NASA Contractor Report 185272

A Study of Mass Data Storage Technology for Rocket Engine Data

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(NASA-CR-185272) A STUDY OF MASS DATA STORAGE TECHNOLOGY FOR ROCKET ENGINE DATA Final Report (Honeywell) 121 p CSCL 21H

N92-14110

Unclas

G3/20 0058226

June 1990

Prepared for
Lewis Research Center
Under Contract NAS3-25714

National Aeronautics and
Space Administration

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A. SUMMARY

This section presents a summary of the study program on a Study of Mass Data Storage for Rocket Engine Data, conducted by Honeywell, Inc. for NASA Lewis Research Center under contract NAS3-25714. The work was performed by Honeywell Systems and Research Center, Minneapolis, MN, with Rocketdyne Division of Rockwell International Corp., Canoga park, CA, as a subcontractor. The work was performed over the period from September 1989 through May 1990.

This summary includes the objectives and scope of the work and the results obtained. It emphasizes the conclusions reached during this study program. The processes and reasoning leading to those conclusions are presented in following sections.

The objectives of this program were:

- To recommend a candidate mass data storage (MDS) technology development for rocket engine health monitoring and control (HMC).*

- To develop a project plan and specification (PPS) for the technology development.

The scope of the work included four defined tasks:

I. Program Management
II. Development of HMC MDS Requirements
III. Survey of MDS Technologies
IV. Development of MDS HMC Project Plan and Specification (PPS)

Task I included management to ensure successful completion of the work within the constraints of the budget and available time.

Task II included a review of current MDS technology for HMC. During Task II, we identified and analyzed the requirements and approaches to MDS, determined limitations and critical areas, and developed a weighted prioritization for the various requirements. Two of the most important

* Acronyms will be defined the first time that they are used in this document. For reference, a listing of acronyms is compiled in the Appendix.

requirements were the total data capacity, determined to be 3.3 G bytes for a three-engine vehicle, and the recording rate, determined to be 23.2 M bits/second, also for a three-

During Task III, we surveyed and analyzed both the current state-of-the-art MDS technologies and also new developing concepts for MDS. In the survey, we included a variety of optical approaches, plus electronic and magnetic techniques. We rated each technology with respect to each of the requirements defined in Task II and established a scoring matrix for the technologies. The result of this procedure led to a recommendation for the best candidate for technology development.

Specifically, the recommendation was optical disk technology, with emphasis on increasing capabilities in the areas where the technology can be upgraded to meet the defined requirements. The technology development should thus emphasize factors like increase of recording rate, increase in packing density or use of multiple element writing heads.

In addition, because of rapid advances in so-called digital paper, a related optical recording technology, we suggested that a second technology development be undertaken, if funds are available. The second program would emphasize advances in digital paper systems.

In the final Task IV, we developed a PPS for the technology development. This PPS is based on the results of the earlier tasks. It includes a work breakdown structure, i.e., definition of a set of tasks to develop, test, analyze and demonstrate a proof of concept (POC) model for the technology development. It also included estimation of a level of effort to complete the POC.

The critical issue addressed in formulation of the PPS was the need to increase the recording rate by about one order of magnitude above the current state-of-the-art for optical disk systems. The specific concept defined for the POC demonstration included the following features:

- Write-once read-mainly (WORM) recording media in a banded format on a two-sided 10-inch-diameter glass disk.

- Use of 780 nm laser diode sources.

- Data spaced 1.3 μm center-to-center along a spiral track within a band, with 1.6 μm between adjacent loops of the spiral.

- Use of current focus/tracking servo controls.

- Development of heads incorporating four laser sources, two for writing, and two for direct read after write (DRAW).

We estimate that this development could be performed over a 20-month period, beginning January 1991, and would require 13058 person-hours (with a labor mix of senior engineers, junior engineers and technicians), plus $174K of materials.

We also developed a PPS for an alternate program of reduced scope, which would emphasize modification of a currently available optical disk memory unit by addition of a 4-source laser head. This would not meet the full capacity requirement, but would demonstrate the most important advances needed to achieve the increase in recording rate.

This development could be carried out over a 20-month period, and would require 8036 person-hours of labor plus $201K of materials.

In conclusion we have developed a specific recommendation for optical disk technology development, leading to a POC model. The emphasis would be in writing head technology development leading to increased data recording rate. The objective would be to achieve an order of magnitude increase in recording rate on a single optical disk system.

B. INTRODUCTION

Health monitoring and control (HMC) represents an important technology for determining the condition and performance of rocket engines. HMC utilizes the outputs of many sensors operating at high data rates, and therefore generates large amounts of data which are recorded and stored for analysis and evaluation after a flight. Thus, mass data storage (MDS) technology is required to record these large amounts of data. Current approaches for onboard MDS utilize magnetic tape recorders, which were developed many years ago. In recent years there have been significant advances in MDS technology. The use of these more advanced technological approaches could improve the collection and availability of the HMC status information. The program described in this report defines technology which can increase the health evaluation productivity for rocket engines, especially the space shuttle main engine (SSME), by providing increased storage capacity and functionality.

In response to the need for advanced MDS for HMC, this program had as its objective the development of recommendations and a project plan and specification (CPPS) for the best candidate for technology development to meet the requirements for MDS for rocket engine HMC.

The process by which this objective was met included:

- Generation or prioritized requirements for HMC.
- Performance of a survey of state-of-the-art technology for collecting critical mission flight data in a hostile environment to determine SSME performance and to increase engine health evaluation.
- Combination of the results of the survey with the prioritized requirements in order to generate a recommendation for the best candidate for NASA development for HMC MDS.
- Generation of a set of tasks required to carry out the technology development.

In this program, Honeywell, as prime contractor, was strongly aided by Rocketdyne Division of Rockwell International Corporation, as a subcontractor. In particular, Rocketdyne contributed to the generation of requirements for HMC and to the definition of environmental requirements.

The work in the program was organized into four tasks:

I. Program Management
II. Development of MDS Requirements for HMC
III. Survey of MDS Technologies
IV. Development of a Project Plan and Specification for MDS Technology Development

The first task involved management of the contract to ensure successful completion within cost and schedule. It utilized Honeywell's computerized project status reporting system and ran concurrently throughout the program with the other tasks.

The other three tasks represented the technical work carried out under the program. They were carried out in order sequentially, with each task drawing heavily on the results of the preceding task(s). The technical work was accomplished over a nine-month period from September 1989 through May 1990.

In Task II on development of requirements, we reviewed the current technologies for HMC MDS, identified and analyzed the requirements and defined and prioritized the critical areas and requirements.

The subtasks in Task II included:

- Summary of MDS technology now in use for HMC.
- Evaluation of its effectiveness.
- Definition of critical requirements and limitations.
- Prioritization of requirements.

Task II concluded with a teleconference review of the task with NASA personnel in January 1990.

The work in Task III emphasized survey and analysis of MDS technologies, including both current and newly developing concepts and approaches. The survey included optical technologies, especially optical disks, holographic systems, fiber optic systems, optical card readers and digital paper. We also included magnetic technology (disks and tape) and electronic technology (semiconductors) in order to ensure a complete evaluation. We folded the results of the survey together with the prioritized requirements generated in Task II in a matrix format in order to obtain a quantitative ranking of the technologies for MDS applications. As a result, we generated a recommendation of optical disk technology as the best candidate for NASA investment for future MDS for HMC.

