SPACE ETERNAL MEMORY

storing information in space for a very long time

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Abstract

This report explores the rationales for an eternal memory concept for space. The report also develops three eternal memory concepts for space. Eternal memory is information encoded in some medium and capable of surviving in storage for a very long time. 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. This paper uses product development methodology to develop three 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.

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Abbreviations

ISU	International Space University
ITN	Interplanetary Transport Network
NASA	National Aeronautics and Space Administration
SSP	Space Studies Program

1. 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, et al., 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 a remote chance that these probes will ever meet an advanced spacefaring nation (Sagan, et al., 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 are terrestrial, although they are interested in thinking about the questions and design demanded by a space eternal memory concepts (Welcher, 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 technology and to inspire global science education. The storage of human information is a product for the general public and supports a financially strategic business plan (Lunar Mission One, 2015). A loosely conjoined group of university professors and multidisciplinary enthusiasts have formed the Human

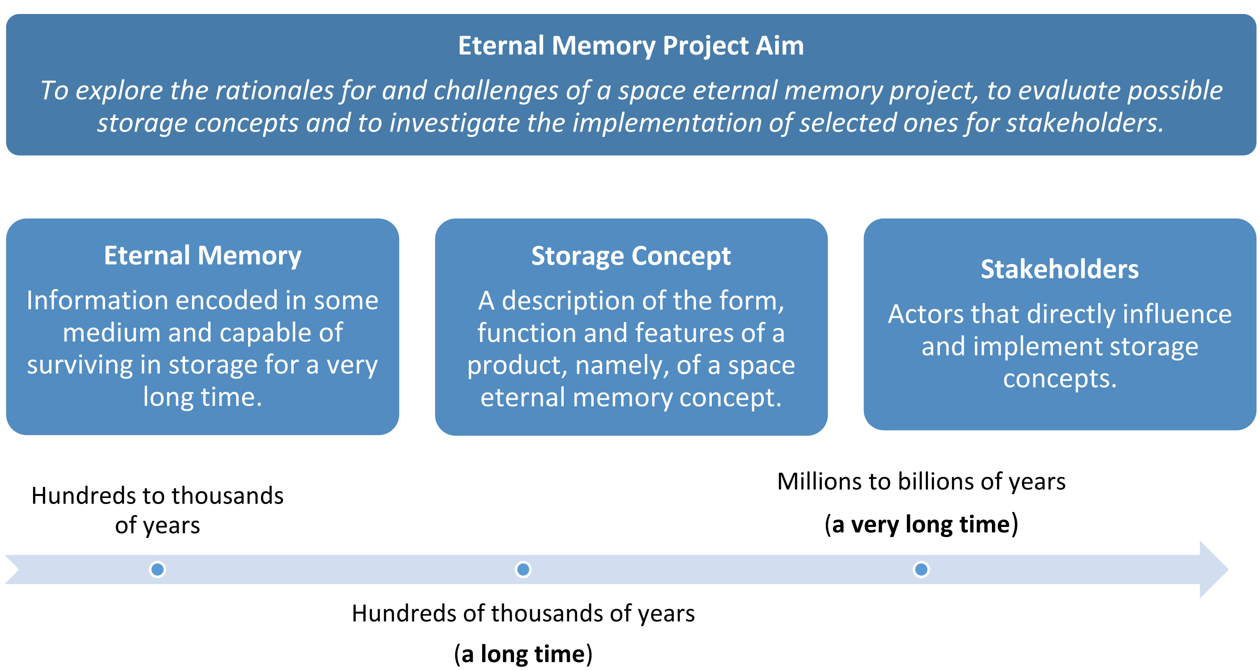

Figure 1: Project aim and important definitions.

Document Project, which seeks to preserve a document about humankind for one million years (Human Document Project, 2014). Founder Andreas Manz expresses skepticism over storage in space, but also articulates a need for redundancy and security for the preserved document (Manz, 2015).

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, et al., 2013). As depicted in Figure 1, 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 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. These technologies vary from tungsten embedded in a silicon-nitride (de Vries, et al., 2013) to femtosecond laser writing on transparent material (Zhang, et al., 2013) to DNA microchips (Church, et al., 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 report. The report begins by exploring the rationales for a space eternal memory concept, with the assumption that motivation will inform design. The report also generates three space eternal memory concepts (see Figure 1). 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 project 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 hominids will potentially read the information. This report 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 of this report to be a part of that eventual implementation of a space eternal memory concept.

2. Report Structure

This section outlines the structure of Chapters 3 to 7. Chapter 3, Product Development Methodology, outlines the methodology used throughout the report to identify stakeholder needs, establish target specifications of the space eternal memory concepts, and to generate those concepts. The work completed in Chapter 4, Review of Related Work, sets the foundation for identifying stakeholders for which to develop concepts. Stakeholders are selected at the end of Chapter 4. Chapter 5, Analysis and

Results, covers the development of concepts. In Chapter 5, target specifications are established and storage concepts are generated for the Rosetta Project, Lunar Mission One, and the Human Document Project. Chapter 6, Performance to Plan, describes how closely this process mirrored the original Project

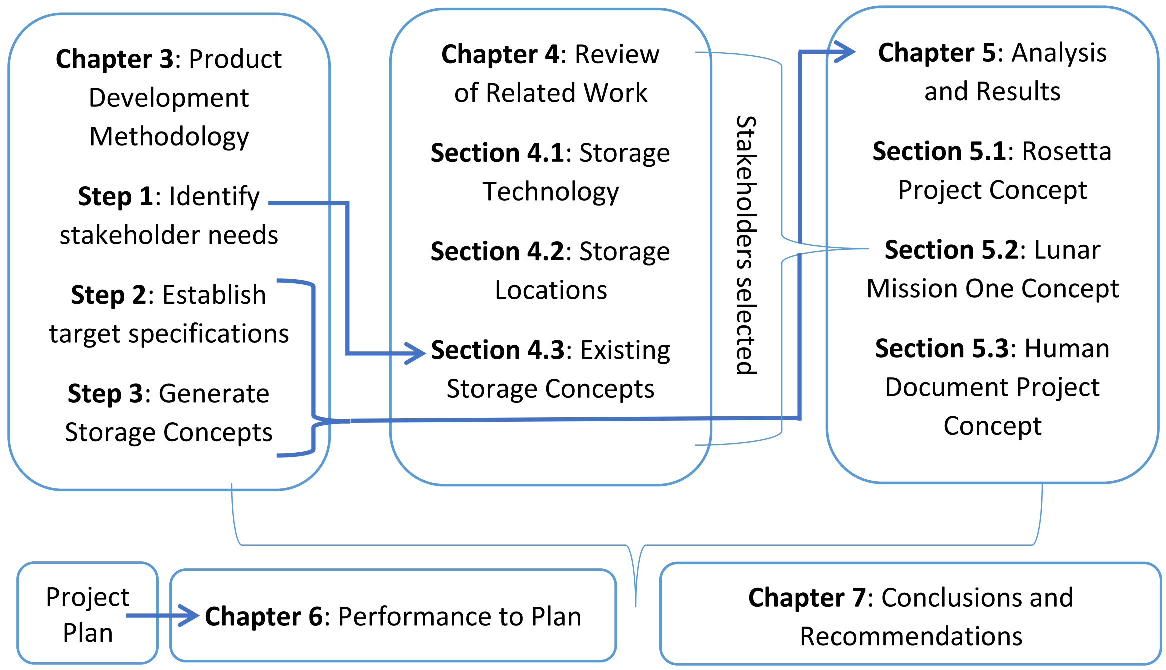

Figure 2: An illustration of how to read this report by chapter and sections.

Plan. Chapter 7, Conclusions and Recommendations, draws conclusions and proposes recommendations based on findings and analysis in Chapters 3, 4 and 5.

3. Product Development Methodology

Since the project vision is toward an actual launch of eternal memory into space, product development methodology is used in this report. 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. 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 (Ulrich & Eppinger, 1995).

Although the methodology is based on that of product development, it has been modified as seen below in 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.

