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# Eternal Memory: Long-Duration Storage Concepts for Space

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## ETERNAL MEMORY: LONG-DURATION STORAGE CONCEPTS FOR SPACE

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Eternal memory is information encoded in some medium and capable of surviving in storage for a very long time. This paper explores the rationales for an eternal memory concept for space and also develops three concepts for it using product development methodology. Historical development drivers for data storage are storage density and processing speed, while longevity of data has been limited to decades. Recent advances in storage technologies, such as optical storage and DNA storage, allow data storage for timescales of millions to billions of years. Eternal memory concepts for space are of interest to initiatives such as Lunar Mission One, the Long Now Foundation and the Human Document Project. The recent technological advances and the focused initiative of these projects produces a gap for the development of eternal memory concepts for space. The study first identifies potential stakeholders, such as Lunar Mission One, the Long Now Foundation and the Human Document Project, and categorizes stakeholders by motivation. Stakeholder needs are interpreted from statements of motivation. Stakeholders want an eternal memory concept to encourage global public engagement, to move humanity toward becoming a dual-planet species, to embrace and constrain the information age, and to allow storage of information for a very long time. These needs are arranged hierarchically for each stakeholder and the most prevalent needs are selected. Metrics are then assigned to each need. A suggested storage technology and storage location are recommended for each case study. Each storage concept attempts to add value to stakeholders, addressing financial, scientific, technological, and socio-cultural needs.

### I. INTRODUCTION

Eternal memory is information encoded in some medium and capable of surviving in storage for a very long time (Figure 1). Motivations for space eternal memory include communication with extraterrestrials (Sagan, A Message From Earth, 1972), stimulation of the human spirit (KEO, 2015), and crowdfunding efforts for new entrepreneurial pursuits (Lunar Mission One, 2015). The Voyager and Pioneer probes set a precedent for space time capsules in the 1970s, carrying selected visual and audio messages away from the Earth and across the galaxy. Though it is estimated that these probes will still traverse the universe in half a billion years, there is only a remote chance that these probes will ever meet an advanced spacefaring nation (Sagan, Murmurs of Earth, 1978) or that humans on Earth will communicate with the spacecraft again.

Contemporary eternal memory projects strive to operate within the scope of human agency. The Long Now Foundation, founded in 1996, dedicates itself to thinking about long-term archiving (Kelly, 2008). The Long Now Foundation's archiving projects

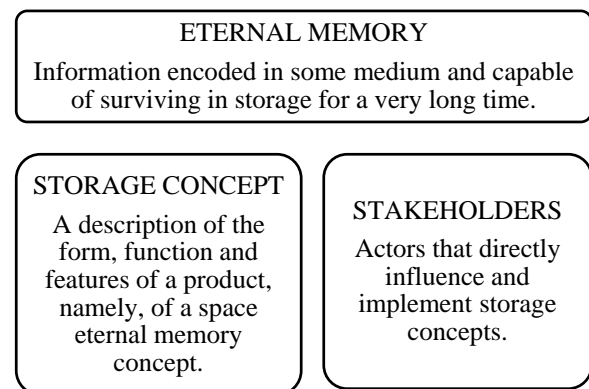


Figure 1: Important definitions.

are terrestrial, although they are interested in thinking about the questions and design demanded by a space eternal memory concept (Welcher, Browseable DVD Version of the Rosetta Disk now available, 2008). The recently proposed Lunar Mission One project seeks to preserve publically-sourced 'digital memory boxes' and human hair as well as a comprehensive record of human history. They also seek to use pioneering robot

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\*Contact author

technology and to inspire global science education. The storage of human information is a product for the general public and provides a source of revenue to support mission costs (Lunar Mission One, 2015). A loosely conjoined group of university professors and multidisciplinary enthusiasts have formed the Human Document Project, which seeks to preserve a document about humankind for one million years (Human Document Project, 2014). Project organizers express skepticism over storage in space, but also articulate a need for redundancy and security for the preserved document (Manz, 2015).

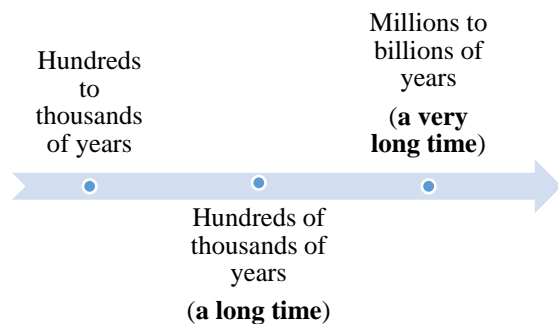


Figure 2: Defining "a very long time."

Alongside these ongoing questions of how and where to preserve, longevity of storage technologies has increased in the last five years. Current digital data storage systems are capable of storing huge amounts of data, but the longevity of the data is limited to decades (de Vries, 2013). The aim of this research is to explore the rationales for and challenges of a space eternal memory project, to evaluate possible storage concepts, and to investigate the implementation of selected ones for stakeholders. As depicted in Figure 2, timescales of an eternal memory concept are on the order of hundreds of thousands to billions of years. This is not the time scale of concern to most humans. However, increased longevity for storage could provide practical global applications. For example, contracts made between two nations often have to be replicated and restored every couple of decades and this is legally complicated (Manz, 2015). Recent attempts to fabricate long-duration storage disks with embedded data and to prove the data will not disappear for a million to billion year time frame have been promising. The technologies used vary from tungsten embedded in a silicon-nitride (de Vries, 2013) to femtosecond laser writing on transparent material (Zhang, 2013) to DNA microchips (Church, Gao, & Kosuri, 2012).

The combination of space eternal memory stakeholders (see Figure 1) and emerging long-duration storage technologies set the stage for the

explorations in this research. This paper begins by exploring the rationales for a space eternal memory concept, with the assumption that motivation will inform design. This paper also generates three space eternal memory concepts (see Section VI). Space eternal memory demands different questions and design than terrestrial eternal memory, although some questions are the same. Critical issues for concept design include how the content will be selected, how content will be decoded and read many years in the future, where the information will be stored and in what form, how the storage device will be protected in its space environment, and how the storage device will be distributed and found. Although the space environment offers a safer barrier against erasure in terms of pressure and chemical reactions, the space environment has extreme temperature and radiation. Space offers security to eternal memory, but raises questions of discoverability.

