image of the same patterned region. The achieved patterned line width is approximately 0.5 μm. Image B was obtained on a Keyence VHX-7000 microscope.

data storage. Lastly, chrome is also inexpensive, which is clearly not the case for the noble metals. Other materials are also being studied.

To date, we have attained initial and quite promising results from FIB writing on chrome-coated Mylar. Figure 4A shows an FIB-patterned text box approximately 42 μm long by 27 μm wide. This patterning took place in a first-generation Helios NanoLab 600 DualBeam FIB/SEM from FEI equipped with a gallium liquid metal ion source. In the attempt shown in Fig. 4A, the text box was patterned utilizing an ion accelerating voltage of 15 kV and a current of 0.22 nA. Under these parameters, a line width of approximately 500 nm was achieved; writing characters were approximately 1.3 μm wide by 1.6 μm tall (using the "N" character as reference). The same region was further imaged using a Keyence VHX-7000 optical microscope as shown in Fig. 4B. The contrast observed in the optical image suggests that it is a promising method for producing area-dense yet human-readable text that is visible and readily accessible via relatively inexpensive optical imaging methods.

Writing in a single 27 μm × 18 μm text box under these parameters took approximately 9 min, yielding a write speed of about 0.09 $\mu m^2/s$. Although this is significantly slower than conventional storage technologies such as HDDs (∼200 MB/s) and magnetic tapes (∼400 MB/s), it is comparable to other high-precision nanolithography methods. The trade-off for this slower write speed is an exceptional level of data density and longevity, making Nano Libris a viable solution for archival storage where optical contrast and readability is the primary concern.

Figures 5A and 5B demonstrate additional attempts at FIB text-box patterning, driving the resolution of finer patterned lines. In Fig. 5A, using the same starting ion-beam parameters of 15 kV and 0.22 nA, the ion beam was focused to attain a line width of approximately 250 nm, with the "N" character measuring roughly 900 nm × 1100 nm in size. In Fig. 5B, the ion-beam current was lowered from 0.22 nA to 45 pA, achieving a focused beam to yield a line-width spatial resolution in the neighborhood of 120 nm and an "N" character 600 nm tall.

To achieve optimal contrast and line sharpness as demonstrated in Figs 4 and 5, we followed a specific preparation procedure. First, we placed double-sided carbon tape on the top surface of the SEM stub mount and then applied blank Mylar tape on top, leaving a portion of the carbon tape exposed to ensure proper grounding from the deposition surface on the Mylar tape to the stub mount. We then cleaned the Mylar surface in a plasma cleaner for 30 s to enhance adhesion for the deposition. After this, we deposited a 15 nm layer of chrome on the Mylar tape by placing the stub in a sputter coater. Once coated, the sample was ready for patterning with an FIB. The FEI Helios NanoLab 600 DualBeam FIB/SEM is the ion-beam microscope that we used to write on the chrome samples. We loaded a bitmap file into the microscope's software to serve as the milling pattern for the chrome layer. After milling, the patterned chrome on the Mylar tape could be viewed under a microscope—SEM or optical depending on the resolution of the writing.

We have been able to produce readable words with good contrast and good letter edges where each letter is about the size of 800 × 800 nm, but we expect that we will be able to write even smaller to the scale of 100 nm letters as we continue fine-tuning our FIB settings and with the help of E-beam writing technology. The 100 nm characters would be smaller than the achievable spatial resolution of optical microscopes (Fig. 4 shows the capabilities of optical microscopes for readback) and must be viewed with a scanning electron microscope. Looking forward to future applications of our technology, we have considered writing within the visibility of optical microscopes to improve accessibility to archived data. For the purpose of high density, the letters would be as small as 100 × 100 nm. The cutting edge of magnetic tape storage boasts 580 TB of storage on 9.44 μm^2 of magnetic tape with a density of 317 billion bits per square inch (https://techxplore.com/news/2020-12-fujifilm-ibm-unveil-terabyte-magnetic.html). If we were to write at 100 × 100 nm per letter, we could fit 9.44×10^{14} letters on that same piece of magnetic tape. If each letter represents a byte of data, that would equate to about 944 TB, which would be 1.5 times the amount of