The subtasks in Task III were:

- Compilation and analysis of state-of-the-art MDS technologies.
- Computation and analysis of new concepts and technologies.
- Development of a recommendation for technology development.

Task III culminated with a teleconference review with NASA personnel in March 1990.

Task IV involved development of a PPS for the recommended technology development. It involved generation of a specific recommendation for a proof-of-concept (POC) demonstration, along with a work breakdown structure to accomplish this.

Subtasks in Task IV were:

- Generation of the technology concept.
- Compliance with operating environment specifications.
- Compliance with HMC MDS requirements and specifications.
- Development of POC requirements and specifications.
- Generation of tasks to develop the POC.
- Determination of required level of effort and costs.

Task IV culminated in a final review conducted at NASA Lewis Research Center on 14 June 1990.

The next section will describe the work and results from Tasks II, III and IV in detail. Although Tasks II and II have been reported earlier in separate reports, they will be fully described here in order to make this final report a complete description of the program.

C. TECHICAL DISCUSSION

This section describes the details of the work performed under contract NAS3-25714, a study of Mass Data Storage Technology for Rocket Engine Data, by Honeywell Systems and Research Center, Minneapolis, MN. The program had the objective of developing a recommendation and a program plan and specification for the best candidate(s) for technology development for MDS for HMC.

The program had four main tasks:

- Program management to ensure successful completion within cost and schedule constraints
- A review of current data storage technology, leading to development and prioritization of MDS requirements
- A survey and analysis of current and new MDS technologies, leading to a recommendation for technology development
- Generation of a program plan and specification for the recommended concept

This section reviews the technical tasks (i.e. the second, third and fourth of the above tasks) in sequence, presenting the approach and methodology used in each task and the conclusions reached in each case.

C-1. Definition of Requirements

This subsection presents a summary of the conclusions of Task II, the development of requirements for MDS for HMC. In this work, we reviewed current data storage technology used in the Space Shuttle Main Engine (SSME) performance and health monitoring for both flight and ground testing missions. We identified and analyzed the requirements, approaches and methods for MDS and determined limitations and critical areas for current MDS approaches.

The work in this task relied heavily on data inputs from Rocketdyne, acting as a subcontractor to Honeywell on this program. Information provided by Rocketdyne included the following documents and communications:

RSS-8561 SSME STRUCTURAL LOADS CRITERIA

RC1493 CONTROLLER, SPACE SHUTTLE MAIN ENGINE, PROCUREMENT SPECIFICATION

RC1494 INTERFACE CONTROL DOCUMENT, CONTROLLER/ENGINE AND GROUND SUPPORT EQUIPMENT

TECHNOLOGY TEST BED ENGINE TEST PLAN (DRAFT, EXERPTS)

MECN:WB/1/029 (UNTITLED, EXERPTS)

SPECIFICATION CODE IDENTIFICATION NO. 03953, Environmental Requirements and Test Criteria for the Orbiter Vehicle

Letters and Communications:

14 November 1989, Letter on Rocketdyne Subcontract, Submittal for Mass Data Storage, Ian Cannon
Facsimile Transmissions, 12 December 1989, 21 December 1989, and February 7, 1990
Telephone Conference, 12 December 1989

Using the input from Rocketdyne, the Honeywell personnel have defined and prioritized critical areas and requirements relative to SSME engine environments. The conclusions based on this work were used as inputs for Task III, the survey of MDS requirements.

The remainder of this sub section is organized as follows:

Sub sub section C-1a.	Review of Present Day MDS Technology for HMC
Subsub section C-1b.	Analysis of the Present MDS Approach
Subsub section C-1c.	Requirements for HMC
Subsub section C-1d.	Prioritization of Critical Areas and Requirements for HMC

C-1a. Review of Present Day MDS Technology for HMC

The present MDS system records both analog and digital data on two separate data recording units, the Modular Auxiliary Data System (MADS) and the Mass Memory Unit (MMU), respectively.

The MMU is a magnetic tape unit manufactured by Odetics. There are two units on each shuttle. All critical data are recorded three times on each unit. If the first unit fails, one switches to the second; then if the second fails, one switches back to the first. The performance of this unit exceeds the expected life.

The MMU is a sealed unit under a positive pressure (minimum 3.28, maximum 18.0 PSIA). The details of the Odetics drive mechanism are proprietary but it is called a "delta drive", delta because of the triangular set of drive belts/pulleys which are redundant in that if one belt breaks the unit still performs its function. Another interesting note is that the MMU has burst error correction capability; it can handle 2 single bit errors stretched by 50 bits, i.e., it covers "gaps" up to and including 48 bits, which is typical of tape flaws or missing oxide. The MMU access time is 700 ms.

MMU requirements for vibration test include: random vibration peaks in the range 150-1000 Hz with ground requirements of 0.067 G squared/Hz. This is ramped up at 6 db/octave form 20 to 80 Hz, flat from 80 to 350 Hz, and ramped down at 3 db per octave from 350 to 2000 Hz, with duration 2.5 minutes. Flight vibrations are flat at 0.03 G squared per Hz, with the a ramp schedule of 6db/octave from 120 to 150 Hz and ramp down at 3 db/octave to 1000 Hz, with duration 48 minutes. Acceleration requirement is 5 G, and shock is 20 G. The MMU operating temperature is specified at 35 to 105 F, with nonoperational storage from minus 10 to 120 F. The unit is cold plate cooled and typically operates between 55 to 80 F. The size is 14 x 10 x 7.5 inches, weight 27 lbs max. It requires 28 VDC. The power is 20 watts stand by, and 94 watts maximum. Some additional characteristics of the MMU are presented in Table 1.

The MADS recorder (Modular Auxiliary Data System) is a single point system, i.e., no redundancy measures are incorporated. If the tape drive fails, that is that. It is a wideband magnetic tape system. It can switch tracks and make three complete passes at 2 hr/pass. One pass is for ascent, one for orbit, and one for reentry. Specs/requirements include: temperature range +35 to -120 F (the MADS is in the crew compartment). The unit typically operates between 65-95 F. The temperature specification is for the sake of the tape more than anything: it keeps tape from sticking or flaking; the tape does not like to be "frozen". The unit breathes and has 0.5 PSI relief valves. Random vibration peaks in the range 20-2000 Hz with ground requirements of 0.067 G^2/Hz. This is ramped up at 3 db/octave from 20 to 80 Hz, is flat from 80 to 350 Hz, and ramped down at 3 db per octave from 350 to 2000 Hz. Flight vibrations are 0.09 G^2 per Hz, with the same ramp schedule as ground vibe testing and the same peaks. Acceleration required is 5 G, and shock is 20 G. Life requirement is for 100 hr head life. These units operate until failure and are replaced.