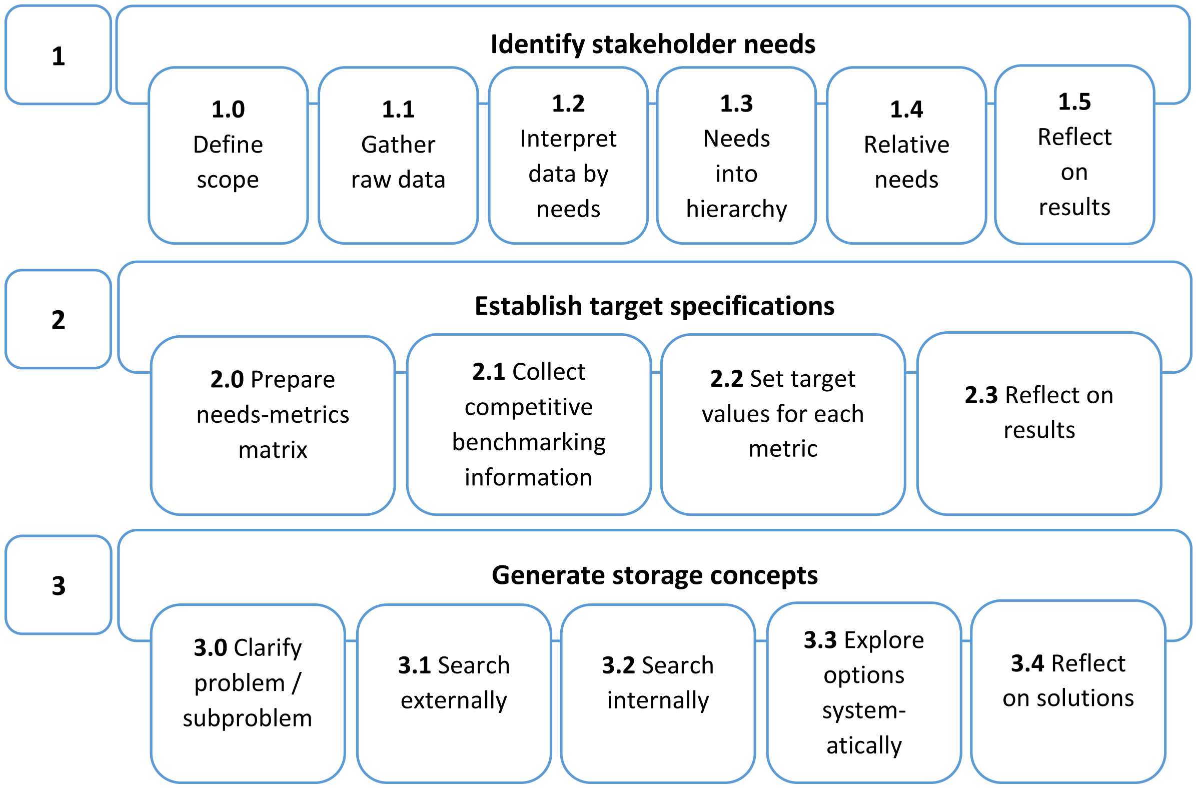

Figure 3: Product development methodology steps and substeps used for identifying stakeholder needs, establishing target specifications, and generating space eternal memory concepts.

4. Review of Related Work

The first two parts of this chapter, Section 4.1 and 4.2, survey existing long-duration storage technology and possible storage locations in space. Research revealed viable options for long-duration storage technology including optical storage technologies (Zhang, et al., 2013) and DNA storage technologies (Church, et al., 2012). Literature on potential storage locations include the Moon (International Space University, 2007), Mars (timecapsuletomars, 2015), a comet (Kelly, 2008) and icy moons (Manz, 2015). A gap in the literature is in potential storage locations outside of our Solar System. Elwenspoek, a member of the Human Document Project, analyzes the problems with long-duration storage in our Solar System, but does not offer explicit alternative options (Elwenspoek, 2011). The third part of this chapter surveys existing and past interest in space storage, beginning with the Pioneer plaques (Planetary Society, 2015).

4.1 Storage Technology

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 types of storage encode human experience to different levels, ranging from the use of written language, to the use of binary code, to the synthesizing of DNA bases to represent binary values.

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 encodes human experience directly to the written form of human language (Welcher, 2015). This report will develop a space eternal memory concept for the Rosetta Project in Chapter 5, Analysis and Results.

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 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).

Figure 5: Tungsten Silicon-nitride gigayear storage technology developed at the MESA+ Institute for Nanotechnology (ExtremeTech, 2013).

For example, a medium where the data is represented by one material, tungsten, embedded within a second material, Si_3N_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, et al., 2013). The research was partially inspired by the work of the Human Document Project (described in more detail in Section 5.3, 5.3 Storage Concept #3: the Human Document Project). Due to the motivations of this project, the data means to be a 'write-once-read-many' type data system, have a high chance of surviving without established environmental conditions, and a high energy barrier against erasure. Data is written in two-dimensional bar codes, specifically quick response codes (Figure 5), 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 report that hominids 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.

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 Southhampton 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. The birefringence parameters are the slow axis orientation (4^{th} dimension), controlled by polarization, and the strength of retardance (5^{th} dimension), controlled by the intensity of the incident beam of the laser. Using this technique, the researchers successfully recorded and retrieved a digital copy of a text file. The text, a copy of the paper's abstract, was recorded into two different levels of retardance as one bit and as four slow axis orientations as two bits, meaning that each laser-imprinted spot stored 3 bits of information. The retrieval of the recorded text file was achieved by an optical microscope based quantitative birefringence measurement system (Zhang, et al., 2013). Figure 6 shows the setup of the laser, optics and sample. This diagram is important because it shows how the setup consists of lasers, lenses and a sample of silica glass. Although the technique itself is more difficult to communicate to future hominids, the required materials are basic.

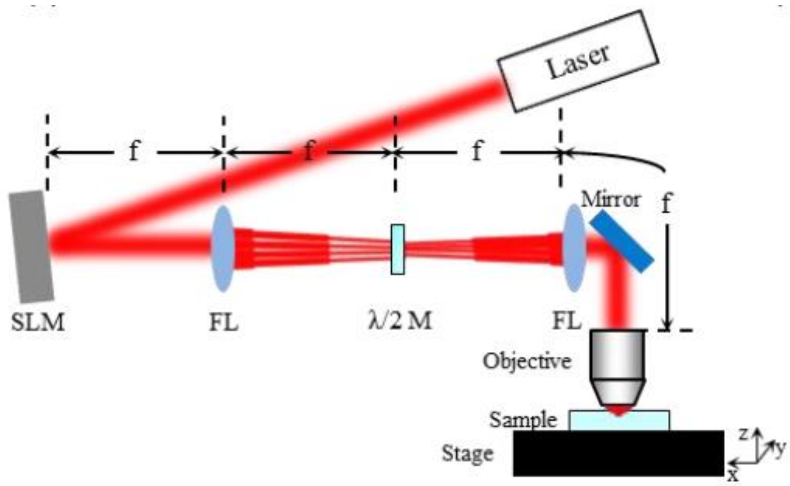

Figure 6: 5D optical storage writing setup.

The oldest digital documents 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, 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, et al., 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 team also had overlapping strings of DNA code, each with 117 letters and with indexing information to indicate where that string belongs in the overall code. In this way, any errors on a string can be checked against three other strings. 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, et al., 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 resident in the Harvard lab which encoded DNA in 2012. He plans to insert a DNA-encoded version of the online Wikipedia library into an apple and create a tree library. A strain of bacteria will carry the coded DNA and insert its genome through the plant cell walls of saplings. Then Davis will graft the modified saplings onto apple stock which will then grow into trees. The metaphor of the project is its recreation of the Biblical Tree of Knowledge and its forbidden fruit (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 hominids would need tools we have available today to decode the layers of encoding. In this case, the challenge is discoverability, decodability and readability

(Welcher, 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, et al., 2013). This technology is not assessed in this report because the research concerns finding materials for possible future quantum dot storage, but it is an area for further exploration.

4.2 Storage Locations in Space

This report assumes 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 New Horizons Message, 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 4.1, Storage Technology) 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). A storage device located on the comet itself would be more stable though difficult to reach.

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. The recommended data storage systems are hard drives or solid state memory, with the main design drivers for selection being speed of accessibility, number of moving parts, data storage capacity, power requirements, cost and lifetime. It is mentioned that optical storage or quantum computing techniques could be utilized (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. This project will be discussed in more detail (Section 4.3 Existing Interest in Space Storage) and a space eternal memory concept will be developed for this mission.

Groups such as the Helena Payload Project (Richards, et al., 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 (Manz, 2015). 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. Current and planned missions to the Jovian system will study the radiation environment in more detail (NASA, 2015) and also test new methods for radiation shielding (Cook, 2010).

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 like Mars or the Jovian moons (Ross, 2006). An artist's depiction of the Interplanetary Transport Network (ITN) is pictured in Figure 7. 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.

Figure 7: An artist's depiction of the Interplanetary Transport Network. The green ribbon shows a path from among many which is mathematically possible. Locations where there is an abrupt change in direction signify a Lagrange point trajectory change (Wikipedia Public Domain, 2015).

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. The increased rate of star formation and supernova explosions as well as higher radiation levels near these regions will probably end complex life on Earth. 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 (see the next section, Section 4.3 Existing Interest in Space Storage).

4.3 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 1.5 from Figure 3 in Chapter 3, Product Development Methodology. This step is analogous to identifying customer needs in the concept development phase of product development (Ulrich & Eppinger, 1995). Identifying stakeholder needs will allow the selection of at least three stakeholders for which to develop space eternal memory concepts (Chapter 5, Analysis and Results).

Define the scope

The scope of the effort is defined through a brief description of the product and the criteria for stakeholders (Ulrich & Eppinger, 1995). This includes a basic definition of the product, and primary and secondary stakeholders. 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 report develops storage concepts considering the needs of the primary stakeholders; however, those needs are of course informed by the secondary stakeholders. Based on the aim of this project seen in Figure 1, the initial review of related work shall result in the selection of 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 the criteria illustrated in Figure 8.

1 **Stakeholders are interested in timeframes on the scale of hundreds of thousands to billions of years.**

This criterion acknowledges that stakeholder needs will vary depending on time frame; e.g. technology longevity, decodability challenges.

2 **Stakeholders are interested in storage in space.**

This criterion acknowledges that questions of terrestrial storage vary from the questions of space storage.