It is an important assumption of this paper that space will be colonized by humans within the next million years and that space can be a valuable storage location for human preservations. It is also assumed that one million years ahead can be precisely extrapolated for geology and astronomy. One million years back is also assumed to be similar to one million years ahead for biology (Manz, 2015). These assumptions will help in the analysis of where to store information in space and how future humans will potentially read the information. This paper will provide conceptual recommendations for space eternal memory. Further research on specific space environments and laboratory testing of storage device design is necessary before system-level and detailed design, testing and refinement, production and implementation can be possible. It is the hope that this research will be a part of that eventual implementation of a space eternal memory concept.

## II. METHODOLOGY

Since the project vision is toward an actual launch of eternal memory into space, product development methodology is used in this analysis. The goal is to develop a concept with value to stakeholders. The product is the space eternal memory concept.

This review uses methodology developed for interdisciplinary product development by Karl Ulrich and Steven Eppinger (1995). Their text was chosen because these authors attempt to integrate both product development theory and product development practice, recognizing that a purely theoretical approach is ineffective.

Although the methodology is based on that of product development, it has been modified as seen below in Figure 3 for the purposes of a concept

development process. The challenge of modification is appropriately segregating and specifying the stakeholder needs for different parts of the entire storage concept. The storage device, instead of being the product to be developed, is only part of the whole storage concept, in addition to other factors such as content, storage location, and decoding method.

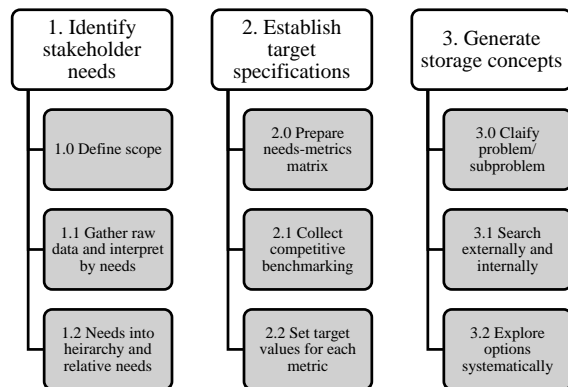


Figure 3: Product development methodology steps and substeps used.

### III. EXISTING STORAGE TECHNOLOGIES

From efforts in spoken language and their written analogues to the digitization of zetabytes, information storage provides a shared set of norms and tools for expressing ideas about the world in which we live (Evers, 2014). The goals of technological development in storage technology usually revolve around data density. However, in the last five years, the development of several diverse types of information storage now allow for storage on the time scale of tens of thousands to millions of years. These storage technologies store information in different ways, ranging from the use of written language, to the use of binary code, to the synthesizing of DNA bases to represent binary values.

Alongside its longevity, a storage technology for an eternal memory concept should fulfill three main functions: the technology should write data into a device, store the data (the principle function), and read out the data. The following section explores available technologies and how each fulfills these three functions.

The Rosetta Project by the Long Now Foundation uses electroformed, etched nickel disks for storage of textual and image data for thousands of years (Kelly, 2008). The Rosetta Disk, pictured in Figure 4, was developed by Los Alamos National Labs and needs only a 750-power optical microscope to read its 14,000 pages of language translations. The Rosetta Disk has only one layer of encoding since it stores information in the written form of human

language (Welcher, Director of The Rosetta Project, 2015). This paper will develop a space eternal memory concept for the Rosetta Project in Section VI.I.

There has also been promising research with the use of laser-writing on silica glass and the embedding of a material in silicon-nitride. Silica is an attractive material for eternal memory concepts because it is stable against temperature, stable against chemicals, has established microfabrication methods, and has a high Young's modulus and Knoop hardness (Manz, 2015).

For example, a medium where the data is represented by one material, tungsten, embedded within a second material,  $\text{Si}_3\text{N}_4$ , has been developed at the MESA+ Institute for Nanotechnology. The storage technology survived high temperature testing for sufficient time scales to suggest the data would survive for at least one million years (de Vries, 2013). The research was partially inspired by the work of the Human Document Project. Due to the motivations of this project, the system is intended to be a 'write-once-read-many' type, to have a high chance of surviving without established environmental conditions, and to have a high energy barrier against erasure. Data is written in two-dimensional bar codes, specifically quick response codes, which are both popular and recognizable to the contemporary human eye but also decodable with devices such as a camera and a computer. Although easily decodable by contemporary standards, it is not an assumption of this paper that humans one million years from now would be using the same devices for decoding. A challenge of using this technology for an eternal memory concept would be how to ensure readability for an end user.



Figure 4: An image of the Rosetta disk designed by the Long Now Foundation (Kelly, 2008).

There has also been promising research with the use of laser-writing on silica glass. The Hitachi Central Research Center Laboratory and the Miura Laboratory of Kyoto University have developed encoded silica glass that can last for hundreds of millions of years with no degradation. Four layers of dots, representing information in binary form, are

embedded in silica glass using a femtosecond laser. The storage density is comparable to a CD-ROM. The information can be read with an optical microscope. The disk is waterproof, resistant to chemicals and weathering, and was undamaged after being exposed to 1,000-degree heat for two hours in testing (Hitachi, 2014).

At the University of Southampton in Great Britain, researchers have stored optical memory again using femtosecond laser writing on silica glass. It can reportedly last for millions to billions of years. The information encoding is realized by two birefringence parameters in addition to the three spatial coordinates, hence the 5D title. Using this technique, the researchers successfully recorded and retrieved a digital copy of a text file using an optical microscope-based quantitative birefringence measurement system (Zhang, 2013). The lab setup consists of lasers, lenses and a sample of silica glass. Although the technique itself is complex to communicate to future humans, the required materials are basic.