TABLE 1

SHUTTLE MASS MEMORY UNIT

Data storage	8 data tracks
	8 files
	8 subfiles/file
	32 blocks/subfile
	512 words/block
	16 bits/word
	128 M bits total (data)
	16 M bytes
Data transfer	1 M bit/sec
Useful life	100 orbital missions over a ten year period (20,000 equivalent tape passes)

The signals from the sources go through a Frequency Division Multiplexer (FDM) and a linear amplifier. Up to 15 signals drive a VCO (Voltage Controlled Oscillator). It "FMs" the voltage by swinging frequencies relative to voltage changes. The 15 signals are then summed together and the composite signal goes to one track on the MADS. On the output/recovery side the data goes through a discriminator narrow band filter producing the DC voltages initially input. There are 4 multiplexers on each FDM. The signal-to-noise ratio of each composite signal is 1.5% of full scale.

The unit is similar to the Bell and Howell 3700 lab recorder but reconfigured for packaging. The reels are coaxial (over/under) and use two tensioning systems for feed and take up sides. The MADS package is 20 x 14 x 8 inches and weighs 65 lbs. including tape. The cost is around $200K (recorder only). A playback suitcase has 28 reproduce boards on it and is used as ground support equipment to off-load the data after the orbiter lands. Capacity can be assessed as 9200 feet of tape (full 14" reel of 1" tape), at 15 inches per second. It records 128 kbit per inch per track, for 9200 feet times 28 tracks.

The zero G challenge is addressed by use of transport guides on rollers, large wrap around angles on capstans, and tape path helpers, some of which are built into the cover to limit tape travel. Potential problems can result if the system is not operated "properly". The tape tends to go slack if the system is powered off at 60 IPS speed; the braking system cannot handle this without slack. This results from built in measures designed to prevent stretching the tape, but one could picture it simply as an inertia characteristic. If the tape comes off the guide rollers, it can scrape on the erase head.

Another possible consideration is the ease of post flight data distribution. It currently takes a week to get the MADS data to Rocketdyne. First the orbiter has to cool; then the data passes out the umbilical through the reproduce boards GSE "suitcase" to ground recorders. These go to NASA MSFC for archival storage and reproduction before being distributed to various NASA centers and vehicle and rocket engine contractors. It would be desirable if right after landing one could "hand out CDs" to all the entitled parties.

The next section presents discussion and analysis of the present day technology.

C-1b. Analysis of the Present Mass Data Storage Approach

The definition of a state-of-the-art mass data storage system must include an identification of the strengths and weaknesses of the present engine mass data storage system. We have performed an analysis of the present MDS system and identified, with the help of Rocketdyne, several system characteristics which must be included in future mass data storage system.

Digital vs Analog Data Storage

The present MDS system records both analog and digital data on two separate data recording units, the Modular Auxiliary Data System (MADS) and the Mass Memory Unit (MMU) respectively. This separation of data as a function of format is inefficient in overall system weight, due to multiple recorder systems, and data access (see Data Access below). Analog-to-Digital (A to D) technology exists which will allow the realtime digitization of all of the analog data which must be recorded. Having all of the data in a digital format will simplify the MDS unit requirement and improve access to the data. Improved redundancy management will also be possible. Finally, having only digital data will allow the use of the more sophisticated and efficient data storage technologies, like optical and magnetic discs and solid state memory systems, to meet all of the mass data storage needs of the HMC system.

Distributed vs Centralized Data Recording

The sensor and data storage architecture is also an important system characteristic. The issue is whether one should have a single centralized data collection system or a distributed architecture with "smart sensors". The present system has a centralized architecture and the advantages of a centralized architecture make it the best choice for future MDS systems. Cost effectiveness and reliability are the two biggest advantages. A distributed system will have more expensive sensors, an additional data bus to manage the transmission of data from the distributed systems to the controller, and will require extremely highly reliable individual parts in order to make the entire system as reliable as the centralized MDS system. The centralized system is easier to implement with the engine controller, easier to make reliable, and less complex and thus less expensive. There would continue to be a separate controller for each engine.

The HMC architecture envisioned during this study is very similar to that presently used for the SSME. We assumed that there would be individual controllers for each engine and that the HMC function for each would reside in its individual controller. We assumed also that the output data to be stored by the MDS system would be transferred to a single central location (e.g. mission controller). This is similar to what is done on the space shuttle. In this architecture, a single HMC

MDS hardware set could be used for storage of all HMC data. This single HMC MDS system would meet the overall memory capacity requirements and recording rate requirements defined during Task II.

Data Access

Data access can be broken down into two parts: 1) post-mission access and 2) real time access. The real time access of engine data is not seen as an immediate requirement at this time, but scenarios can be conceived where real time access will be important. Post-mission access is important now, however, and the present system has an access time to the analog data of roughly 1 week. Future mass data storage systems must have post-mission access time on the order of hours, not weeks, and should probably have some real time access potential. The centralized all digital system discussed above can fulfill both of these access requirements.

We should be careful to distinguish between the different time scales of interest for memory technology. One time scale involves the access to a particular desired bit (or block) of information. On any rotating disk system, that access time is usually taken as aproximately one-half the reciprocal of the rotation rate. This is because, on the average, one must wait for the disk to complete one-half of a revolution before the desired bit comes to the read head. In addition, one must add the time that it takes for the read head to move to the track that the bit is on. This is usually shorter than the time for one-half revolution of the disk. For example, in current optical disk systems, the rotation rate is typically 1800 RPM or 30 revolutions per second. The average time for the desired bit to come under the head is thus about 17 ms. The time for the head to shift tracks is around 8ms. Thus the total access time is usually quoted as 25 ms.

This access time, which is the time to reach a particular random piece of information in an operating system, is different from the time to reset the memory. That time becomes an issue in maintainability and in getting the memory system ready for use again after a mission.

In our analysis of the operation of the HMC MDS system, Task II, we concluded that real time access to the data is not an important factor. In the current space shuttle, the data is in fact not used on board the shuttle, and we could not identify any application for which it would be required. Still, we recognize that real time access to the data could add a dimension of versatility of the MDS system, perhaps for additional future applications. The specific system which we will propose later for the POC demonstration (Section C-3) will in fact be compatible with real time access on board a flight (with a latency around 25 ms).

Media Alternability

Optical disks use a variety of recording media, some of which may be written only once and thereafter read but not rewritten. On others, the media allows complete writing, reading and erasing. These media are referred to as rewritable. (The term erasable has fallen into disfavor because it seems to imply a chance of losing data).

Thus, we judge that use of a rewritable media would be a somewhat desirable feature, mainly from the point of view of resetting the memory after a mission. The specific technology development that we propose later for the POC technology development is based on WORM media. But we note that the technology development would be compatible with and useful for rewritable media also, as they become more widely available.

For an optical disk which uses an unalterable medium, like the current write-once read-mainly (WORM) systems, the memory can be reset only by physically disassembling the unit, removing the media and replacing it with a new unwritten media. This is an operation that may take several hours, but should not exceed one day. For rewritable optical memory units, which are now beginning to become available, the reset time would be the time to erase all the data. For a memory with the capacity and data rate defined in Task II, this would be about 20 minutes. This factor would tend to favor the use of rewritable memories, but we judge that it would not be an extremely critical advantage.

Recorder Environment

The choice of the environment in which the MDS system will operate will strongly impact the cost of the system. The choices trade off distance from the sensors, available space, and the harshness of the environment. The present system resides in the cabin environment. The future system will also greatly benefit from this choice of locations if it is possible in a manned vehicle. In an expendable advanced vehicle, there may be no environment available which is as benign as the cabin. An environment such as the area of the engine interface unit might be a reasonable compromise area for location of the recorder on such a vehicle. In addition to having more benign environmental requirements, which translate directly into cost, the cabin environment also opens up the opportunity to use the MDS system for additional data storage tasks like mission and experimental data. The most versatile and cost effective future MDS systems should take advantage of this choice of environments.