3 **Stakeholders are interested in the storage of encoded information.**

This criterion narrows the scope so as not to include the storage of physical artifacts such as seedbanks or nuclear waste (Charles, 2006).

Figure 8: Stakeholder criteria and rationales.

Organizations, space agencies, private companies and student-led projects have expressed these three criteria within their mission statements, even if they have not launched an eternal memory into space or even fully developed a space eternal memory concept. 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.

Existing Proposals and Initiatives		*Longevity Criteria (years)*	*Information Storage Medium*	*Location in Space*
Already in space	"Visions of Mars" Disc	500 to thousands (NASA, 2008)	Mini-DVD (NASA, 2008)	Martian surface; Phoenix Lander (NASA, 2008)
	Pioneer Plaques	Unspecified	Etched plaque (Sagan, et al., 1972)	Moving through space on spacecraft (Sagan, et al., 1972)
	LAGEOS-1 Plaques	8.4 million years (NASA, 2012)	Etched plaque (NASA, 2012)	Orbiting earth onboard LAGEOS-1 (NASA, 2012)
	Voyager golden records	Unspecified	Phonograph record (Sagan, et al., 1978)	Moving through space on spacecraft (Sagan, et al., 1978)
In development	Helena Payload Project	500 years (Richards, et al., 2014)	Radiation-hardened microSD cards (Richards, 2015)	Mars (Richards, et al., 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)
	Ozymandias Archive (Green, 2015)	Unspecified	Unspecified	Unspecified
	The Rosetta Disk	10,000 years (Kelly, 2008)	Electroformed, etched disk (Welcher, 2015)	67P/Churyumov-Gerasimenko (Kelly, 2008); International Space Station (Rose, 2011)
	The Human Document Project	1 million years (Human Document Project, 2014)	Unspecified	Unspecified
	One Earth Message	Unspecified	Digital content (One Earth New Horizons Message, 2015)	Moving through space on spacecraft (One Earth New Horizons Message, 2015)

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

Gather raw data

Data on stakeholder needs was gathered from available literature on homepages, in journals, books and press releases. This was an initial stage of gathering data; later personal interviews were also conducted. Key pieces of raw data included a brief summary of the mission or project, the motivation(s) driving the mission or project, and as many available statistics on the storage concept, e.g. type of content, project budget, readability of information, etc. At this stage, information was based on public availability; later metrics of the storage concept would be homogenized (see Chapter 5, Analysis and Results). 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. Definitions are articulated in Figure 9. Table 2 outlines explicit "outward"-facing motivations of each stakeholder.

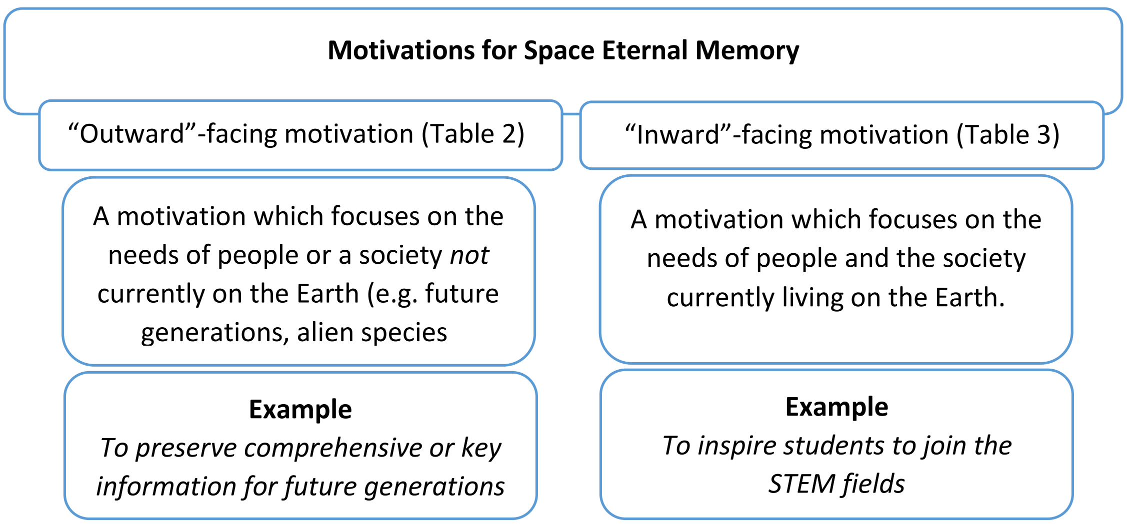

Figure 9: Definitions and examples for the categories of existing motivations for space eternal memory.

Existing Proposals		To preserve comprehensive or key information for future generations	To communicate with future generations on Earth, Mars or the Moon	To provide a map for extraterrestrials to find Earth	To send a message to be received by extraterrestrials
Already in space	"Visions of Mars"		✓		
	Pioneer Plaques			✓	✓
	LAGEOS-1 Plaques		✓		
	Voyager records			✓	✓
	Helena Payload				

Existing Proposals		To preserve comprehensive or key information for future generations	To communicate with future generations on Earth, Mars or the Moon	To provide a map for extraterrestrials to find Earth	To send a message to be received by extraterrestrials
In develop-ment	Digital Memory Boxes	✓	✓		
	Time Capsule to Mars		✓		
	KEO	✓	✓		
	Ozymandias Archive	✓			
	Rosetta Disk	✓			
	Human Document Project	✓			
	One Earth				✓

Table 2: "Outward"-focused motivations for storage separated by stakeholder.

Projects which have as a motivation, or as a possibility, the contact and communication with extraterrestrials are already in space and were developed during the 1970s by the National Aeronautics and Space Administration (NASA) and cooperating scientists such as Carl Sagan (Sagan, et al., 1978). The exception to this statement is the One Earth Message (One Earth New Horizons Message, 2015). Although its originator is Jon Lomberg, a visionary of the Voyager records, there are distinctions between this project and the Voyager and Pioneer messages. For example, the One Earth Mission allows the updating of information which holds people responsible for global change over a decade (Welcher, 2015). The One Earth message will also leave the Solar System. As soon as a spacecraft is sent outside of our Solar System, humans will not encounter the information unless they develop capabilities to leave the Solar System.

Table 3 outlines explicit “inward”-facing motivations of each stakeholder. Personal interviews were conducted for Lunar Mission One’s Digital Memory Boxes (Iron, 2015), the Long Now Foundation’s Rosetta Disk (Welcher, 2015) and the Human Document Project (Manz, 2015). These are more comprehensive.

Existing Proposals and Initiatives		*To inspire students to join STEM fields*	*To provide simple, direct avenues for people to engage with space missions through social media*	*To encourage engagement toward becoming a dual-planet species*	*To contribute to promotional and crowdfunding efforts for space projects*	*To do something never done before in space*	*To encourage positive human collaboration on a global scale*	*To ensure artistic expression is part of the colonization of Mars*	*To inspire global science education*	*To involve students worldwide*	*To use advanced new technology*	*To honor those who inspire space missions*	*To expand the individual human spirit*	*To make connections with extraterrestrials an expectation*	*To focus attention on the problem of digital obsolescence*
Already in space	"Visions of Mars"											✓			
	Pioneer Plaques														
	LAGEOS-1 Plaques														
	Voyager records												✓	✓	
In development	Helena Payload	✓	✓	✓	✓	✓	✓	✓		✓			✓		
	Digital Memory Boxes		✓		✓	✓	✓		✓	✓	✓				
	Time Capsule to Mars		✓	✓		✓	✓		✓	✓	✓				
	KEO		✓												
	Ozymandias Archive										✓		✓		
	Rosetta Disk		✓				✓								✓
	Human Document Project					✓	✓								✓
	One Earth		✓				✓			✓			✓		

Table 3: "Inward"-focused motivations for storage separated by stakeholder.

Table 2 and Table 3 reveal that space missions have shifted over the last 40 years from being more explicitly "outward"-focused to being more explicitly "inward"-focused. Many of the missions already in space, such as the Pioneer plaques and the Voyager records, sought to leave the Solar System, to communicate with extraterrestrials, or at least to encourage people to think of these communications as possibilities. 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. Although each organization has key players interested in space eternal memory, they are currently unconnected with specific space missions which could accomplish these goals.

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. Generation Y, those born between the 1980s and 1990s, are stereotypically known to be tech-savvy, family-oriented, ambitious, communicative, people-pleasing team players (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.

Eternal memory projects have perhaps 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 will be no system to support it. Short-term focus overweighs long-term thinking in society. This is an innate challenge of and balancing act for the success of eternal memory concepts.

Interpret raw data in terms of stakeholder needs

The interpretation of stakeholder needs is extracted from explicit motivations. Table 4 only includes projects for which storage concepts are later developed. All programs were still assessed at this stage in order to develop a comprehensive framework of needs. The “Stakeholder Statement” in Table 4 is a direct statement from public data, while the “Interpreted Need” has been extracted and will form a basis for establishing space eternal memory concept specifications in subsequent development stages.

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 technology (T).

Mission	Stakeholder Statement	Interpreted Need
Lunar Mission One	We want to preserve a comprehensive record of human history (Lunar Mission One Ltd, 2015).	The T supports large amounts of information; the SC has a comprehensive selection of human history information.
Lunar Mission One	We want to inspire global science education (Lunar Mission One Ltd, 2015).	The SC inspires global science education.
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 focus attention on the problem of digital obsolescence and to address that problem through creative archival storage methods (The Long Now Foundation, 2015).	The SC raises public awareness on the problem of digital obsolescence.
The Rosetta Disk	We want to draw attention to the drastic and accelerated loss of world languages (The Long Now Foundation, 2015).	The SC raises public awareness of world language loss.