The oldest digital information on our planet are DNA and proteins (Manz, 2015). The advantages of archival DNA data storage are its information density, energy efficiency, and stability (Welcher, Storing Digital Data in DNA, 2012). In 2012, researchers at Harvard successfully stored about 700 terabytes of data in a gram of DNA. They wrote using DNA microchips and then read using DNA sequencing. Instead of binary code being encoded as magnetic regions, as on a hard drive, strands of DNA are synthesized and each of the bases (TGAC) represents a binary value (T and G = 1, A and C = 0). Sequencing machines sometimes had difficulty reading the long stretches of the same letter and this led to errors (Church, Gao, & Kosuri, 2012). However, in 2013, a team led by Nick Goldman of the European Bioinformatics Institute (EBI) in the UK successfully encoded DNA using a more complex encoding system: every byte is represented by a word of five letters that are each A, C, G, or T. The DNA code was synthesized by an external source and returned to the researchers who then reconstructed the files with 100% accuracy (Goldman, et al., 2013).

Teams have also explored the encoding of DNA into the genome of bacteria. The data is then transmitted over generations, preserving the data for the lifetime of the bacteria, which is sometimes millions of years. The DNA is subject to mutation, so parts of the DNA that are not used during the organism's lifetime are chosen for data storage. Bacteria are also chosen that can survive in extreme external environments. The host cell duplicates the data, which ensures data integrity by redundancy (Mohan, Vinodh, & Jeevan, 2013). These options are

attractive and intriguing to the public and there is already movement to bring artistic outreach into the digital DNA world. For example, Joe Davis is an artist in residence in Church's Harvard lab. He plans to insert a DNA-encoded version of the online Wikipedia library into an apple and create a tree library (House, 2014).

The challenge of using DNA data storage is the possible discontinuity in technological knowledge and access to tools that can read the information. Future humans would need tools we have available today to decode the layers of encoding. In this case, the challenge is discoverability, decodability and readability (Welcher, Storing Digital Data in DNA, 2012). Clear sign posts must aid discovery, and the use of bioluminescence is a possibility for DNA storage (Manz, 2015).

There is ongoing research on quantum dot memory storage. A handful of materials have been identified to increase the storage time of electrons and holes possibly up to millions and billions of years at room temperature (Nowozin, Bimberg, Daqrouq, Ajour, & Awedh, 2013). This technology is not assessed here because of its readiness level, but it is an area for further exploration.

A summary of possible storage technologies for space eternal memory is summarized in the heading of Table 5.

#### IV. STORAGE LOCATIONS IN SPACE

It is assumed that humans will probably colonize surrounding bodies in the Solar System, such as the Moon and Mars and even moons of the gas giants, over the next million years. It is also assumed that off-world backups away from prying human hands will be vital for the preservation of eternal memory for these time periods. In addition, the involvement of eternal memory in space projects lends itself to public outreach for long-term thinking initiatives. People naturally get excited about space launches and want to share in them. This section provides a brief overview of possible storage locations in space for eternal memory.

Travelling on-board a spacecraft has been the traditional mode of travel for eternal memory in space, as with the Pioneer plaques and the Voyager records. Some messages are even updatable over a short time period (One Earth, 2015). However, mixing large distances with large time frames is not the best way to increase the likelihood of human interaction with the information (Manz, 2015). There is currently a Rosetta Disk (see Section III.) onboard the Rosetta orbiter at Comet 67P/Churyumov-Gerasimenko. Although the comet will orbit the Sun for hundreds of millions of years, the orbiter will probably only continue to orbit



the comet while it has fuel due to the low gravity of the comet (ESA, 2014). There is discussion of crashing or landing the orbiter on the comet at the end of its mission (ESA, 2015). The lack of stability of comets that come close to the Sun and the difficulty of retrieval are major challenges to storing eternal memory on or orbiting a comet.

In 2007, a Space Studies Program (SSP) team project at the International Space University (ISU) recommended a lunar archive as a solution for the preservation of the human race after a catastrophic event. The motivations of the project drive the requirements of the data archive design, including only a 30-year requirement for the archive lifetime and a power system requirement to enable regular communication with Earth. The project identifies environmental considerations for Moon storage design, including lower gravity, extreme temperature, hard vacuum, and harsh ionizing radiation, dust, and micrometeoroid impacts (International Space University, 2007).

The recently proposed Lunar Mission One archive, in addition to other goals, attempts to eliminate issues such as dust and micrometeoroid impacts by burying the archive underground. The Lunar Mission One project will be discussed in more detail and a space eternal memory concept will be developed for this mission.

Groups such as the Helena Payload Project (Richards J. , 2014) and Time Capsule to Mars (timecapsuletomars, 2015) have explored long-duration storage on Mars. However, little has been written about the effects of the Martian environment on these storage concepts and this is a gap to be further explored. It may be a better decision to choose a location in the Solar System which will be accessible in the next million years but will not be ideal for colonization, in order to protect the information from human trespassing. For example, if humans settle on Mars, information could be stored on Phobos as a type of library which people can access, take a quick look or make a copy, and then return back to the main planet (Manz, 2015). The destruction of recent precious sites in Iraq demonstrates the alarmingly quick rate at which humans can destroy preserved information (Lostal, 2015).

Saturn and Jupiter both have several icy moons which may be accessible in the next million years to humans, but may not be settled for colonization. An arctic vault has already been built in the Svalbard archipelago and holds over 400,000 seeds in order to preserve the Earth's agricultural diversity (Charles, 2006). This vault is particularly safe because it is unlikely to be a habitat for humans. This storage model could be applied to icy bodies in the Solar

System, although the extreme geologic activity of some moons must be considered. In addition, Saturn is an attractive planet in the night sky. The rings around Saturn may identify it as 'the important planet' in the Solar System just as rings around the heads of people in Middle Aged paintings signified 'important people.' Saturn is a celestial body which naturally serves as a pointing device, visible from Earth with the use of a small telescope. In addition to possible storage locations on the moons of Saturn, there are parts of the Saturnian atmosphere which have liquid water at around 0-20°C. Despite high pressures, DNA encoded into bacterial life could survive here for long time periods (Manz, 2015). The ethics and legal practicalities of such a proposition should be further explored.

The Lagrange points of Jupiter are also a possibility: there are already more than 2200 catalogued asteroids librating about the L4 and L5 points of the Sun-Jupiter system (Lissauer & John, 2007). However, the orbits of the planets in the Solar System are chaotic over long timescales and thus difficult to predict. It is impossible to predict a planet's orbit with any certainty after a period of 2-230 million years and even these predictions are associated with computational and inherent uncertainty due to unknowns such as asteroids, the solar quadruple moment, mass loss from the Sun, solar wind effects on planetary magnetospheres, galactic tidal forces, and the effects of passing stars (Hayes, 2007). In addition, Jupiter has the harshest radiation environment in the Solar System and still little is known about some parts of its magnetic system (NASA, 2015).