Redundancy Management

Redundancy is an important issue for all space missions for obvious reasons. The present MDS recorders have two different levels of redundancy. The MMU system has two separate recorders and a recording algorithm which records the data in triplicate to avoid tape difficiencies. The MADS recorder has no redundancy. Future MDS systems must have redundancy but preferably at a lower cost, weight, and power expense than the MMU redundancy scheme. The newer, more dense digital recording technologies are expected to offer this type of redundancy option.

Recorded Data Format

The data recording format issue is whether to store the raw sensor data or processed engineering data. The processed data offers quicker use of the data in the post-mission analysis, but if the data are suspected to be in error, the effort required to reconstruct the original raw data can be enormous. Engineering data can also require as much as 10 times as much memory per data element due to the necessary inclusion of conversion and scaling factors. The present system records raw data and future systems should do the same, although all of the data should be digital as described above.

Catastrophic Event Data Recovery

The analysis of a catastrophic event will require as much mission data as can be made available and engine data will have a high priority in such an analysis. Both the MMU and the MADS data of the Challenger were recovered. Future MDS systems must offer similar catastrophic event survivability. The entire MDS unit may not be able to survive such an event, and the design of a unit which would might be prohibitively expensive, but the systems recording media must have a high probability of surviving so the the engine data can be recovered.

C-1c. Requirements for HMC

In this section, we evaluate the requirements for HMC MDS. First, we defined a variety of general categories of requirements for the MDS system. The categories are the following:

- Data Storage Capacity
- Reliablity
- Resource Usage
- Environmental Factors
- Access Time
- Reusability
- Risk

Then within these categories we defined specific individual factors relevant to the system operation. These specific factors are defined later. We finally derived quantitative crtieria for these factors for each of three types of mission scenarios:

- Current Flight System (i.e. the space shuttle)
- Ground Test Stand
- Advanced Vehicle (i.e. a future mission requiring a reusable engine)

We first discuss these missions, then return to a description of the various requirements.

1. Current and Advanced Shuttle Vehicles

Functional Architecture- Figure 1 illustrates the functional data path for main engine data. The main engine controller is a computer/controller which acts as a control and monitoring interface between the shuttle vehicle and the engines. Some of the engine data is derived from transducers on the engine, while other data originates from the controller. For instance, actuation command signals originating in the controller are recorded as engine data.

The figure basically shows the flow of the data gathered by the sensors for each engine. The sensors are listed near the top left of the figure. Each engine is controlled by a main engine controller, which is a dual channel device containing two digital computers. The controller controls all main engine components and operations. When engine data are sent to the engine controller, the data are stored in a vehicle data table in each comuter's memory. The vehicle data table is periodically output by the controller to the engine interface unit (EIU).

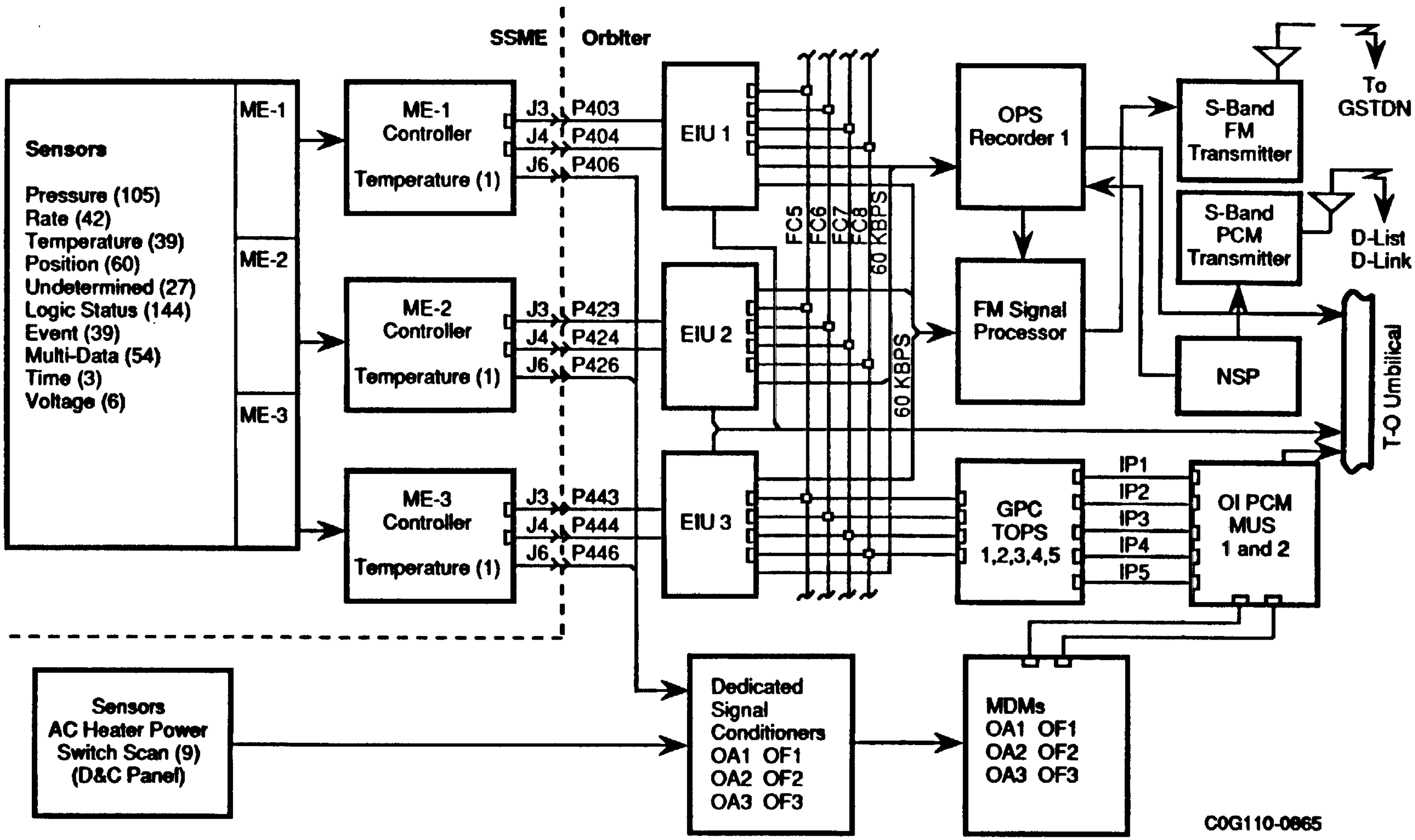


Figure 1. Block Diagram for Flow of Data from Space Shuttle HMC Measurements

The EIU is a specialized multiplexer/demultiplexer that interfaces the general purpose computers with the main engine controller. When SSME data are received by the EIU, the data are held in a buffer until a computer requests data from the EIU. The EIU then sends the data to the computer. Each EIU is dedicated to one SSME and communicates only with the main engine controller for that engine. The EIU's do not interface with each other.