Mission	Stakeholder Statement	Interpreted Need
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.

Table 4: Needs interpreted from stakeholder statements of motivation.

These interpreted needs will be used in the following sections to establish target specifications for space eternal memory concepts.

Organize needs into a hierarchy

This section will take identified needs and eliminate redundant statements. It will group needs according to similarity. The need is starred if it appears more than once. 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). Figure 10 illustrates Primary Needs on the left and Secondary Needs on the right. This hierarchy will inform the needs for which metrics are applied. When developing storage concepts for specific stakeholders, the needs which are most important to those stakeholders will be analyzed.

Establish relative importance of needs

The hierarchical list of needs in the previous step does not necessarily provide information on the relative importance that stakeholders place on different needs. However, having a sense of the relative importance of these needs to an individual stakeholder is important while making tradeoffs in later phases (Ulrich & Eppinger, 1995). There are two basic approaches to the task of establishing a numerical importance weighting for a subset of needs, either to rely on a consensus of the development team based on experience with stakeholders or to base the importance assessment on further stakeholder surveying (Ulrich & Eppinger, 1995). Since further interviewing of selected stakeholders was already planned at this stage, this report will rely on the second option.

Process the results

An outcome of this stage was specific research questions, as found in Table 6 on page 19, which would be used for assessing viable technologies and locations for the storage concepts.

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

Figure 10: Hierarchy of needs for space eternal memory concepts. Primary needs are seen on the left with Secondary Needs providing more details for each Primary Need.

Section Number and Title	Important Research Questions
Section 4.1: Storage Technology	• Which of the available technologies may satisfy stakeholder needs? • What is the perceived satisfaction of each technology to stakeholder needs?
Section 4.2: Storage Locations	• Which of the available locations in space may satisfy stakeholder needs? • What is the perceived satisfaction of each location to stakeholder needs?
Section 4.3: Existing Interest in Space Storage **Section 5: Analysis and Results**	• Who are the contemporary stakeholders in the development of a space eternal memory concept? • What are the needs of these stakeholders? • What are the values and benefits a space eternal memory concept could add to stakeholders and the general public?

Table 6: Research questions from review of related work and initial analysis.

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. Possible continuing participants included the Helena Payload Project, Lunar Mission One, Time Capsule to Mars, KEO, the Long Now Foundation's Rosetta Disk, and the Human Document Project. KEO and the Helena Payload Project were eliminated because progress was significantly affected by recent events, the death of a founder and the selection of another team for funding from Mars One (Richards, 2015) respectively. Time Capsule to Mars was an option, but is completely initiated and implemented by university students and there seemed to be less likely options for involvement long-term. Lunar Mission One, the Long Now Foundation and the Human Document Project all had viable contacts for interviews and, therefore, were selected for the development of space eternal memory concepts for this report.

5. Analysis and Results

Three interviews were conducted with Laura Welcher, Director of Operations and the Rosetta Project at the Long Now Foundation, Andreas Manz, originator of the Human Document Project, and David Iron, founder of Lunar Mission One. Using these interviews as the data and using the methodology from Steps 2 and 3 in Figure 3 (Target Specifications and Concept Generation). The following sections will address the problems of storage concepts and will generate concepts for these specific stakeholders.

5.1 Storage Concept #1: the Long Now Foundation and the Rosetta Disk

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 the section on Storage Technology.

In addition to the Stakeholder Statements articulated in Table 4, an interview with Laura Welcher revealed additional motivations behind the Rosetta Disk and important to a potential space eternal memory concept. These additional Stakeholder Statements are shown in Table 7. Communication with future humans is core to the motivation behind making the Rosetta Disk.

Additional Stakeholder Statement	Interpreted Need
We want to keep within the realm of human agency, so people feel they can affect things with their own lives (Welcher, 2015).	The storage concept instills human agency, so that people feel like they can actually affect things with their own lives.
The mind must learn to think long-term for [global] problems to be solved (Welcher, 2015).	The storage concept encourages society to think long-term.
Future humans must be capable of interacting with the disk (Welcher, 2015).	The storage device is accessible and decodable to future generations of hominids.
I am designing for humans that basically think the way we do or at least are symbol-producing creatures (Welcher, 2015).	The information is communicated in visual symbols.
Space could offer off-world backups (Welcher, 2015).	The storage device is redundant and replicable.

Table 7: Additional stakeholder needs extracted from an interview with Laura Welcher of the Long Now Foundation.

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 (Figure 10) 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 from Figure 10, on the level of Secondary Needs (called 'Important Needs' in Table 8). Some needs cannot be easily translated into quantifiable metrics, and these are indicated by entering "subj." (Ulrich & Eppinger, 1995).

Important Needs	Metric	Units (if applicable)
3d The storage concept encourages global public engagement.	Instills human agency	# of people involved Level of direct involvement Attractiveness for human use (Subj.)
3c, 4d The storage concept raises awareness of the problem of digital obsolescence and information loss.	Public awareness of the storage concept and its message	Outreach methods Publicity (Subj.)
	Adaptability of technology to changes in storage preference	Levels of encoding (Subj.)
	Inclusion of material experiencing drastic and rapid loss	Rate / magnitude of disappearance
4a The storage concept supports large amounts of information.	Raw capacity	Bits
	Memory storage density	Raw capacity divided by units of volume, length or width
4b The storage concept has a method for comprehensive selection of information.	System for involving subject experts	e.g. Official positions, loose collaboration
	Density of contributors	# of contributors per topic area
	System to process received content	Workforce for processing and storage
5b The storage concept is decipherable by future descendants.	Probability of discovery	# of storage systems Beacon/"sign posting"
	Mutability	How it writes / reads
	Levels of encoding	Difficulty of decoding process

Important Needs	Metric		Units (if applicable)
5c The storage device has a high chance of surviving without established environmental conditions.	Storage location parameters	Stability	Lifetime of orbit / geological stability
		Harsh ionizing radiation	Radiation hardening (rad)
		Micrometeoroid and dust environment	Probability of impact Dust impactor environment (size, frequency)
		Temperature	K
		Hard vacuum	Pressure units
	Storage technology parameters	Energy barrier against erasure	K
		Storage medium type	Material / mechanism
		Maximum lifetime	Years

Table 8: List of needs with corresponding metric for the Long Now Foundation's Rosetta Project.

The most direct need-to-metric relationships were identified above, but some needs might be measured by multiple and overlapping metrics. A need-metrics matrix is constructed to visualize these overlaps and is shown in the Appendix in Table 29. These overlaps are used when assigning "Perceived Satisfaction" of the stakeholder in Table 11.

The next step in product development is to compare the product to other products and determine success through comparing perceived satisfaction of the customer based on needs (Ulrich & Eppinger, 1995). This report will use that methodology to compare available storage technologies and storage locations discussed in Section 4.1, Storage Technology, and Section 4.2, Storage Locations in Space, and will score the perceived satisfaction each offers to the stakeholder needs.

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, 2015). Looking at the Interpreted Needs of the Rosetta Project from Table 4 and Table 7 almost immediately communicates that the Rosetta Disk is the best storage technology for its content selection system, decodability, and inclusions of material experiencing obsolescence. However, a comparison of the Rosetta disk with other technologies is completed as per traditional competitive benchmarking practice (Ulrich & Eppinger, 1995) and can be found in the Appendix in Table 30. A more significant analysis for the Rosetta Project will be the comparison of viable locations for storage (Table 9). Some of the metrics are assessed qualitatively on a 1-5 point scale. This scale is described in detail in Table 31 in the Appendix.

As expected, only the Rosetta Disk technology scores high enough in terms of human agency, discoverability and readability. It has the lowest encoding of experience because it communicates with human language directly and this is highly satisfactory for the Rosetta Project. Longer time scales than 10,000 years are somewhat unattractive for the Rosetta Project because of increased uncertainty in how to communicate with these hominids using language (Welcher, 2015). The design of a new space-specific Rosetta disk is a possible future project which will be discussed in more detail in the concept generation phase. Table 9 compares the metrics of different storage locations based on the needs of the Rosetta project. A full description of qualitative measurement values is in Table 32 in the Appendix.

Metric	Under the surface of the Moon	Under the surface of Mars	Comet	Travelling 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, et al., 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, et al., 2013)	343 K (ESA, 2014)*	Varies	Varies	Varies

*Table 9: Compared metrics for various storage locations in space based on Rosetta Project needs. * signifies that this information is for one comet only and numbers will vary substantially.*

Based on the metrics in Table 9, each storage location is analyzed qualitatively on a 1 to 5 dot scale (see Table 10 for key) to show the perceived satisfaction of needs by the above locations. This perceived satisfaction for different storage locations in space is shown in Table 11.

Qualitative measurement of perceived satisfaction of needs	Description of satisfaction level of needs from metric value
*	Provides extreme dissatisfaction to stakeholder.
**	Provides dissatisfaction to stakeholder.
***	Provides some satisfaction to stakeholder.
****	Provides high level of satisfaction to stakeholder.
*****	Provides very high level of satisfaction to stakeholder.