Within the next 10,000 years, it is probable that there will be gravitationally-determined pathways within our Solar System through which objects such as spacecraft can travel with little energy expenditure. This would provide greater ease in access to locations such as Mars or the Jovian moons (Ross, 2006). A system such as this could provide accessibility to storage, but eternal memory devices could be stored in less frequented locations as a way to keep the information secure.

In terms of increasing the accessibility of the information to future human populations, storage locations within our Solar System are preferred. Larger dynamics on long timescales include the merge between the Andromeda galaxy and our galaxy within the next billion years, which is within the lifetime of our Sun. Bacteria may survive this period. When the Sun swells to a red giant after about five billion years, the Earth's orbit could be inside the star. At this point, no manmade structure will survive on the Earth or the Moon. In this case, it may be feasible to send a robotic spacecraft to search for a cooler star with planets, land

on one of the planets and then use energy from the star to build a beacon and send out information of humanity's existence into the galaxy. A cooler star is suggested because of its longer lifetime and M-stars may be preferred because they stay on the main sequence for hundreds of billions of years (Elwenspoek, 2011). However, there is little evidence that interest from the space eternal memory community would support this type of project currently.

A summary of possible storage locations in space for eternal memory is summarized in the heading of Table 4.

## V. EXISTING INTEREST IN SPACE STORAGE

This section surveys existing missions or proposals, both past and ongoing, for space eternal memory and categorizes them by motivation. The steps used are those to 'Identify stakeholder needs,' substeps 1.0 to 1.4 from Figure 3.

### V.I Define the scope

The product is a space eternal memory concept. The product shall be capable of surviving in a space environment, capable of surviving for a very long time, and shall store information rather than a

physical artifact. Physical artifacts include nuclear waste or a seedbank. The primary stakeholders are those persons or organizations necessary for the direct implementation of storage concept components such as space agencies, space entrepreneurs, university consortiums, and non-profit organizations. Secondary stakeholders are those persons and organizations necessary for indirect implementation of storage concept components such as the general public, crowdsourcing participants and the media.

This paper develops storage concepts considering the needs of the primary stakeholders; however, those needs are of course informed by the secondary stakeholders. It is important to note that stakeholders are not synonymous with customers in this context because although their investment is vital for the success of the product (the storage concept), it will be their investment of time, further development, etc. that is vital rather than a purchase, in monetary form, of a product. The scope of primary stakeholders was determined based on fulfillment of three main criteria: stakeholders are interested in timeframes on the scale of hundreds of thousands to billions of years, stakeholders are interested in storage in space, and stakeholders are interested in the storage of encoded information (rather than physical artifacts).

Table 1: An assessment of criteria used to identify primary stakeholders for space eternal memory concepts.

Existing Initiatives	Longevity (years)	Storage Medium	Location in Space
Helena Payload Project	500 years (Richards J. , 2014)	MicroSD cards (Richards J. , 2015)	Mars (Richards J. , 2014)
Digital Memory Boxes	1 billion years (Iron, 2015)	Digital content and DNA (Iron, 2015)	Deep Moon (Iron, 2015)
Time Capsule to Mars	Unspecified	Digital content (timecapsuletomars, 2015)	Mars (timecapsuletomars, 2015)
KEO	50,000 years (KEO, 2015)	DVD (KEO, 2015)	Orbiting Earth (KEO, 2015)
The Rosetta Disk	10,000 years (Kelly, 2008)	Electroformed, etched disk (Welcher, 2015)	67P/Churyumov-Gerasimenko (Kelly, 2008); ISS (Rose, 2011)
The Human Document Project	1 million years (Human Document Project, 2014)	Unspecified	Unspecified
One Earth Message	Unspecified	Digital content (One Earth, 2015)	Moving through space on spacecraft (One Earth, 2015)
Moonspike	Unspecified	Flash data memory vault (Moonspike, 2015)	Subsurface Moon (Moonspike, 2015)

Table 1 outlines primary stakeholders and specifies how they meet the criteria to the precision that is

currently available from the literature and some personal interviews. Some of the projects in Table 1



specify longevity as a concept development driver, although quantitative timespans are not specified in available data.

## V.II Gather raw data

The most important raw data for determining stakeholder needs are motivations for storage. Motivations for storage will inform design of the storage concept. This section will group and analyze these motivations as targets (needs) that the space eternal memory concept must enable and support.

After looking at the motivations of these various initiatives, motivations were organized into two groups, “outward”-focused motivations and “inward”-focused motivations. “Outward”-focused motivations are defined as motivations which focus on the needs of people or a society *not* currently on the Earth (e.g. future generations, alien species). An example is the motivation to preserve comprehensive or key information for future generations. “Inward”-focused motivations are defined as motivations which focus on the needs of people and the society currently living on the Earth. An example is the motivation to inspire students to join STEM fields.

Each space mission from Table 1 was analyzed and tabulated in terms of its “outward”- and “inward”-facing motivations. This analysis revealed that space missions have shifted over the last 40 years from being more explicitly “outward”-focused to being more explicitly “inward”-focused. Ongoing initiatives which seek to communicate with ancestors far away in time do exist, such as the Rosetta Disk and the Human Document Project, but these initiatives are still primarily terrestrial.

Many contemporary proposals are motivated by potential affects to humans currently living on Earth. For example, projects are focused on connecting people via social media on a global scale or looking to a near-future colonization of Mars. The focus on connectivity, entrepreneurship and do-it-yourself submission of information mirrors generational shifts over the last 50 years (Gibson, 2013). Motivations accommodate these tendencies while also inviting people to consider the negative effects of accelerated pace and use of technology. Motivations of initiatives such as the Rosetta Disk include addressing digital obsolescence and information loss so that society can benefit from the abundance of information by collecting it coherently and storing it with care.