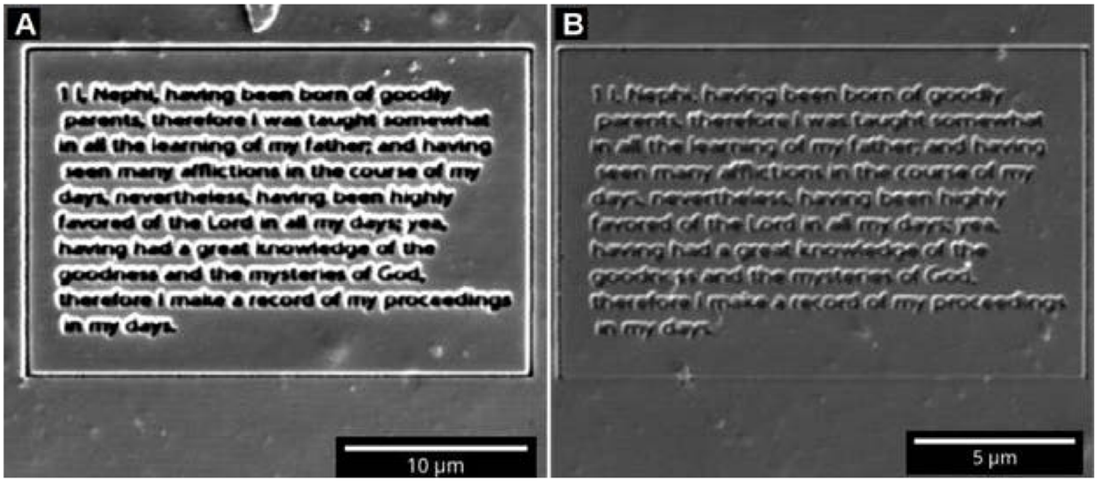

Figure 5. Additional attempts reducing the size of the patterned text box. Patterned character line widths are approximately (A) 0.25 μm and (B) 0.13 μm.

storage achieved by the leaders in magnetic tape density while being human-readable.

Future considerations for Nano Libris include the challenge of large-scale E-beam patterning. Our results using FIB patterning demonstrate that nanoscale feature definition and fidelity can be reliably achieved, suggesting that E-beam patterning should also be viable. Ion beams offer higher mass and momentum, allowing for direct material removal and precise milling; electron beams use lighter and smaller particles, which may increase write times. Despite these differences, both techniques achieve sub-10 nm resolution, reinforcing the feasibility of E-beam lithography for Nano Libris. Additionally, given that E-beam lithography is already widely used for high-resolution nanofabrication, it offers a promising pathway for scaling Nano Libris while maintaining the precision required for data encoding. Although these technologies offer exceptional precision, they are inherently slow and costly. For instance, with our current FIB setup, writing a 27 nm × 18 nm section takes approximately 9 minutes. Moving forward to large-scale archival data, this could turn into an impractically long production time for high-volume storage needs. Moreover, FIB machines operate at costs ranging from $50 to $300 per hour, significantly impacting economic feasibility.

To improve scalability, a promising approach is parallelized writing. One potential solution involves adapting field-emission display (FED) technology, which utilizes multiple nanoscale electron emitters to write data using electron beams simultaneously. This method could increase efficiency while reducing production costs, making large-scale Nano Libris implementation more feasible.