Table 10: Dot scale used to score perceived satisfaction of customers based on specific metrics (Ulrich & Eppinger, 1995).

Metric	Under the surface of the Moon	Under the surface of Mars	Comet	Travelling on-board a S/C	Icy moon	Planet around an M star
Instills human agency	*****	*****	***	***	****	***
Public awareness	****	****	****	****	****	**
Adaptability of technology	****	****	***	*****	****	*
Memory density	***	***	**	***	**	*
System for involving experts	****	****	***	****	**	Unknown
Probability of discovery	****	****	*	*	***	***
Stability (years)	*****	*****	*****	*****	*****	*****
Radiation	***	***	***	***	**	**
Micrometeoroid, Dust	*****	****	***	***	***	Unknown
Temperature	*****	*****	*****	****	****	****

Table 11: Competitive benchmarking chart based on perceived satisfaction of Rosetta Project needs for storage location in space.

Table 11 will help 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.

Storing something on the Moon, Mars or an icy moon makes the information more accessible to future generations, especially with current interest in exploring these locations further. Missions to the Moon, Mars and the gas giants will provide more information on these environments as well as increasing public interest in the locations. Within the next 10,000 years, the ITS (see Section 4.2, Storage Locations in Space) 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. Our close proximity and likelihood of settlement increases the probability of the information being found. Possible beacons and markers are discussed in more detail in the concept generation phase.

The last step before the concept generation phase is to set marginal and ideal target values for the storage technology and the storage location (Table 12). In the concept generation phase, these marginal target values will set the foundation for which solutions are considered.

Metric		Marginal value	Ideal value
Instills human agency	Technology / Location	**4**	**5**
Public awareness	Technology	**4**	**5**
	Location	**4**	**5**

Adaptability of technology	Technology	4	5
	Location	4	4
Inclusion of material experiencing drastic and rapid loss	Technology	4	5
Memory storage density	Technology	40 GB	Hundreds of GB
	Location	3	5
System for involving experts	Location	3	5
System to process content	Technology	3	5
Probability of discovery	Technology	3	5
	Location	4	5
Mutability	Technology	Write-once-read-many	Write-once-read-many
Levels of encoding	Technology	Digital data	Human language
Storage location parameters	Stability	2,000 years	10,000 years
	Radiation	Underground storage	See marginal value
	Micrometeoroid and dust environment	Underground storage	See marginal value
	Temperature	370 K (Los Alamos Laboratories, 1999)	See marginal value
	Hard vacuum	Tested in space	Tested in space
Storage technology parameters	Energy barrier against erasure	370 K (Los Alamos Laboratories, 1999)	See marginal value
	Maximum life	2,000 years	10,000 years

Table 12: Marginal and ideal target values for Rosetta Project metrics. Full descriptions of qualitative values can be found in the Appendix.

The eternal memory shall be in an accessible location to human beings and a location likely to be colonized and rediscovered by future descendants, e.g. the Moon, Mars, or an icy moon. The Rosetta disk has higher data density than de Vries and Hitachi and also uses a lower level of encoding which is more accessible to hominid readers. These technologies only win 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, 2015). A space-rate Rosetta Disk should be buried on a nearby celestial body.

Concept generation

This step consists of breaking down complex problems into subproblems and identifying solution concepts at the subproblem level. Concept combination tables are used to explore systematically and to integrate subproblem solutions into a total solution. This report decomposes problems by key customer 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 11 shows the main problems decomposed into subproblems which are expressed as questions to be answered.

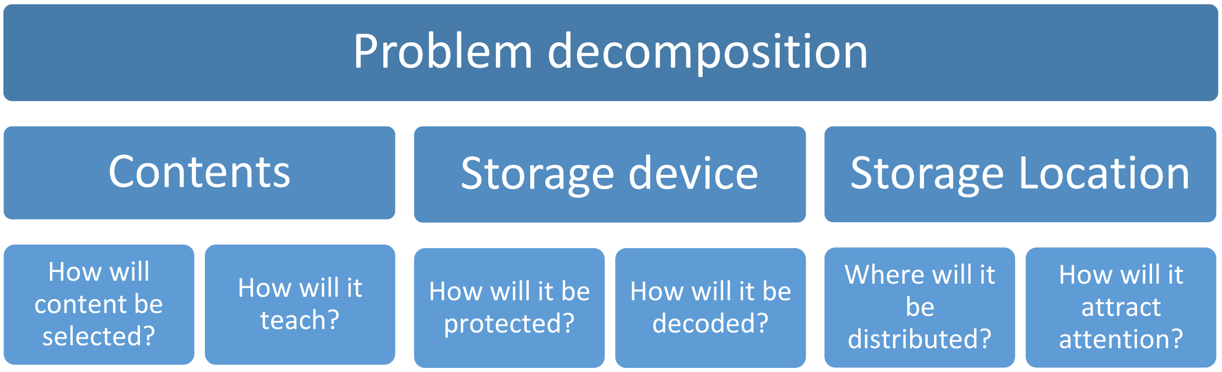

Figure 11: Decomposition of problems by key stakeholder needs.

Some subproblems are interrelated. For example, how it will be decoded is connected to what the content will be and in what form it will be presented.

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, 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 with rays (Benford, 1999)	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	Dictionary	Silicon device with protective coating (Manz, 2015)	Combination astronomical events (Timer)		Metal residuals (Davies, et al., 1988)
Input of key stakeholders interested in eternal memory	Picture-based dictionary	Redundancy (sheer number of copies)	Pictures based on nature		Permanent magnets producing artificial pattern (Clarke, 1968)
Randomly selected documents	Use of sound				Granite disks perceived by acoustic probes (Benford, 1999)
Combination system	Combination system				Radioactive marker

Table 13: Concept combination table with components selected for the Rosetta Project.

The concept combination table in Table 13 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. A complete description of the concept with rationale is provided in Table 14.

Subproblems	Description of solution
(a) Selecting content	The Long Now Foundation already does involved work to integrate expert knowledge with information submitted to an online portal. Regular focused conferences, including linguists or others who live in remote locations, may supply additional information.
(b) Teach the information to future hominids	In addition to the decoder ring system already used by the Rosetta Disk, pictures based on nature could be added as a type of ontology tree. These objects could be easily seen in nature even as language changes. Super, master, and slave pictures could communicate interrelations that may not be communicated only in dictionary form (Manz, 2015).
(c) Protect the storage device	The most effective form of protection is redundancy. The Rosetta Disk could 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 could be manufactured, although storage density would need to be further explored. This silicon-wafer could be protected with some layer, perhaps amber.
(d) Decode the information	Providing a cocktail of radioisotopes would not only date the storage of the device but would also be easy to sense if the device was 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.
(e) Distributing the Storage Device	See (c) and (d)
(f) Attract the attention of future hominids	See (d)

Table 14: A concept solution from the combination of those sub-solutions highlighted in Table 13.

#	Description	Probability	Severity	Mitigation
1	Orbital perturbations	D	4	Bury device on (multiple) bodies
2	Human intervention	D	4	Place on accessible planets of lower interest
3	Oblivion (never found)	C	5	Radioactive marker
4	Cosmic catastrophe	B	5	Material selection; redundancy of device
5	Inability for future humans to decipher information	D	4	Include several different methods of teaching

Table 15: Risks affecting success of the project. Probability and severity shown before mitigation.

Severity	5	4	3				
	4		1,2	5			
	3						
	2						
	1						
		A	B	C	D	E	
	Probability						

Table 16: Risk matrix after mitigation.

Table 14 is a first iteration of a concept solution. An example of risk mitigation for a space eternal memory concept is shown in Table 15. The concept should be refined through the concept selection phases as will be explained further in Chapter 7, Conclusions and Recommendations.

5.2 Storage Concept #2: Lunar Mission One

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 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 report as a necessary combinatory to the storage of digital data.

This report determines that Primary Needs 1, 3 and 5 and Secondary Needs 1b, 1c, 1d, 3b, 3d, 5a, 5b, and 5c (Figure 10) are most important for a space eternal memory concept for Lunar Mission One. As before, a metric is applied to each need from Table 4. Needs and Metrics are summarized in Table 17.

Important Needs	Metric	Units (if applicable)
1b, 3d The storage concept encourages global public engagement.	Instills human agency	# of people involved Level of direct involvement Attractiveness for human use (Subj.)
1d, 3b The storage concept encourages global science education	Global educational outreach opportunities	# of countries actively participating (Subj.)
1c The storage concept supports large amounts of information.	Raw capacity	Bits
	Memory storage density	Raw capacity divided by units of volume, length or width
5a The storage concept uses advanced new technologies	Current application and use	# of applications of technology utilized
	Time since development	Years

<table>
<tr><th>Important Needs</th><th colspan="2">Metric</th><th>Units (if applicable)</th></tr>
<tr><td rowspan="3">5b The storage concept is decipherable by future descendants.</td><td colspan="2">Probability of discovery</td><td># of storage systems
Beacon/"sign posting"</td></tr>
<tr><td colspan="2">Mutability</td><td>How it writes / reads</td></tr>
<tr><td colspan="2">Levels of encoding</td><td>Difficulty of decoding process</td></tr>
<tr><td rowspan="8">5c The storage device has a high chance of surviving without established environmental conditions.</td><td rowspan="5">Storage location parameters</td><td>Stability</td><td>Lifetime of orbit / geological stability</td></tr>
<tr><td>Harsh ionizing radiation</td><td>Radiation hardening (rad)</td></tr>
<tr><td>Micrometeoroid and dust environment</td><td>Probability of impact
Dust impactor environment (size, frequency)</td></tr>
<tr><td>Temperature</td><td>K</td></tr>
<tr><td>Hard vacuum</td><td>Pressure units</td></tr>
<tr><td rowspan="3">Storage technology parameters</td><td>Energy barrier against erasure</td><td>K</td></tr>
<tr><td>Storage medium type</td><td>Material / mechanism</td></tr>
<tr><td>Maximum lifetime</td><td>Years</td></tr>
</table>

Table 17: List of needs with corresponding metrics for Lunar Mission One.