Engine data are currently recorded on the two recorders described earlier, the Mass Memory Unit (MMU), and the Modular Auxilary Data System (MADS). The Mass Memory Unit is a digital recorder, and is recording data from other systems aboard the vehicle as well as engine data. It has a weight of 27 pounds, a volume of 1050 cubic inches, and consumes a maximum of 94 watts. All engine data on the digital data bus are recorded on the MMU.

The MADS recorder is a wideband analog tape recorder. It weighs 65 pounds, and has a volume of 2240 cubic inches. The MADS unit records all of the analog data described below.

We considered that digital processing technology has advanced so far that any retrofit or modification of the shuttle mass data storage would eliminate the analog storage and all analog measurements would be converted to digital information. Thus, one digital mass storage device would be used to record all engine data. Of course, the recorder may well be duplicated for redundancy as is done with the present MMU.

In Table 2, we summarize the requirements for MDS capacity and recording rate on a per engine basis. If one uses a single MDS unit for a multi-engine vehicle, as we have recommended in Section C-1b, one multiplies the capacity and rate by the number of engines. In particular, Table 2 includes the capacity and recording rate for a three engine vehicle, like the space shuttle. The numbers presented in Table 2 represent an important result, one which had a strong influence on the requirements definition as described later.

We note that these numbers represent user-available data. The total capacity of any MDS system must be larger than the user-available data because of the requirements of error correction, formatting, etc.

An advanced reusable spacecraft was also considered. We note that there is not yet any design or specifications defined for such a vehicle. We considered that the total engine health data to be recorded would be very similar to the baseline shuttle. There are two competing factors. One is a desire to gather more data with a wider variety of sensors in order to do a more complete job of

HMC. The second is the probability that future engines will be designed with more performance margin built in, so that less data would be required for HMC. We judge that these two tendencies will approximately balance so that HMC data requirements on a per-engine basis will not change signficantly. The architecture would be also similar, and again we envision the engine health data to be entirely digital, and stored on a single recorder. The mission duration was considered much longer, so that data permanence and reliability must be enhanced. Additionally, the longer mission duration created a desire for access to health data during the mission, so that engine health data could be transmitted during the mission. In a future vehicle, there could be a larger number of engines, perhaps as many as 10 for the ALS (Advanced Launch System). Thus the results shown in Table 2 should also apply to an advanced flight system. Since Table 2 presents data on a per engine basis, it is easy to scale for a number of engines other than 3.

Engine Health Data - Data from the baseline shuttle contains both digital and analog data. There are 128 digital parameters and 8 wideband analog parameters recorded for each engine. The digital words are either engine controller digital command words or switch and valve discrete status parameters. Data is recorded for a total of 1140 seconds.

The present analog data consists of 6 channels at 1000 Hz. and 2 channels at 5 KHz. There is some desire by Rocketdtyne to increase both the number and frequency response of analog channels. This would increase the analog data to 12 channels at 20 KHz. Table 2 summarizes the data requirements in terms of rate and the total capacity required, using the higher "wish list" analog requirements.

Although the parameters recorded may be different for an advanced system, there are separate tendencies which both increase and reduce the amount of data required. We believe these tendencies will approximately cancel out, and the maximum data rate and total capacity will be the same for the advanced space transportation system.

TABLE 2

SHUTTLE AND ADVANCED VEHICLE DATA REQUIREMENTS

Data Per Engine -

Digital	128 ch @ 25 samples/s, 16 bit	= 51.2 Kbits/s
Analog	12 ch @ 40,000 samples/s, 16 bit	= 7.68 Mbits/s
	Total	= 7.73 Mbits/s

Record Time, 1140 sec

Total Storage per engine = 7.73 Mbits/s x 1140 s = 8.81 Gbits

Total Storage per vehicle = 8.81 Gbits x 3 = 26.4 Gbits (3 engines)

Maximum Vehicle Rate = 7.73 Mbits/s x 3 = 23.2 Mbits/s (3 engines)

Environmental Requirements - The shuttle cabin environment at the location of the MMU was taken as the environmental requirement for both the existing shuttle and an advanced spacecraft. Table 3 summarizes the environmental requirements. An additional requirement considered was survivability of a catastrophic failure. Although this is not a primary requirement for a health monitoring recorder, if such a requirement can be met without a major development, cost, or resource usage increase, this would be a desirable feature, and should be considered in ranking candidates.

2. Ground Test

Ground testing for research and development purposes creates many differences in requirements. The data quantity and rate are greatly increased, but the environment requirements are much more benign. We considered the environment to be inside in a laboratory, so that the environment is considered to be a "laboratory environment". We felt that the architecture should be considered very flexible, but the most stressing requirement would be if all data were recorded on a single data recorder. This was thus specified, although a single recorder in our terminology could contain several separate media packages in a single case.

Rocketdyne has a test plan for an engine development experiment that contains measurements desired for a highly instrumented test firing[2]. The measurement rate and total data quantity are shown in Table 4. The table is based on the same engine operation times as for the shuttle engines.

TABLE 3

ENVIRONMENTAL REQUIREMENTS

Temperature (Operating) - 35F to 120F

Temperature (Storage) - -10F to 120F

Acceleration - 5G

Shock - 20G

Vibration

Flight - 20 - 150 Hz, +6 dB/octave
150 - 1000 Hz, $0.03G^2/Hz$ constant
1000 - 2000 Hz, -6 dB/octave
Equivalent to 6.48 G RMS

Duration 48 minutes

TABLE 4

TEST BED DATA REQUIREMENTS

Digital- 750 ch @ 50 samples/sec, 16 bit	= 600Kbit/s
Analog- 132 ch @ 40K samples/sec, 16 bit	= 84.5 Mbit/s
Total	= 85.1 Mbit/s

Record Time, 1140 sec

Total Storage = 85.1 Mbit/s x 1140 = 97.0 Gbits

3. Analysis of Requirements

In comparing the current flight system with the advanced vehicle, we determined that there may well be a reduced set of parameters required for the advanced vehicle, which is expected to have a simpler engine with more margin built in. At the same time, the capability of sensors continues to increase, so there may be a desire to include new types of sensors for HMC, with operation at higher frequency. On average, these two trends may offset each other, so that there would not be a large change in total required capacity.

We present in Tables 5, 6 and 7 the specific factors, plus their quantitative desired values, that we have derived. These tables form the most important part of our requirement definition. These tables also contain comments on the relative importance of the categories; we will return to this in Section C-1d on prioritization.

The results in these tables represent our judgement, and are based on certain assumptions.

The assumptions that were used in deriving these quantitative results include the following:

- All analog to digital conversions have been done and data are all digital
- The requirements for data storage are presented on a basis of three engines per vehicle for the flight systems, and on a basis of a single engine for the ground test
- Environmental - unit is in space shuttle cabin for the current system. For the advanced system, two environments are defined, one in the cabin for a manned mission and one in the same area as the engine interface unit, defined as a "compromise" environment
- Resources are expressed in terms of a limiting maximum
  Since current technology comes close to meeting data storage requirements, we use current requirements (analog and digital) as the maxima for resource requirements
- Permanence - we assume data is recovered and backed up, so there are no long term requirements
- Survivability - assumes catastrophic survivability, protect data only
- A byte for these purposes consists of 8 bits of data
- Maintainability - all boxes could be replaced within a day - maintenance is on command or on demand, similar to military requirements
- Future capacity - some requirements go up, some down as simpler engines are developed, on average we predict little net change
- The capacity and data rate are specified on a "user-available" basis. Requirements for formatting and error correction would add additional capacity requirements.