## V.III Interpret raw data in terms of stakeholder needs

The interpretation of stakeholder needs is extracted from explicit motivations. The “Stakeholder Statement” in Table 2 is a direct statement from public data or personal interviewing, while the “Interpreted Need” has been extracted and will form a basis for establishing space eternal memory concept specifications in subsequent development stages. Table 4 offers a sampling of Stakeholder Statements and Interpreted Needs and is not comprehensive for each stakeholder.

Storage concept was defined in Figure 1 as a description of the form, function and features of a space eternal memory concept. At this stage, the “Interpreted Need” will distinguish between only the storage concept (SC) as a whole and the capabilities of the storage technology (T).

Table 2: A sampling of needs interpreted from stakeholder statements of motivation.

Mission	Stakeholder Statement	Interpreted Need
Lunar Mission One	We want to support other project goals by providing funding sources (Lunar Mission One Ltd, 2015).	The SC provides a funding source.
The Rosetta Disk	We want to encourage the principle that for information to last, people have to care (The Long Now Foundation, 2015).	The SC encourages public engagement.
The Human Document Project	We want to assure that key aspects of contemporary culture remain for a very long time (Manz, 2015).	The SC establishes a method for selecting key aspects of culture; the T stores information for one million years.

#### V.IV Organize needs into a hierarchy and establish relative importance

The interpreted needs establish target specifications for space eternal memory concepts. Redundant statements from the identified needs are eliminated. Needs are grouped according to similarity

in Table 3. The primary needs on the left side are the most general needs, while the secondary needs on the right side are expressed in more detail (Ulrich & Eppinger, 1995). This hierarchy informs the needs for which metrics are applied.

Table 3: Hierarchy of needs for space eternal memory concepts.

Primary Need	Secondary Need
<b>1</b> The storage concept is directly accessible through social media to people everywhere.	<b>1a</b> The storage concept is simple. <b>1b</b> The storage concept encourages global public engagement.* <b>1c</b> The storage concept supports large amounts of information.* <b>1d</b> The storage concept encourages global science education.*
<b>2</b> The storage concept moves us toward becoming a dual-planet species.	<b>2a</b> The storage concept survives in the Martian or lunar environment. <b>2b</b> The storage concept sets the precedent for art as a pillar of future life on Mars. <b>2c</b> The storage concept is accessible to future colonists on Mars or the Moon.
<b>3</b> The storage concept encourages positive human relationships on a global scale..	<b>3a</b> The storage concept encourages freedom of expression and artistic expression. <b>3b</b> The storage concept encourages global science education.* <b>3c</b> The storage concept raises awareness of the problem of digital obsolescence and information loss. <b>3d</b> The storage concept encourages global public engagement.
<b>4</b> The storage concept serves as a way to both embrace and constrain the information age.	<b>4a</b> The storage concept supports large amounts of information. <b>4b</b> The storage concept has a method for comprehensive selection of information. <b>4c</b> The storage concept provides a funding source. <b>4d</b> The storage concept raises awareness of the problem of digital obsolescence and information loss.*
<b>5</b> The storage device stores information without damage for a very long time.	<b>5a</b> The storage concept uses advanced new technologies. <b>5b</b> The information is decipherable by future descendants and/or other species. <b>5c</b> The storage concept has a high chance of surviving without established environmental conditions.

#### V.V Needs-metrics matrix

At this stage, it was considered if all important stakeholders had been assessed, if latent needs had been considered, and which identified

stakeholders would be good participants in ongoing development efforts. Lunar Mission One, the Long Now Foundation and the Human Document Project all had viable contacts for interviews, had public

evidence of ongoing progress, and were proposing the longest time durations. These three stakeholders were selected for the development of space eternal memory concepts for this research.

The Long Now Foundation is a non-profit organization that was established in 1996 to foster long-term thinking and responsibility in the framework of the next 10,000 years (Long Now Foundation, 2015). One of its projects is the Rosetta Disk which is described in Section III.

The Rosetta Project has designed the Rosetta Disk specifically for its purposes. However, these purposes have been primarily focused on terrestrial storage. Development of a completely new Rosetta disk for space is for future work and is of interest to

the Rosetta Project (Welcher, Director of The Rosetta Project, 2015). A more significant analysis in this research for the Rosetta Project will be the comparison of viable locations for storage (Table 4).

Based on the collection of interpreted needs, it is determined that Primary Needs 3, 4 and 5 and Secondary Needs 3c, 3d, 4a, 4b, 4d, 5b, and 5c (Table 3) are the most important for a space eternal memory concept for the Long Now Foundation and the Rosetta Project. A metric is applied to each need on the level of Secondary Needs. Some needs cannot be easily translated into quantifiable metrics, and these are indicated by a qualitative 1-5 point scale (Ulrich & Eppinger, 1995).

Table 4: Compared metrics for various storage locations in space based on Rosetta Project needs.

Metric	Under the surface of the Moon	Under the surface of Mars	Comet	Traveling on-board a S/C	Icy moon	Planet around an M star
Instills human agency	5	5	3	3	4	3
Public awareness	4	4	4	4	4	2
Adaptability of technology	4	4	3	5	4	1
Memory density	3	3	2	3	2	1
System for involving experts	4	4	3	4	2	Unknown
Probability of discovery	4	4	1	1	3	3
Stability (years)	1 billion	1 billion	Hundreds of millions (Kelly, 2008)	Millions (Sagan, 1972)	Millions to billions of	Millions to billions
Radiation	Anorthosite rock (Iron, 2015)	Background radiation	Harsh ionizing	Harsh ionizing	Harsh ionizing	Harsh ionizing
Micrometeoroid, Dust	Negligible	Negligible	Protection needed	Protection needed	Protection needed	Unknown
Temperature	~123 K (Iron, 2015)	Varies (Paton, 2013)	343 K (ESA, 2014)*	Varies	Varies	Varies

The Lunar Mission One initiative is distinctive from the Rosetta Project because the project already selected a location for storage, the Moon. In this case, competitive benchmarking is completed only for a viable storage technology for the Lunar Mission One but with the same methodology as seen in Table 4.