Field-emission displays (see Figure 6) use microtips to emit electrons and hit a phosphor-coated screen, which emits light to produce an image on the screen. The pixels are controlled by the voltage of the tips and the gate that the electrons pass through to get to the phosphor layer. What we find useful about the FED is its electron-emission capability. The FIB and the E-beam essentially do the same thing—emit

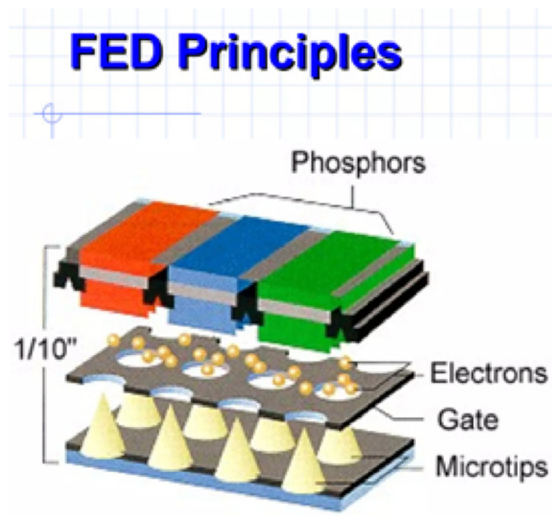

Figure 6. Schematic of an FED (from https://www.slideshare.net/slideshow/fed-ppt/34815967).

electrons (or ions) to remove the chrome layer to write letters. Because the FED is basically an array of electron-emitting tips, we expect that it can mill several letters at a large scale and increase the rate of writing data by many orders of magnitude.

Compared to other archival storage solutions, such as those from Norsam Technologies and Cerabyte, Nano Libris offers a robust approach that could be more widely accessible as its tape format and larger scale writing with the FED would be more suited to archival storage. Though Norsam very similarly uses FIB to store data on metals and ceramics, achieving marks as small as 500 nm and capable of lasting centuries, its application is more for novel art pieces with scalability limited by equipment. Cerabyte utilizes a ceramic nanolayer on glass with ultra-short laser pulses, enabling rapid data writing and reading at speeds comparable to LTO tapes and HDDs, with a projected lifespan of up to 5,000 years. However, Cerabyte's drawback is that the readback technology would also need to survive the 5,000 years. Together, these storage methods demonstrate that high-resolution, durable materials like those used in Nano Libris represent a viable and lasting solution for permanent data storage across various fields.

The 3D printing technology offers intriguing possibilities for archival data storage by enabling the precise creation of microscopic text and patterns on durable substrates. By leveraging advanced 3D printing methods, it is possible to store information in a compact, long-lasting format. However, different 3D printing techniques, such as high-resolution stereolithography and TPP, vary in their mechanisms and applications for archival purposes.

One approach involves using traditional high-resolution 3D printing techniques like stereolithography or digital light processing to create microscopic text on robust substrates. These methods utilize ultraviolet or visible light to selectively harden a photosensitive resin, building up tiny three-dimensional letters layer by layer. These nanoletters can withstand environmental factors better than traditional ink-based printing, and their raised nature provides an additional layer of readability as it can be discerned tactilely or through advanced imaging techniques even if surface discoloration occurs over time. A significant drawback of this approach, however, is the potential difficulty in achieving consistent quality at such a small scale, as any imperfections in the raised text could hinder legibility.

The TPP technology is a more advanced 3D printing technique that offers significantly higher precision for archival storage. Unlike standard 3D printing methods, TPP uses a femtosecond laser to induce polymerization at precise focal points within a photosensitive material through two-photon absorption. In this process, two lower-energy photons are absorbed simultaneously at the laser's focal point, triggering a chemical reaction exclusively at that point. This allows for the creation of intricate nanoscale patterns with sub-micrometer accuracy, far exceeding the resolution of conventional 3D printing methods. The resolution of features of sub-100 nm has been demonstrated by other researchers using TPP [15], which means that the throughput of data storage would be equal to or potentially higher than the throughput demonstrated in Nano Libris using FIB milling. For archival purposes, this technique could theoretically be applied to a Mylar substrate.