- No requirements have been identified for real time access to the data on the current flight vehicle or on the ground test stand. Because of the possibility of additional applications and increased versatility, real time access has been given some weight for an advanced vehicle.
- It would be desirable to use rewritable media, because this would allow resetting the memory more easily after a mission. But this is not an extremely critical need, and so long as a WORM media could be physically replaced within a few hours, it would not be an extreme disadvantage.

Table 5
Flight System
Requirements

Data Storage
Total capacity — 3.3 G bytes
Data rate — 23.2 M bits/sec
Architectural compatibility — single, stream or 16 bit parallel, all digital

Reliability
Error rate — 10^{-6}
Permanence — 1000 hrs
Maintainability — no periodic
Read cycles — 20000
Write cycles — 100 (for non removable media)

Resource Usage
Size — 3000 in^3
Power — 150W
Weight — 100 lbs
Cost — $300K

Environment
Operating temperature — 35-105°F spec
Vibration — 6.48G RMS, 20-2000 Hz defined spectrum
Shock — 20g
Pressure — 0-1000 Torr
Humidity — 0-95%
Acceleration — 0-5 g
Survivability — 100g, salt water, hi temp, explosion pressure

Access Time — no requirement

Reusability - erase or remove
Ease of access, reset or removal - 1 day max

Risk
Cost of development
Growth potential
Readiness (1991)

Table 6
Test Stand
Requirements

Data Storage

Total capacity — 12.1 G bytes
Data rate — 85 M bits/sec
Architectural compatibility — flexible

Reliability

Error rate — 10^{-6}
Permanence — months
Maintainability — commercial
Read cycles — 20000
Write cycles — 100

Resource Usage

Size — truck portable
Power — 1500 W
Weight — truck portable
Cost — $300K

Environment

Operating temperature — 0-100°F w. solar heating
Vibration — commercial
Shock — commercial
Pressure — 1 Atm
Humidity — 0-95%
Acceleration — 1 g
Survivability — not an issue

Access Time — no requirement

Reusability - erase or remove

Ease of access, reset or removal - 1 day max

Risk

Cost of development
Growth potential
Readiness-must be available in 1991

Table 7
Advanced Vehicle
Requirements

Data Storage
Total capacity — similar to current flight
Data rate — similar to current flight
Architectural compatibility — single digital line

Reliability
Error rate — 10^{-8} - 10^{-7}
Permanence — months
Maintainability — no periodic
Read cycles — 200000
Write cycles — 1000

Resource Usage

Size —	
Power —	1/2 current flight (cost cons't $)
Weight —	
Cost —	

Environment	Manned System	Expendable System
Operating temperature —		-65 - +160° F
Vibration —		Defined spectrum peaked at 0.067 G^2/Hz
Shock —	Same as current flight	—
Pressure —		~0 - 15.23 PSIA
Humidity —		0 - 100% RH
Acceleration —		—
Survivability —		Catastrophic

Access Time — mission dependant, few seconds desirable

Reusability - erase or remove

Risk
Cost of development
Growth potential
Readiness

Doc Merge

The derivation of the total required capacity and bit data rate requirements has been performed previously, for flight vehicles and ground test, respectively.

The error rate requirement is estimated from considerations of the inherent error rate of the transmission. The errors have a tendency to occur as burst errors, affecting a number of bits at a time. The error detection for the burst errors is accomplished via BCH coding, in which 31 bit blocks are transmitted, with 16 bits of data and 15 bits for parity checking. If the word is bad, the word is required to be retransmitted. This type of coding is designed for burst noise, which is the common type of transmission noise. This method gives an error rate around 3×10^{-5} for errors in transmission.

Specification of an error probability of 1×10^{-6} for the recording process means that the total system error will not significantly increase above the transmission error rate. At the same time, it does not seem productive to specify a significantly lower recording error rate, because a tighter specification in that area would not appreciably improve the total system performance.

For the current flight system and the ground test, the MDS is considered to be purely archival; there are thus no requirements for access time during flight or during test. For the future vehicle, it is judged that there may be advantages to accessibility of the data during flight, so a requirement is included.

The results presented in Tables 5, 6 and 7 represent our best quantitative judgement about the important performance requirements for the MDS technology. In the next section we describe a prioritization to determine the relative importance of these factors.

C-1d. Prioritization of Critical Areas and Requirements for HMC

This section is concerned with the establishment of a prioritization scheme for the requirements which have previously been defined in Section C-1c. In that section, we established quantitative requirements for a number of important factors in a variety of categories for the MDS system. The categories included:

- Data storage capacity
- Reliability
- Resource usage
- Environmental factors
- Access time
- Reusability
- Risk

This prioritization represents a culmination of the activities for Task II of the contact. It also served as an input for Task III.

In our prioritization, we adopted the following approach, in order to account for the tradeoffs that can be made between various relevant factors. (For example, the capacity of an MDS system can be increased by adding more units, but at a cost in resource usage, e.g. increased size, weight, etc. Or, in order to meet environmental specifications, a memory unit could be enclosed in an elaborate temperature-controlled vibration-isolated package, but this package could be unacceptable from the standpoint of size or cost.) The total required data capacity and data rate and the environmental factors are to be treated as requirements that must be met, i.e. the system must have enough total capacity to perform its task and it must operate in the prescribed environment. A technology that cannot meet the total capacity, data rate, or environmental requirements under any conditions will be rejected. During Task III, we defined specific systems using the various candidate technologies, so as to meet these minimal requirements. Then the distinguishing factors became issues such as the resource usage and risk associated with the development of the technologies.

Table 8 presents statements on the relative importance of each broad category of requirements, for each of the three mission scenarios. The categories of data storage and environmental catability are treated as binary go/no go requirements, i.e. a candidate technology which cannot meet the minimal requirements will not be considered further.

The other categories have their individual factors weighted in importance according to a scale of weighting factors defined by Table 8. This table represents our considered judgement about the relative importance of the various factors. These factors were used in Task III as weighting factors, w_i. For a candidate technology, we defined a system configuration which can meet the data capacity and environmental requirements.

The performance of a given system was evaluated and given a score, s_i, relative to the minimum requirements. The scoring system and the scores, s_i, were defined in Task III. At the conclusion of Task III, we evaluated the various candidate technologies by forming the sums $s_i w_i$ for each specified system.

This assignment of priorities and establishment of quantitative criteria for important parameters of an MDS system represents a conclusion to the work of Task II.