Lunar Mission One recently received sufficient funding through Kickstarter to begin developing space missions and programs for further Moon science and education (Lunar Mission One Ltd, 2015). The project seeks to preserve individual ‘digital memory boxes’ alongside a public archive and an encyclopedic archive of the Earth’s biodiversity. Currently the public can reserve a digital memory box for a 50-500 USD pledge (Iron, 2015). This project is also distinctive from the Rosetta Project because of its crowdsourcing nature. The project is concerned with its business plan and how this plan will support

broader mission goals such as preserving information and advancing drill technology. The lynchpin of the business plan is the storage of human hairs under the Moon’s surface. It is still undecided how these hairs alongside the digital data will be stored, and the selection of digital technology is something the project coordinators expect three years to decide on (Iron, 2015). Although these hairs are physical artifacts, they are considered in this paper as a necessary combinatorial to the storage of digital data.

This research determines that Primary Needs 1, 3 and 5 and Secondary Needs 1b, 1c, 1d, 3b, 3d, 5a, 5b, and 5c (Table 3) are most important for a space eternal memory concept for Lunar Mission One. As before, a metric is applied to each need and metrics are compared for various long-duration storage technologies explored in Section III (Table 5).

Table 5: Compared metrics for various long-duration storage technologies based on Lunar Mission One needs.

Metric	Si <sub>3</sub> N <sub>4</sub> /T-based Gigayear Storage (de Vries, 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, 2013)	Rosetta micro- etched nickel (The Long Now Foundation, 2015); (Kelly, 2015)	DNA microchips (Church, Gao, & Kosuri, 2012)	Generational bacteria DNA storage (Mohan, Vinodh, & Jeevan, 2013)
Instills human agency	5	4	4	5	4	4
Global education	4	2	2	3	3	3
Readout	Camera + computer	Optical micro- scope	Optical microscope	Optical micro- scope	DNA sequencing	DNA decoding
Memory density	Dep. on photo- lithography (Manz, 2015)	40 MB/in <sup>2</sup>	360 TB / DVD-sized disk	40 GB / 2.4-in diameter (Welcher, 2015)	Hundreds of TB / 1g of DNA	0.1 GB / genome
Current application	Research	Industry	Research	Non-profit outreach	Research	Research
Development	2 years	1 year	2 years	7 years	3 years	8 years

Metric	Si <sub>3</sub> N <sub>4</sub> /T-based Gigayear Storage (de Vries, 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, 2013)	Rosetta micro- etched nickel (The Long Now Foundation, 2015); (Kelly, 2015)	DNA microchips (Church, Gao, & Kosuri, 2012)	Generational bacteria DNA storage (Mohan, Vinodh, & Jeevan, 2013)
Probability of discovery	4	3	3	4	4	4
Mutability	Write- once-read- many	Write- once-read- many	Write-once- read-many	Write-once- read-many	Read/write	Mutating
Levels of encoding	Binary	Binary	Binary	Human language	Digital encoded in DNA	Digital encoded in DNA
Space environ- ment	Untested	Shin-en 2 (Hitachi, 2012)	Untested	Space station (Rose, 2011)	Untested	Untested
Energy barrier against erasure	1 hour at 848 K (de Vries, 2013)	2 hours at ~811 K (Hitachi, 2014)	Thermal stability at ~1273 K (Zhang, 2013)	65 hours at ~372 K and ~572 K (Los Alamos Laboratories, 1999)	Unknown	Unknown
Storage medium type	Tungsten in silicon- nitride	Silica glass encoded	Silica glass encoded	Electroplate/ microetching on nickel (Welcher, 2015) Tested	Encoded DNA	Encoded Bacterial DNA
Hard vacuum	Untested	Untested	Untested	Tested	Untested	Untested
Maximum lifetime of technology	Millions to billions of years	Millions to billions of years	Millions to billions of years	2,000 to 10,000 years	10,000 years	Millions of years

These analyses were completed for all stakeholders for either storage technology, storage location or both. These needs-metrics matrixes were used to develop the storage concepts shown in Section VI.

#### VI. STORAGE CONCEPT CASE STUDIES

The following sections will address the ‘problems to solve’ in the development of storage concepts and will generate concepts for three specific stakeholders: the Rosetta Project, Lunar Mission One, and the Human Document Project. The methodology

used is step 3.0 from Figure 3. This step consists of breaking down complex problems into subproblems and identifying solution concepts at the subproblem level. Concept combination tables, as seen in Table 6, are used to explore systematically and to integrate subproblem solutions into a total solution. This paper decomposes problems by key stakeholder needs, which is an approach most useful for products in which form is the primary problem (Ulrich & Eppinger, 1995). This method made the most sense for assessing different parts of the storage concept such as the contents to be stored, the storage device, and the



storage location selection. Figure 5 shows the main problems decomposed into subproblems which are expressed as questions to be answered.

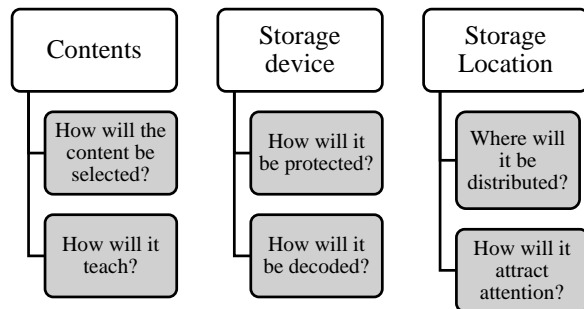


Figure 5: Decomposition of problems by key stakeholder needs.

The concept combination table in Table 6 is an example of a concept combination table for the

Human Document Project. The concept combination table provides a way to consider combinations of solution fragments more systematically. Sometimes combinations of two or more options from a single column allow for a synergetic solution. Complete descriptions of each concept for each of the three selected stakeholders are given in Sections VI.I through VI.III.

#### VI.I The Long Now Foundation and the Rosetta Disk

Table 4 helps establish a location which satisfies the needs of a Rosetta Disk in space. Difficult to access locations such as a comet or a location outside of our Solar System lose value because they are inaccessible to future descendants 10,000 years in the future.

Table 6: Concept combination table with components selected for the Human Document Project.