To utilize TPP for writing data on Mylar, the film must first be coated with a thin layer of a photosensitive polymer, which could be applied through techniques such as dipping or vapor deposition. The laser system, often incorporating spatial light modulators and lenses, focuses the laser beam to fabricate nanosized letters or patterns within this coating. Once the writing process is complete, the unexposed polymer is washed away, leaving behind a durable, high-resolution pattern. However, challenges such as ensuring uniform coating thickness and maintaining the flatness of the Mylar surface during laser writing are crucial for consistent results [16]. This method, though potentially costly due to the precision required in laser systems and materials, offers another potential alternative for creating long-lasting, human-readable data formats suitable for archival storage.

The Nano Libris technology can also be used to write binary bits. The format for this type of writing has not been formalized, but we would seek to make it self-describing and as simple as possible. The readback hardware for the Nano Libris technology would embrace the tape movement equipment used in LTO tapes and the concept of a microfilm reader—the user simply scans to the region of the tape they are interested in and then reads and copies as desired. The tape would also contain an index that could be read manually or by automation. We have shown that an optical microscope can produce excellent images of very tiny letters on the tape.

3.3 *Solid-State Storage (Mil Chispa)*

Our team's Solid-State Drive research focuses on determining the longevity of data stored on solid-state drives (SSDs) under controlled conditions aimed at simulating extended periods of aging. This study was initiated upon reading in Mizoguchi et al. [17] that writing only once to SSD storage could allow that data to persist for a millennium. Accordingly, we are investigating whether data written to an SSD only once can withstand read cycles for hundreds or thousands of years without corruption or degradation. To evaluate this, we place SSDs in an oven set to 106°C, simulating accelerated aging at about 256 times faster than the actual time. We determined this temperature based on the Arrhenius equation, which states that an increase of 10°C equates to an approximate doubling of the simulated aging time, and because 106°C is well below the glass transition temperature of the SSD package. This accelerated aging process uses specific scripts to periodically monitor drives, analyze Self-Monitoring, Analysis, and Reporting Technology (SMART) attributes, and graph the results, offering insight into SSD data retention and the impact of environmental stresses. These SMART attributes provide insights into drive health by condensing values—such as the Raw Read Error Rate—into interpretable metrics from 0 to 100, where declines indicate degradation. By tracking these attributes, we aim to observe the rate and pattern of deterioration under extreme conditions. Through our oven-based aging technique, each 6-hour cycle represents approximately 1 year of natural aging.

The experimental procedure involves several key phases. First, a baseline measurement is conducted to assess the initial data integrity and log the electrical characteristics of the SSDs. Following this, the heating cycle begins, where the SSDs are placed in a Tenny Jr. oven set at 106°C for a duration of 6 hours, simulating 1 year of aging. After 1 hour of cooling down from the heating cycle, read cycles are performed using a Python script, running the specified number of read cycles for each drive. During the data collection phase, SMART data is gathered after each heating and read cycle. Finally, in the data analysis phase, the collected SMART attributes are examined to detect any abnormal behavior or signs of degradation. The procedure involves doubling the simulated aging time with each cycle.

This research will contribute to understanding SSDs' viability as long-term data storage solutions. The use of high-temperature testing and read-cycle monitoring allows us to approximate the lifespan of SSDs in read-only applications, advancing the field's knowledge of solid-state memory endurance especially for archival storage.

4. SUMMARY

Table I presents the desirable characteristics discussed above and the performance of each of the technologies discussed in this paper and Ref. [1] along with our assessment of these technologies in each characteristic.

The characteristics listed in Table I are described as follows. Longevity refers to how long the data will persist on the media; the persistence is with regard to both the physical media and the contrast required for the data to be readable. Accessibility refers to how the data is normally provided to the technology, where Online basically means Tier 1 or 2; Nearline means Tier 3; and Service means Tier 4 or 5. A Yes on Human readability means that only an appropriate magnification device is needed. For Read/Write speed, Very high is roughly 50 MB/s or higher; High is between 10 and 50 MB/s; Medium is between 1 and 10 MB/s; Low is between 1 kB/s and 1 MB/s; and Very low is lower than 1 kB/s. Cost/GB is a relative measure only, as the actual values change quickly with time and vendors. Capacity/Scalability refers to the expected future capacity of the storage technology.