Table 8
Prioritization

Weighting of Major Categories

Category	Flight System	Test Stand	Advanced Vehicle
Data storage	Binary, must define system that meets requirements	Binary, must define system that meets requirements	Binary, must define system that meets requirements
Reliaiblity	See weighting factors below	See weighting factors below	See weighting factors below
Resource usage	See weighting factors below	See weighting factors below	See weighting factors below
Environment	Binary	Binary	Binary
Access time	0	0	See weighting factors below
Reusability	See weighting factors below	See weighting factors below	See weighting factors below
Risk	See weighting factors below	See weighting factors below	See weighting factors below

Scale of Weighting Factors

Factor	Flight System	Test Stand	Advanced Vehicle
Weight	10	3	10
Size	8	3	8
Cost	8	10	8
Permanence	5	4	5
Reusability	5	5	5
Maintainability	5	5	5
Write cycles	5	4	5
Read cycles	4	4	4
Access time	0	0	3
Error rate	3	5	3
Survivability	3	1	3
Power	3	3	3
Cost of development	3	3	6
Growth potential	6	6	8
Readiness (1991)	Binary	Binary	2

C-2. Survey of Mass Data Storage Technologies

This subsection is a review of the survey of available technology for Mass Data Storage (MDS) for Health Monitoring and Control (HMC) for rocket engines.

In this subsection, subsubsection C-2a describes the various technologies. Subsubsection C-2b discusses our evaluation procedure. We evaluated the various technologies for possible use in three different scenarios: a current flight system (space shuttle), a ground test stand, and an advanced flight system. The requirements for each of these were defined in Task II. Finally, subsubsection C-2c presents our recommendation for the best candidate for technology development.

C-2a. Survey of Mass Data Storage Technology

In this section we describe the various technologies which were included in our survey. These include optical technologies, magnetic technologies and solid state (or electronic) technologies.

1. Optical Technologies

In accordance with our original statement of work, we have considered the following technologies:

- Optical Disks
- Holographic Memories
- Optical Fibers
- Optical Heterodyne

As described below, after consideration, we decided to treat optical heterodyne as a subset of other optical storage technology. In addition, we identified two additional optically based technologies which we have included in the survey.

- Optical paper
- Optical cards

a. Optical Disks

Optical disk memory technology is similar to that of magnetic disk storage technology in that the data are stored on the surface of a spinning disk[3]. In the case of the magnetic system there are minute magnetic regions. In the optical disk case the region undergoes a change in optical property caused by a photochemical, ablation, thermomagnetic, or other process. This change is induced by a laser beam focused onto the spinning media. (In the jargon of optical data storage, the word media is used for the recording material, despite the fact that it has an apparently plural form.) In magnetic memories the energy responsible for the readout signal is contained in the media itself. In the case of optical disk memory the stored data bits act as gates for the readout laser beam, which provides all the required energy. These gives rise to the fact that the reading device need not be in close contact with the storage medium. since laser beams can be focused to micron size spots data packing densities of $>10^8$ bits per square inch are possible.