Contents		Storage Device		Storage Location	
(a) Select Content	(b) Teach	(c) Protect	(d) Decode	(e) Distribute	(f) Attract Attention
Online portal	Ontology tree	Embed in amber (Manz, 2015)	Instruction manual for how to build reader	One copy (with key)	Bioluminescence
Integration of databases	Line drawings	Acrylic case (Welcher, Director of The Rosetta Project, 2015)	Map included of different burial sites	LOCKSS (Lots of Copies Keeps Stuff Safe) (Welcher, 2008)	Historical markers (Nazca lines, Stonehenge)
Input of key experts	Use of universal mathematical symmetries in nature, e.g. a lunar crater	Meteorite-safe box	Cocktail of radioactive isotopes (Timer) (Manz, 2015)	Parts of a puzzle, referring to each other	Dispersed tags of magnetic, acoustic or radioactive signs (Benford, 1999)
Focused conference	with rays (Benford, 1999)	Silicon device with protective coating (Manz, 2015)	Combination astronomical events (Timer)		Metal residuals (Davies, Bintliff, Gaffney, & Waters, 1988)
Input of key stakeholders interested in eternal memory	Dictionary	Redundancy (sheer number of copies)	Pictures based on nature		Permanent magnets producing artificial pattern (Clarke, 1968)
Randomly selected documents	Picture-based dictionary				Granite disks perceived by acoustic probes (Benford, 1999)
Use of sound					Radioactive marker
Combination system	Combination system				

The eternal memory will be in an accessible location to human beings and a location likely to be colonized and rediscovered by future descendants. Storing something on the Moon, Mars or an icy moon makes the information more accessible to future generations. Within the next 10,000 years, an interplanetary transport network (see Section IV) may provide greater ease in access to locations like Mars or the Jovian moons (Ross, 2006). Memory density becomes less of an issue with more frequent access because multiple packages of information can be sent across trips. The close proximity and likelihood of settlement increases the probability of the information being found.

The Rosetta disk itself has higher data density than the de Vries and Hitachi technology (see Table 5) and also uses a lower level of encoding which is more accessible to human readers. These other technologies are only superior in the longevity category, but the Rosetta project does not look at periods longer than 10,000 years in order to keep the project within the scope of human agency (Welcher, Director of The Rosetta Project, 2015). A space-rated Rosetta Disk will be buried on a nearby celestial body.

The Long Now Foundation already selects its content by integrating expert knowledge with information submitted to an online portal. Regular focused conferences, including linguists or others who live in remote locations, will supply additional information.

In addition to the decoder ring system already used by the Rosetta Disk, pictures based on nature will be added as a type of ontology tree. These objects are easily matched to nature even as language changes. Super, master, and slave pictures will communicate interrelations that are not communicated in dictionary form (Manz, 2015).

The most effective form of protection is redundancy. The Rosetta Disk will fly aboard spacecraft to the Moon, Mars and the icy moons. It is recommended, for example, that the Rosetta Disk information fly in some form with Lunar Mission One. Burying the disk will protect it, with background radiation still needing more exploration. Eventually, a silicon-wafer Rosetta Disk will be manufactured, although storage density would need to be further explored. This silicon-wafer will be protected with some layer such as amber.

Providing a cocktail of radioisotopes will not only date the storage of the device but will also make it easy to sense if the device is buried. Difficulties of this solution include that the radioactivity may change the material of the device. A solution is to store the radioactive material in a separate location with a more

durable key holding limited information and instructions for finding multiple burial sites.

This description is a first iteration of a concept solution. The concept should be refined through the concept selection phases seen in Figure 3.

## VI.II Lunar Mission One

Ideal storage technologies for the Lunar Mission One project were discussed in Section V.V. The tungsten silicon-nitride data storage and the DNA data storage score well in terms of human agency, outreach and longevity. The DNA storage is unbeatable in terms of data density but would be sensitive to radiation if not carefully protected. Since the hair strands are a vital part of the Lunar Mission One business plan, it should be assumed that the protection from radiation of the DNA must be a problem worked out before launch and burial. Other considerations with DNA storage are the processing cost, which are potentially very high, and the decodability for future generations, which is more involved than a disk with human language.

These technologies would also need to undergo further testing in a simulated or actual space environment. The cost of specific materials and manufacturing techniques of these devices need to be further explored due to the importance of cost for Lunar Mission One. The Rosetta Disk, for example, is extremely expensive to produce. It sells at about 10,000 to 15,000 USD for a disk (Welcher, Director of The Rosetta Project, 2015) and would not be viable for the general public to purchase to send to the Moon.

Table 5 presents the extent to which a given storage technology satisfies the needs of Lunar Mission One. The Rosetta Disk does not meet requirements in terms of longevity and cost, although it is the most easily decodable. The optical storage technologies have greater longevity but are more difficult to decode and have not been tested in a space environment. It is also unknown if the tungsten silicon-nitride storage would have an appropriate memory density while retaining its longevity (Manz, 2015). DNA data storage has huge memory density but has not been tested in a space environment and would be difficult for future generations to decode. A combination of storage technologies may be the best solution.

A combination of encoding schemes will be used. It is likely that human hair will survive for extremely long time scales at these low temperatures, as in a vacuum temperature will dominate the decay process (Grass, 2015). However, it will be possible to use digital DNA storage for redundancy if processing costs can be minimized. This DNA storage will also serve as the data carrier of the Lunar Mission One's

proposed Encyclopedia of Life, an integration of existing biodiversity archives (Iron, 2015).

Lunar Mission One will involve publically-submitted data. It will also compile a global database of biodiversity (Iron, 2015). Universities and institutions worldwide will be contacted and a team will be established for combining databases.

The device will be stored near or at radial symmetries found in nature, such as a lunar crater with rays (Benford, 1999). These symmetries will be linked to mathematical series used in the encoding. One Rosetta Disk will appear as the top layer of information or another disk with a spiral of human symbols which entices the reader to learn more and to build a device to read more.

The most effective form of protection is redundancy. Including several types of devices is recommended. Lunar Mission One is the first in a planned series of flights to the Moon by the same consortium. The first mission will take the first capsule and bury it. Additional markers and locations will follow in later missions. Burying the disk will protect it, with background radiation needing more exploration. Tungsten silicon-nitride disks will be manufactured, depending on further exploration of cost and storage density.