Lunar Mission One is distinctive from the Rosetta Project because it already has an established location for storage, the Moon. In this case, competitive benchmarking will be completed only for a viable storage technology for the Lunar Mission One, as seen in Table 18.

Metric	Si_3N_4/T-based Gigayear Storage (de Vries, et al., 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, et al., 2013)	Rosetta micro-etched nickel (The Long Now Foundation, 2015); (Kelly, 2008)	DNA microchips (Church, et al., 2012)	Generational bacteria DNA storage (Mohan, et al., 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

Metric	Si_3N_4/T-based Gigayear Storage (de Vries, et al., 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, et al., 2013)	Rosetta micro-etched nickel (The Long Now Foundation, 2015); (Kelly, 2008)	DNA microchips (Church, et al., 2012)	Generational bacteria DNA storage (Mohan, et al., 2013)
Memory density	Dep. on photo-lithography (Manz, 2015)	40 MB/in^2	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
Develop-ment	2 years	1 year	2 years	7 years	3 years	8 years
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, et al., 2013)	2 hours at ~811 K (Hitachi, 2014)	Thermal stability at ~1273 K (Zhang, et al., 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)	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

Table 18: Compared metrics for various long-duration storage technologies based on Lunar Mission One needs.

The tungsten silicon-nitride data storage and the DNA data storage does 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. Since the hair strands are a vital part of the Lunar Mission One's 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.

Based on the metrics in Table 18, each storage technology is analyzed qualitatively (see Table 10 for key) to show perceived satisfaction of needs. This perceived satisfaction is shown in Table 19.

Metric	Si_3N_4/T-based Gigayear Storage (de Vries, et al., 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, et al., 2013)	Rosetta micro-etched nickel (The Long Now Foundation, 2015)	DNA microchips (Church, et al., 2012)	Generational bacteria DNA storage (Mohan, et al., 2013)
Instills human agency	*****	****	****	*****	****	****
Global education	****	**	**	***	***	***
Readout	****	****	****	*****	***	***
Memory density	****	****	****	***	*****	*****
Current application	****	***	****	**	****	****
Time since development	*****	*****	*****	***	*****	****
Probability of discovery	****	***	***	****	****	****
Mutability	*****	*****	*****	*****	**	**
Levels of encoding	***	***	***	*****	**	**
Space environment	***	***	Unknown	***	Untested	Untested
Barrier against erasure	***	***	***	***	Unknown	Unknown
Medium type	***	**	**	*	***	***
Hard vacuum	**	**	**	***	**	**
Maximum lifetime	*****	*****	*****	**	**	*****

Table 19: Competitive benchmarking chart based on perceived satisfaction of Lunar Mission One needs for available long-duration storage technologies.

These technologies would also need to undergo further testing in a simulated or actual space environment in order to assure satisfaction. 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, 2015) and would not be viable for the general public to purchase to send to the Moon.

Table 19 helps establish a technology which 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 and will be further explored in the concept generation phase. Marginal and ideal target values for the storage technology are set in Table 20.

Metric		Marginal value	Ideal value
Instills human agency		**4**	**5**
Global education		**3**	**5**
Raw capacity		TB (total)	TB to ZB
Current application		Research/Academia	Mass use
Time since development		<10 years	<5 years
Probability of discovery		**3**	**5**
Mutability		Write-once-read-many	Write-once-read-many
Levels of encoding		DNA	Combination of
Storage location parameters	Stability	Millions of years	1 billion years
	Radiation	Mitigation of background radiation	See marginal value
	Micrometeoroid and dust environment	Underground	See marginal value
	Temperature	-150°C	More research, testing needed
	Hard vacuum	Tested in space	Tested in space
Storage technology parameters	Energy barrier against erasure	Dependent mostly on radiation affects	More research, testing needed
	Maximum life	Millions of years	1 billion years

Table 20: Marginal and ideal target values for Lunar Mission One metrics. Qualitative definitions can be found in the Appendix.

We have limited the disk to something with more longevity than the Rosetta Disk. A combination of encoding schemes should 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 may be possible to use digital DNA storage for redundancy if processing costs could be minimized. This DNA storage could also serve as the data carrier of the Lunar Mission One's proposed Encyclopedia of Life, an integration of existing biodiversity archives (Iron, 2015).

Concept generation

The decomposition of problems by key stakeholder needs is used (Figure 11) to construct another concept combination table for Lunar Mission One (Table 21).

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, 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 with rays (Benford, 1999)	Meteorite-safe box	Cocktail of radioactive isotopes (Timer)	Parts of a puzzle, referring to each other	Dispersed tags of magnetic, acoustic or radioactive signs (Benford, 1999)
Focused conference	Dictionary	Silicon device with protective coating (Manz, 2015)	Combination astronomical events (Timer)		Metal residuals (Davies, et al., 1988)
Input of key stakeholders interested in eternal memory	Picture-based dictionary	Redundancy (sheer number of copies)	Pictures based on nature		Permanent magnets producing artificial pattern (Clarke, 1968)
Randomly selected documents	Use of sound				Granite disks perceived by acoustic probes (Benford, 1999)
Combination system	Combination system				Radioactive marker

Table 21: Concept combination table with components selected for Lunar Mission One.

Subproblems	Description of solution
(a) Selecting content	Lunar Mission One will involve publically-submitted data. It will also compile a global database of biodiversity (Iron, 2015). Universities and institutions worldwide should be contacted and a team should be established for combining databases.
(b) Teach the information to future hominids	The device can be stored near or at radial symmetries found in nature, such as a lunar crater with rays (Benford, 1999). These symmetries can be linked to mathematical series then used in the encoding. One Rosetta Disk may 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.

(c) Protect the storage device	The most effective form of protection is redundancy. Including several types of devices is recommended. Since Lunar Mission One will hopefully be the first of many journeys to the Moon, the first mission takes the first capsule and buries it. Additional markers and locations follow in later missions. Burying the disk will protect it, with background radiation still needing more exploration. Tungsten silicon-nitride disks could be manufactured, depending on further exploration of cost and storage density.
(d) Decode the information	Providing several devices helps in decoding of the information. An initial disk with human symbols offers basic enticement and instructions. This disk should appear at the top of a memory package. 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 would also make that part of the concept most accessible to current humans on Earth. It is a good source of science education for then how more complicated storage devices work, 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.
(e) Distributing the Storage Device	See (c) and (d). Also note, manufacturing different parts of a puzzle would result in too much specialization and too much cost. Replicating-based redundancy is better.
(f) Attract the attention of future hominids	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 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.

Table 22: A concept solution from the combination of those sub-solutions highlighted in Table 21.

A full concept solution is suggested in Table 22. For example, since Lunar Mission One plans to take multiple trips to the Moon, the project could build up a more detailed marker system over time, as more is learned about the lunar environment. 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. This solution both entices a future reader to learn more and is valuable educational outreach for Earth's current young math students.

5.3 Storage Concept #3: 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 in 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).

This report determines that Primary Needs 4 and 5 and Secondary Needs 4a, 4b, 5b, and 5c in Figure 10 are the most important for the Human Document Project. As before, a metric is applied to each need from Figure 10. These Needs and Metrics are summarized in Table 23.

Important Needs	Metric	Units (if applicable)
4a The storage concept supports large amounts of information.	Raw capacity	Bits
	Memory storage density	Raw capacity divided by units of volume, length or width
4b The storage concept has a method for comprehensive selection of information.	See Table 8	See Table 8
5b The storage concept is decipherable by future descendants.	Probability of discovery	# of storage systems Beacon/"sign posting"
	Mutability	How it writes / reads
	Levels of encoding	Difficulty of decoding process
5c The storage device has a high chance of surviving without established environmental conditions.	See Table 8	See Table 8

Table 23: List of needs with corresponding metric for the Human Document Project.

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 9 and Table 18, 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. Laura Welcher from the Long Now Foundation is working on a "Skunkworks" project for easier-to-produce Rosetta Disks (Welcher, 2015), although goals and design of the disk are unknown. DNA is also the oldest data storage in existence and is appealing as a use of mimicry to ensure survival of (Manz, 2015). Perceived satisfaction to the Human Document Project for various storage locations is shown in Table 24.