In summary, Cerabyte, Norsam Technologies, DOTS, Project Silica, Folio Photonics, Piql, C-PROM, Nano Libris, and Mil Chispa each represents promising advancements in the field of archival data storage, leveraging unique technologies to address the challenges of durability, readability, and data density. Together, these projects represent the future of archival storage, each addressing specific needs and limitations and pushing the boundaries of how we preserve information for generations to come.

ACKNOWLEDGMENT

The authors acknowledge and greatly appreciate the imaging services provided by the Electron Microscopy Facility at BYU and the close collaboration with Dr. Felipe Rivera of this facility. They also acknowledge the funding by the Department of Chemistry and Biochemistry of BYU.

REFERENCES

[1] B. M. Lunt, D. Kemp, M. R. Linford, and W. Chiang, "How long is long-term? – An update," *Proc. IS&T Archiving 2024* (IS&T, Springfield, VA, 2024).

[2] W. Jansen, "The 100-year archive dilemma," Computerworld (2017). https://www.computerworld.com/article/1693754/the-100-year-archive-dilemma.html.

[3] K. Thibodeau, "Overview of technological approaches to digital preservation and challenges in coming years." The State of Digital Preservation: An International Perspective," *Council on Library and Information Resources* (2002).

[4] D. S. H. Rosenthal, "Bit preservation: A solved problem?," Int. J. Digit. Curation **5**, 134–148 (2010).

[5] https://www.cerabyte.com/wp-content/uploads/2024/08/Cerabyte-white-paper.pdf.

[6] StorageNewsletter. Cerabyte: Transformative ceramic-based technology for accessible permanent storage. StorageNewsletter (2024).

[7] Structural Ceramics. Wear resistance of ceramics. Structural Ceramic (n.d.). Retrieved March 4, 2025, from https://structuralceramic.com/materials-performance/wear-resistance/?utm_source=chatgpt.com.

[8] Norsam Technologies. *Artifacts and inscriptions* (n.d.). https://norsam.com/services/artifacts-and-inscriptions/.

[9] The International Roadmap for Devices International Roadmap for Devices and Systems 2023. Update mass data storage the IRDS is devised and intended for technology assessment only and is without regard to any. (p. 94). (n.d.). Retrieved February 1, 2025, from https://irds.ieee.org/images/files/pdf/2023/2023IRDS_MDS.pdf.

[10] While a discussion of error correction and its capabilities and versions is beyond the scope of this paper, the reader is referred to an excellent entry in Wikipedia: https://en.wikipedia.org/wiki/Error_correction_code.

[11] What is dots? Group 47. (n.d.). https://group47.com/what-is-dots/.

[12] Folio. Technology (n.d.). Retrieved from https://foliophotonics.com/.

[13] Piql. Technology (n.d.). Retrieved from https://piql.com/about/technology/.

[14] PolymerFilms. *PET Films for PV & Solar* (n.d.). Retrieved February 26, 2025, from https://polymerfilms.com/product/pet-pv-solar/.

[15] M. Rabinovich and O. Spatscheck, *Web Caching and Replication* (Addison-Wesley, 2002).

[16] S. O'Halloran, A. Pandit, A. Heise, and A. Kellett, "Two-photon polymerization: fundamentals, materials, and chemical modification strategies," Adv. Sci. **10**, 2204072 (2023).

[17] K. Mizoguchi, T. Takahashi, S. Aritome, and K. Takeuchi, "Data-retention characteristics comparison of 2D and 3D TLC NAND flash memories," *2017 IEEE Int'l. Memory Workshop (IMW)* (IEEE, Piscataway, NJ, 2017), pp. 1–4.