Providing several devices helps in decoding of the information. An initial disk with human symbols offers basic enticement and instructions. This disk will appear at the top of a memory package as discussed above. Over time, the decoding of optical and digital DNA data storage occurs, and other storage locations are found. Having the instruction manual on how to find other locations and types of storage in human language will make that part of the concept most accessible to current humans on Earth. It is a good source of science education for the public on how more complicated storage devices function, such as the optical and the DNA storage. The integration of technologies is aligned with the Lunar Mission One scaling of memory packages; different investors reserve different types of memory devices for varying costs. Also to note, the manufacturing of different parts of a puzzle in order to distribute the information would result in too much specialization and too much cost. Replicating-based redundancy is preferred for this stakeholder.

Since the mission will occur in phases, a first step is to bury the initial device installed in the drill bit which has about a 3cm-diameter, 10m-height cylinder as the archive volume (Iron, 2015). Subsequent missions will develop a long-term system for marking including leaving “minor moles” (small, dispersed tags of magnetic, acoustic or weakly radioactive signs) (Benford, 1999) or a larger marker such as historical

pyramids or stones corresponding to the sky. Larger markers would need more ethical and legal consideration.

Use of a natural mathematical symmetries found on the Moon’s surface can be used to mark a spot and these symmetries can relate mathematically to a key written in human symbols on the disk as discussed above. This solution both entices a future reader to learn more and is valuable educational outreach for Earth’s current young math students.

### VI.III. The Human Document Project

The Human Document Project is a consortium of loosely-affiliated researchers, academics and enthusiasts who gather for a conference every two years (Manz, 2015). The project is multidisciplinary and aims to preserve a document on key aspects of contemporary culture for one million years. The project is interested in all aspects of storage including content, system, technology, material of the data carrier, protection of the storage media and coding (Human Document Project, 2014). Although mostly terrestrially-based, researchers have considered storage in space (Elwenspoek, 2011).

Unlike the Rosetta Project and Lunar Mission One, the Human Document Project is neither using a specific storage technology nor has it established a specific location in space for storage. Using the same metrics seen in Table 4 and Table 5, storage technologies and storage locations are assessed for the Human Document Project. Because the Human Document Project is interested in longer time scales than the Rosetta Project, only optical storage and digital DNA storage technologies suffice. These technologies offer greater ease for redundancy which is vital over longer time periods. DNA is also the oldest data storage in existence and is appealing as a use of mimicry to ensure survival (Manz, 2015).

Any physical object sent outside our Solar System will be almost impossible to recover by humans on Earth (Manz, 2015). Difficult to access locations such as a comet or a location outside of our Solar System lose value because they are inaccessible to future descendants. Humanity did not look for information about old civilizations outside of the Solar System or at the Lagrangian points of Jupiter (Manz, 2015). But if within the next one million years, the icy moons of the gas giants are part of an interplanetary transport network, then these are potential locations hominids will go looking for information about past civilizations. If a device is stored under the surface, a beacon or marker will be important. It is also an idea to invest planets or the Moon with bacterial DNA holding stored information, but ethical and legal

considerations should be carefully considered before implementation.

Information shall be supported by technology with high data densities, such as DNA, and shall be stored within our Solar System. Content shall be selected through the Human Document Project consortium with input from the public similar in form to the online Rosetta Project database.

Silicon-wafer disk keys will communicate information through ontology trees. Key information in these ontology trees will point toward the bacterial (or other) species carrying the information in its DNA. DNA-encoded species will be protected by redundancy. The silicon-wafer key will be buried in multiple locations on celestial bodies. Burying the disk will protect it, with background radiation needing more exploration. This silicon-wafer will be cut into 5x5mm chips and embedded in amber (Manz, 2015). On moons with oceans or lakes, such as Titan and Europa, DNA will be stored in bacteria. In Earth's history, the deep sea is least affected by events such as asteroids.

Bioluminescence will be used as a marker for the species carrying the information. Markers for the silicon wafer key should be explored in more depth in future research.

## VII. CONCLUSIONS AND FUTURE WORK

The first question many people ask about eternal memory is about why it would or should be done. Motivations for storage inform everything else, from the design of the device to the location of storage. Eternal memory projects have become more "inward"-focused because it is the only way they can pragmatically exist. If projects do not entice the care and investment of currently existing people, there is no system to support them. Short-term focuses outweigh long-term thinking in society. This is an innate challenge of and balancing act for the success of eternal memory projects.

Motivations for space eternal memory range from preserving comprehensive information for future generations, to inspiring young science students, to involving the public directly with space missions, to encouraging humanity toward becoming a dual-planet species. There is also now technological capabilities to store information on the scale of millions to billions of years. In developing space eternal memory concepts for stakeholders, it is a aim of this paper to demonstrate the possible value of storing information in space for a very long time. It is also the aim of this paper to create links between existing stakeholders and to explore these topics in an interdisciplinary way.

The development of storage concepts revealed specific tradeoffs involved in a space eternal

memory concept and possible gaps for further exploration. Choosing bodies in our Solar System such as the Moon or other planetary moons enables easier access to future humans. Burying the information subsurface may protect the information from damage by temperature, moisture, and ionizing radiation. However, the questions of how to mark the spot and how to attract future visitors to the spot become more challenging.

The results of the analyses using product development methodology produced three storage concepts. The Rosetta Project concept and the Lunar Mission One concept have concrete avenues of implementation, given their funding sources and interest in a near-future launch by the stakeholders. The Human Document Project concept is interesting and fits stakeholder needs but may be difficult to implement given planetary protection considerations. However, it offers an interesting thought experiment which may be useful for the general pursuit of putting eternal memory into space.

The most immediate next step necessary for implementation is to develop the product development methodology further and conduct a more robust analysis using a concept selection matrix (Ulrich & Eppinger, 1995). This is a more detailed concept selection phase that could be used for more systematic concept selection. A second important next step is developing the technical robustness of each concept. This includes the testing of storage technologies in a space environment, generating design sketches and CAD models for each concept, and increasing our knowledge of specific storage location environments such as the subsurface Moon. Much is still unknown about the lunar interior in terms of temperature gradients and background radiation levels.

This paper is a combination of exploring the human motivations which drive preservation instinct and setting methodology to those instincts in order to output product-type concepts. It is the hope of the authors that this research into space eternal memory concepts will encourage both philosophical and technical inquiry, and that an eternal memory concept will someday be launched into space.

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