Metric	Under the surface of the Moon	Under the surface of Mars	Comet	Travelling on-board a S/C	Icy moon	Planet around an M star
Memory density	***	***	**	***	**	*
Experts	****	****	***	****	**	Unknown
Probability of discovery	****	****	*	*	***	***
Stability (years)	*****	*****	*****	*****	*****	*****
Radiation	***	***	***	***	**	**
Micrometeoroid, Dust	*****	****	***	***	***	Unknown
Temperature	*****	*****	*****	****	****	****

Table 24: Competitive benchmarking chart based on perceived satisfaction of the Human Document Project needs.

Any physical object sent outside our Solar System will be almost impossible to find back (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 the ITN, 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 deeply considered before implementation. Marginal and ideal target values can be found in Table 25.

Metric		Marginal value	Ideal value
Memory storage density	Technology	TB	TB
	Location	**3**	**5**
System for involving experts	Location	**3**	**5**
System to process received content	Technology	**3**	**5**
Probability of discovery	Technology	**3**	**5**
	Location	**4**	**5**
Mutability	Technology	Write-once-read-many	Write-once-read-many
Levels of encoding	Technology	DNA	Combination of human and DNA
Storage location parameters	Stability	2,000 years	10,000 years
	Radiation	Underground	See marginal value
	Micrometeoroid and dust environment	Underground	See marginal value
	Temperature		See marginal value
	Hard vacuum	Tested in space	Tested in space
Storage technology parameters	Energy barrier against erasure		See marginal value
	Maximum life	2,000 years	10,000 years

Table 25: Marginal and ideal target values for the Human Document Project.

Information should be supported by technology with high data densities, such as DNA, and should be stored within our Solar System. Concept solutions will be explored in the concept generation section.

Concept generation

The decomposition of problems by key stakeholder needs is used (Figure 11) to construct another concept combination table for the Human Document Project (Table 26).

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, 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 with rays (Benford, 1999)	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	Dictionary	Silicon device with protective coating (Manz, 2015)	Combination astronomical events (Timer)		Metal residuals (Davies, et al., 1988)
Input of key stakeholders interested in eternal memory	Picture-based dictionary	Redundancy (sheer number of copies)	Pictures based on nature		Permanent magnets producing artificial pattern (Clarke, 1968)
Randomly selected documents	Use of sound				Granite disks perceived by acoustic probes (Benford, 1999)
Combination system	Combination system				Radioactive marker

Table 26: Concept combination table with components selected for the Human Document Project.

Subproblems	Description of solution
(a) Selecting content	Content is selected through the Human Document Project consortium with input from the public similar in form to the online Rosetta Project database.
(b) Teach the information	Silicon-wafer disk keys communicate information through ontology trees. Key information is a focus on the species carrying information in its DNA.
(c) Protect the storage device	DNA-encoded species is protected by redundancy. The silicon-wafer key is buried in multiple locations on celestial bodies. Burying the disk will protect it, with background radiation needing more exploration. This silicon-wafer is cut into 5x5mm chips and embedded in amber (Manz, 2015). On moons with oceans or lakes, such as Titan and Europa, DNA is stored in bacteria. In Earth's history, the deep sea is least affected by events such as asteroids.
(d) Decode the information	Providing a cocktail of radioisotopes dates the storage of the device and is easy to sense if the device was 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.

Subproblems	Description of solution
(e) Distributing the Storage Device	See (c) and (d)
(f) Attract the attention of future hominids	Bioluminescence is used as a marker for the species carrying the information. Markers for the silicon wafer key should be explored in more depth.

Table 27: A concept solution from the combination of those sub-solutions highlighted in Table 26.

Table 27 is a first iteration of a concept solution. The concept should be refined through the concept selection phases as will be explained further in Chapter 7, Conclusions and Recommendations.

6. Performance to Plan

Performance was to plan in terms of setting personal deadlines and meeting them as per the Project Plan. Some methods of inquiry changed; for example, raw data collection was extremely reliant on personal interviewing and, therefore, more time-consuming than expected. It was also unexpected how much time an inquiry into project motivation would take, since the product development methodology was decided on later and it took significant time to modify that for the project's purposes. Although this step was time-consuming, it provided a systematic framework which in turn sped up the concept development process during the last stage. However, because of the deep inquiry into project motivations, the project is only now arriving at a place where technological and environmental considerations can be analyzed at a deeper level. First iterations of space eternal memory concepts have been considered with basic inquiry into radiation environments and orbital stability, but modelling was not deeply explored as was originally planned.

7. Conclusions and Recommendations

The first question many people will 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 desire of this report to demonstrate the possible value of storing information in space for a very long time. It is also the desire of this report to create links between existing stakeholders and to explore these topics in an interdisciplinary way.

Bodies within our Solar System, such as the Moon, Mars, or other planetary moons, are the best location for storing information if humans are to have access to the information after it leaves Earth. Travelling onboard a spacecraft or on a comet leaves the information relatively safe, but difficult to impossible to access. Motivations for storing outside of our Solar System are hard to substantiate until humans have the ability to leave the Solar System themselves.

The development of storage concepts revealed specific tradeoffs involved in a space eternal memory concept and possible gaps for further exploration. Tradeoffs will be discussed here and possible gaps for further exploration are articulated in Table 28. 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 becomes more challenging. Using radioactive materials, for example, as a detectable beacon are possible but then could damage the information it is called people to come and see. The tradeoffs of eternal memory are interesting and complex and have revealed many interdisciplinary questions.

Three space eternal memory concepts were developed for the Long Now Foundation's Rosetta Project, Lunar Mission One, and the Human Document Project. The Rosetta Disk functions as a decoder ring currently, but could be developed to relate directly to natural phenomena which have longer time scales than human language. The Rosetta Disk could be stored in space, on the Moon, Mars, or planetary moons, and redundancy is the best form of protection. It is recommended that the Rosetta Disk, in some form, fly on the Lunar Mission One. Radioactive isotopes could attract eventual visitors but should be stored with an appropriate distance from the eternal memory.

The concept for Lunar Mission One also relies on redundancy, but looks at solutions for longer time frames than the Rosetta Disk and is limited to a specific environment. It is recommended that Lunar Mission One use a combination of storage devices to meet various goals: technologies such as the Rosetta Disk entice future finders to read more, tungsten silicon-nitride technologies offer longevity and opportunities for public science engagement, and digital DNA storage offers high data density for an archive of Earth's biodiversity. The spectrum of memory packages of Lunar Mission One and its multi-mission strategy are aligned with this recommendation.

The concept for the Human Document Project relies on the encoding of bacterial DNA which is capable of surviving millions of years. These species could be scattered to planetary bodies within the Solar System and made attractive through bioluminescence. A silicon-wafer key gives ontological information about the key species. At this point, this is only a thought experiment and planetary protection should absolutely be considered.

Gap	Description of further research
Markers for silicon wafer key	In the concept solution for the Human Document Project, it is recommended that a silicon wafer key have indications of the key species. Markers for how to find this wafer should be explored.
Increase knowledge of lunar and Martian environment	First of all, a recommendation is to send more scientists on future lunar expeditions. Much is still unknown about the lunar interior, e.g. temperature, background radiation. Groups such as the Helena Payload Project and Time Capsule to Mars have explored long-duration storage on Mars, specifically as a precursor to colonization. However, little has been written about the effects of the Martian environment on these storage concepts
Generate sketches	Design sketches for concepts
Politics of eternal memory	There has been political tensions and cancelled projects before between space agencies and private players (Benford, 1999). This could be further explored and solutions offered.

Gap	Description of further research
Concept selection matrix	After the concept generation phase, there is also a more detailed concept selection phase that could be used for more systematic concept selection (Ulrich & Eppinger, 1995).
Quantum dots	Quantum dot storage is an interesting and developing topic and was not explored as a storage technology in this report.
Ethical considerations	The ethics and risks of storing information in bacterial DNA and depositing it on other celestial bodies should be further explored.
Additional stakeholders	This report has found that some stakeholders use eternal memory for crowdsourcing and promotional efforts. It could be explored whether or not there are other players, such as developing countries and emerging space countries, which could utilize this tactic.
Methodology	A storage concept has multiple components: the technology, the contents, a protective material. Each component could be explored separately using the product development methodology and then integrated. However, it is possible this method would add more tedium than is worth the value.
Testing of technologies	Testing of eternal memory devices in space environments

Table 28: Possible further exploration of space eternal memory.

This report 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 this project that 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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9. Appendix

	Instills human agency	Public awareness of the storage concept and its message	Adaptability of technology to changes in storage preference	Inclusion of material experiencing drastic and rapid loss	Raw capacity	Memory storage density	System for involving subject experts	Density of contributors	System to process received content	Probability of discovery	Mutability	Levels of encoding	Stability of location in space	Harsh ionizing radiation	Micrometeoroid and dust environment	Temperature	Hard vacuum	Energy barrier against erasure	Storage medium type	Maximum projected lifetime of storage technology
Need 3d	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓								
Needs 3c, 4d	✓	✓	✓	✓			✓		✓			✓								✓
Need 4a	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Need 4b	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓								
Need 5b	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Need 5c					✓	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 29: An example of a needs-matrix using the Long Now Foundation's Rosetta Disk.

Metric	Si_3N_4/T-based Gigayear Storage (de Vries, et al., 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, et al.,	Rosetta micro-etched nickel (The Long Now Foundation,	DNA microchips (Church, et al., 2012)	Generational bacteria DNA storage
Instills human agency	5	4	4	5	4	4
Public awareness of the storage	4	2	3	5	4	3

Metric	Si_3N_4/T-based Gigayear Storage (de Vries, et al., 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, et al.,	Rosetta micro-etched nickel (The Long Now Foundation,	DNA microchips (Church, et al., 2012)	Generational bacteria DNA storage (Mohan, et
concept and its message						
Adaptability of technology to changes in storage preference	4	4	4	5	2	2
Inclusion of material experiencing drastic and rapid loss	4	4	4	5	4	4
Readout	Camera + computer (de Vries, et al., 2013)	Optical microscope (Hitachi, 2014)	Optical microscope (Zhang, et al., 2013)	Optical microscope (Kelly, 2008)	DNA sequencing (Church, et al., 2012)	DNA decoding (Mohan, et al., 2013)
Raw capacity	See memory storage density	1.3 GB (Hitachi, 2014)	See memory storage density	See memory storage density	See memory storage density	See memory storage density
Memory storage density	Dependent on photolithography (go down to slightly sub-micron); affects lifetime (Manz, 2015)	40 MB/in^2 (Hitachi, 2012)	360 TB / DVD-sized disk (Zhang, et al., 2013)	200,000 page images / 2.4-in diameter disk (The Long Now Foundation, 2015)	Hundreds of TB / 1g of DNA (Church, et al., 2012)	0.1 GB / genome (Mohan, et al., 2013)
System for involving subject experts	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Density of contributors	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
System to process received content	3	1	1	4	1	1

Metric	Si_3N_4/T-based Gigayear Storage (de Vries, et al., 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, et al.,	Rosetta micro-etched nickel (The Long Now Foundation,	DNA microchips (Church, et al., 2012)	Generational bacteria DNA storage (Mohan et
System to process received content	3	1	1	4	1	1
Probability of discovery	4	3	3	4	4	4
Mutability	Write-once-read-many (de Vries, et al., 2013)	Write-once-read-many (Hitachi, 2014)	Write-once-read-many (Zhang, et al., 2013)	Write-once-read-many (Kelly, 2008)	Read/write (Church, et al., 2012) (Goldman, et al., 2013)	Mutating (Mohan, et al., 2013)
Levels of encoding	Binary	Binary	Binary	Human language	Digital encoded in DNA	Digital encoded in DNA
Space environment	Untested	Mounted on Shin-en 2 payload on Hayabusa 2 rocket (Hitachi, 2012)	Untested	Black oxide coated, laser marked titanium mounted on space station (Rose, 2011)	Untested	Untested
Energy barrier against erasure	1 hour at 848 K (de Vries, et al., 2013)	2 hours at ~811 K (Hitachi, 2014)	Thermal stability at ~1273 K (Zhang, et al., 2013)	65 hours at ~372 K and ~572 K (Los Alamos Laboratories, 1999)	Unknown	Unknown
Storage medium type	Tungsten encapsulated by silicon-nitride (de Vries, et al., 2013)	Silica glass encoded using laser writing (Hitachi, 2014)	Silica glass encoded using laser writing (Zhang, et al., 2013)	Electroplating / microetching on nickel (Welcher, 2015)	Encoded DNA (Church, et al., 2012)	Encoded Bacterial DNA (Mohan, et al., 2013)
Hard vacuum	Untested	Untested	Untested	Tested	Untested	Untested
Maximum projected lifetime of	Millions to billions of years	Millions to billions of years	Millions to billions of years	2,000 to 10,000 years (Kelly, 2008)	10,000 years (Church,	Millions of years (Mohan,

Metric	Si_3N_4/T-based Gigayear Storage (de Vries, et al., 2013)	Hitachi silica glass (Hitachi, 2014)	5D data storage on silica glass (Zhang, et al.,	Rosetta micro-etched nickel (The Long Now Foundation,	DNA microchips (Church, et al., 2012)	Generational bacteria DNA storage (Mohan, et
storage technology	(de Vries, et al., 2013)	(Hitachi, 2014)	(Zhang, et al., 2013)		et al., 2012)	et al., 2013)

Table 30: Compared metrics for various long-duration storage technologies based on Rosetta Project needs.

Metric	Description of qualitative measurements
Instills human agency	**1** Human interaction with the information is not accessible **2** Human interaction is attractive but only sometimes accessible **3** Human interaction is attractive and is accessible for limited time **4** Human interaction is accessible and has some attractiveness **5** Human interaction with the information is easy and very attractive
The storage concept encourages global science education	**1** The technology has no direct outreach or involvement with high school level students **2** The technology has few outreach opportunities or involvement from high school level students **3** The technology has some outreach opportunities or involvement from high school level students **4** The technology has a lot of outreach opportunities or involvement from high school level students **5** The technology has systematized, required outreach opportunities and involvement from high school level students
Public awareness of the storage concept and its message	**1** The storage technology could or has been developed into a storage device completely insularly and without any public outreach **2** The storage technology could or has been developed into a storage device insularly to a specific company or organization with minimal outreach **3** The storage technology could or has been developed into a storage device insularly to a discipline or research group; there is some public outreach **4** The storage technology could or has been developed into a storage device insularly to a specific community with some input from the public; public outreach is a systematized component **5** The storage technology could or has been developed into a storage device in conjunction with diverse

Metric	Description of qualitative measurements
	sources, e.g. academic, public, industry; public outreach is an important component
Adaptability of technology to changes in storage preference	1 Reading system is complex; levels of encoding is high 2 Reading system is buildable; level of encoding on that of DNA 3 Reading system is buildable; information is digital 4 Reading system is buildable; information is optical 5 Reading system relies on simple use of electromagnetic waves; the encoding is human language
Inclusion of material experiencing drastic and rapid loss	1 Technology supports information abundantly available and would not increase its use 2 Technology supports information easily available and would not increase its use 3 Technology supports information which is available and would not change its use 4 Technology supports information which is difficult to find and would increase its use 5 Technology supports information held only by a small group of people globally and could increase its use at a fast rate
System to process received content	1 Processing and preparation of content for technology can be done only by specialized, skilled labor acquired over a lot of time 2 Requires skill and specialization but can be acquired with either low time or low cost 3 Requires skill and specialization but can be acquired quickly and with low cost 4 Requires skill but not specialization and can be acquired quickly 5 Processing of content can be done by unskilled laborers under the advisement of several skilled laborers
Probability of discovery	1 Technology cannot be widely distributed and is not visible 2 Technology is easy to distribute but not visibly catchy 3 Technology is relatively easy to distribute but does not attract much attention visually 4 Technology can be distributed moderately abundantly and visibly 5 Technology can be distributed abundantly and visibly

Table 31: Descriptions of qualitative measurements for metrics of storage technology.

Metric	Description of qualitative measurements
Instills human agency	**1** Human interaction with the information is not accessible **2** Human interaction is attractive but only sometimes accessible **3** Human interaction is attractive and is accessible for limited time **4** Human interaction is accessible and has some attractiveness **5** Human interaction with the information is easy and very attractive
Public awareness of the storage concept and its message	**1** The location is of interest only completely insularly and without any public outreach **2** The location is of interest insularly to a specific company or organization with minimal outreach **3** The location is of interest insularly to a discipline or research group; there is some public outreach **4** The location is of interest to a specific community with some input from the public; public outreach is a systematized component **5** The location is of interest in conjunction with diverse sources, e.g. academic, public, industry; public outreach is an important component
Adaptability of technology to changes in storage preference	**1** Space travel to that location is undeveloped **2** Space travel is not reliable and unlikely to be available for a very long time **3** Space travel is reliable but not always available **4** Space travel is not available but is likely to be available soon **5** Space system to get to that location is reliable and likely to be available for a very long time
Inclusion of material experiencing drastic and rapid loss	**1** Technology supports information abundantly available and would not increase its use **2** Technology supports information easily available and would not increase its use **3** Technology supports information which is available and would not change its use **4** Technology supports information which is difficult to find and would increase its use **5** Technology supports information held only by a small group of people globally and could increase its use at a fast rate
Memory density capacity	**1** Amount of information is highly limited by size and mass of location **2** Amount of information limited by size and mass of location

Metric	Description of qualitative measurements
	3 Amount of information is important but not hugely limiting **4** Amount of information should be considered because of the location but is not highly limited **5** Amount of information is unlimited by location
System for involving subject experts	**1** There are no experts on this location **2** There are some experts on this location but no interest in space eternal memory **3** There are some experts on this location and some interest in space eternal memory **4** There are many experts on this location and some interest in space eternal memory **5** There are many established experts on this location and many interested in space eternal memory
System to process received content	**1** Processing and preparation of content for technology can be done only by specialized, skilled labor acquired over a lot of time **2** Requires skill and specialization but can be acquired with either low time or low cost **3** Requires skill and specialization but can be acquired quickly and with low cost **4** Requires skill but not specialization and can be acquired quickly **5** Processing of content can be done by unskilled laborers under the advisement of several skilled laborers
Probability of discovery	**1** Not settled by humans now and not desirable to be settled by humans at all **2** Not settled by humans now and unlikely to be settled by humans at all **3** Not settled by humans not but likely to be settled by humans but not soon **4** Not settled by humans not but likely to be settled by humans soon and for a very long time **5** Settled by humans now and likely to be for a very long time

Table 32: Descriptions of qualitative measurements for metrics of storage location.