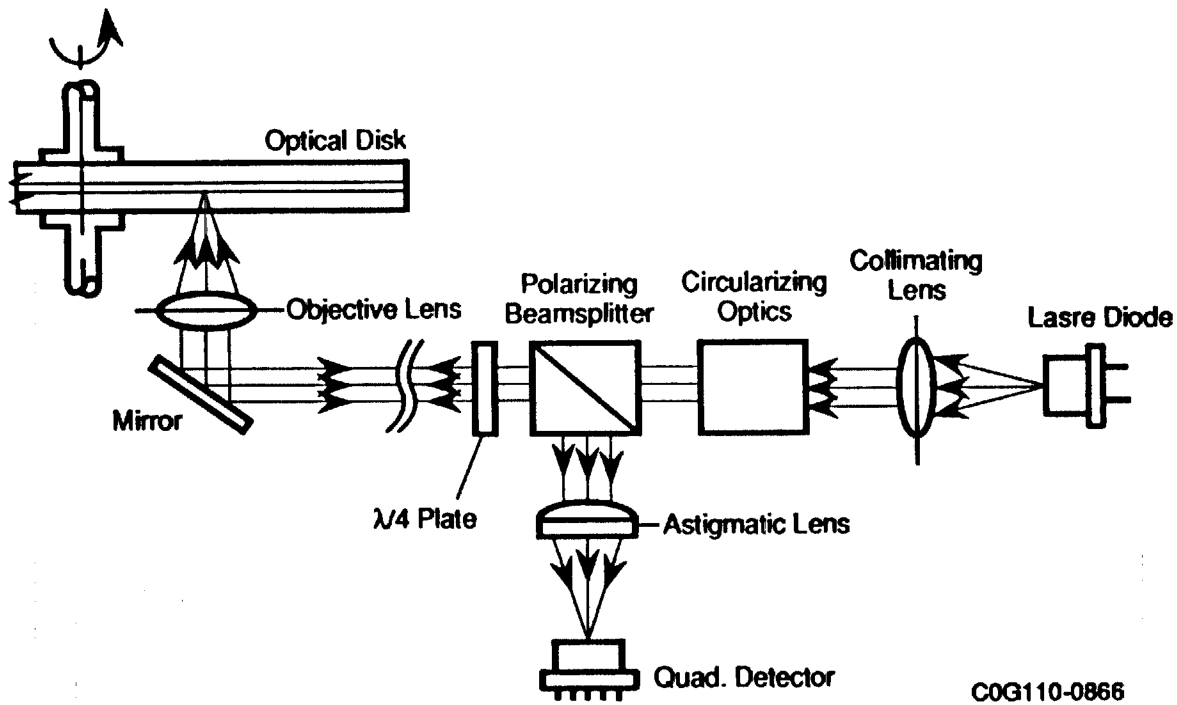


Figure 2. Elements of a Reflectivity-Sensing Optical Disk System

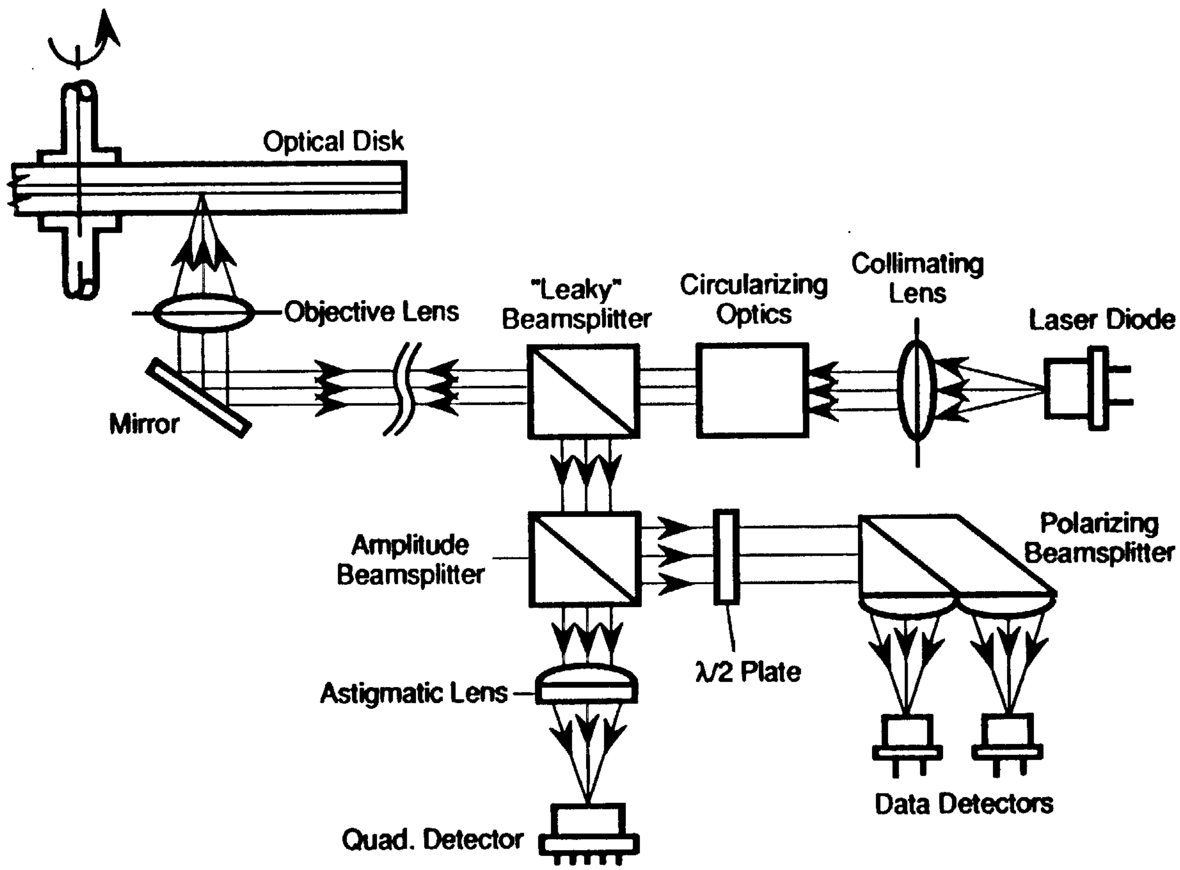


Figure 3. Elements of a Polarization-Sensing Optical Disk System

Optical disk memory systems can be divided into two basic classes depending upon the type of playback process used. The first case is where the light reflected from the spinning medium is altered in amplitude when a written mark is encountered, and in the second case the polarization state of the reflected light is altered, usually a small rotation in the plane of the polarization. A reflectivity sensing scheme is used today in digital audio players, in CD-ROM, (compact disk read only memory, and in write-once-read-many (WORM) systems and is currently under development for rewritable technologies using phase-change and dye-polymer media. The polarization sensing technique is used for rewritable optical disk technology referred to as a magneto-optical (M-O). Both techniques share considerable commonality in that they both must transfer energy efficiently from the laser diode to the recording media for writing a bit and then return light from the media to the detection system to provide data and servo signal acquisition. The basic reflectivity-sensing system is shown in Figure 2 and the polarization-sensing system in Figure 3. The WORM and rewritable technologies are possible candidates for a data recording system.

Optical disk technology has inherent features making it ideally suited for rugged environments requiring storage of large data amounts. These features include:

- large disk/head spacing preventing head crashes (0.8mm typically)
- storage media shielded by protective layers transparent to laser beam
- media tracking and focus remove mechanical alignment problems

These features allow a system with optical disk cartridges to store and randomly access vast amounts of information on a removable disk with greater than 10 year storage life. Optical disks can have Gbytes of data with millisecond access times. The WORM system provides an unalterable data medium once recorded.

Up to the present time, most optical disks have not been rewritable. But rewritable media based on magneto-optic effects are making rapid advances and probably in the near future most commercial systems will be rewritable. For the HMC MDS application, rewritability is not a strong advantage. Our evaluation has thus emphasized the use of WORM technology.

There are numerous companies providing WORM and rewritable disk-drive systems for commercial use. A few companies have focused their efforts on developing rugged military units designed to operate in a MIL-E-5400 environment. These companies are:

Cherokee Data Systems Inc. Longmont, CO
Mountain Optech, Boulder, CO
GE Aerospace, Camden, NJ
Honeywell Inc., Albuquerque, NM
Sundstrand Data Control Inc., Redmond, WA

Sundstrand has announced that its M-O rewritable optical disk system will be flown in the cargo bay of the shuttle on Mission STS-39 in November of 1990 as part of the Data System Experiment project. This system has 5.25 inch disks with 300 Mbytes of user data and a data transfer rate of 5 Mbits/sec.

GE Aerospace is presently working with NASA Langley in modifying their DuraStore M-O rewritable optical disk system that is under development to be space qualified by 1998. This system uses a 14 inch disk with 5 Gbytes per side of user data and a data transfer rate of 25 Mbits/sec.

Honeywell is in production of a WORM system used as digital memory unit for Honeywell's Digital Video Map System on board the AV-8B and F/A-18 Night Attack aircraft. This system has 5.25 inch disks with a user data capacity of 260 Mbytes per side and a data transfer rate of 4.5 Mbits/sec.

Both the Cherokee and Mountain Optech systems under development are 5.25 inch WORM drives with approximately 300 Mbytes per side and 5 Mbits/sec data rates. The flight system mass data storage unit strawman is a system with 3.3 Gbytes of user data capacity and a data rate of 23.2 Mbits/sec. To meet both this data capacity and data rate specification multiple 5.25 inch drives would be required which are multiplexed together. A single 12 or 14 inch optical disk system can meet the data capacity requirements. The data rate capacity for this single drive system can be met by using multiple laser diodes to both write and read the data similar to what is done in the GE DuraStore rewritable optical disk system.

For both the test stand and advanced system strawman systems, the required data capacity of 12 Gbytes and data rate of 85 Mbits/sec would require a multiple drive multiplexed system.

In our evaluation, we have considered two directions for technology development:

- Higher performance optical disks
- Commercial optical disks in a chassis

The first approach is more technology intensive, driving toward the development of higher packing density, larger diameter disks, multiple laser heads, higher rotation speed, etc. The second approach is more aimed at packaging of state-of-the-art optical disk technology to provide the environmental characteristics required and using multiple disks to provide the capacity.

Commercial optical discs can be installed in a ruggedized chassis in the same way the magnetic hard discs were installed in the system described above. The only difference is that optical discs have removable media whereas hard discs do not. The data rate of the commercial optical discs baselined for the system is 4 Mbit/sec, so buffering and multiplexing will again be required to reach the data rate requirements for this application. Erasable optical discs with 1 Gbyte capacity are presently available, but the 1 Gbyte disc is double sided and single side usage was baselined for this application. Each ruggedized chassis system contains four of these drives and would have 2 Gbytes of storage if the discs are not flipped. Multiple chassis's are necessary for some of the applications. Storage densities are expected to improve by a factor of 2 so 1 Gbyte/side drives were baselined for the Advanced Flight system.

The environmental effects on this system will be very similar to the effects seen by the magnetic hard disc system except that the optical disc media is not as sensitive to thermal and humidity extremes and the active tracking of the optical system may make it inherently more robust.

b. Holographic Memory Systems

Optical memory systems based on storage of large blocks of information as a hologram in a recording medium have been under development since the 1960's, almost as long as the bit-oriented laser-based memories such as the laser disks. They have not as yet progressed to the point of broad commercial usage, such as laser disks have, but for some applications, they offer significant advantages as compared to the bit-oriented memories.

The organization of a holographic memory is different from a bit-oriented memory. In a bit-oriented memory, information storage and information readout occur one bit at a time. A holographic memory stores and reads out a large number of bits simultaneously. The basic configuration of a holographic memory is shown in Figure 4. The information is stored as a hologram on some material, the holographic memory medium. The apparatus in Figure 4 contains

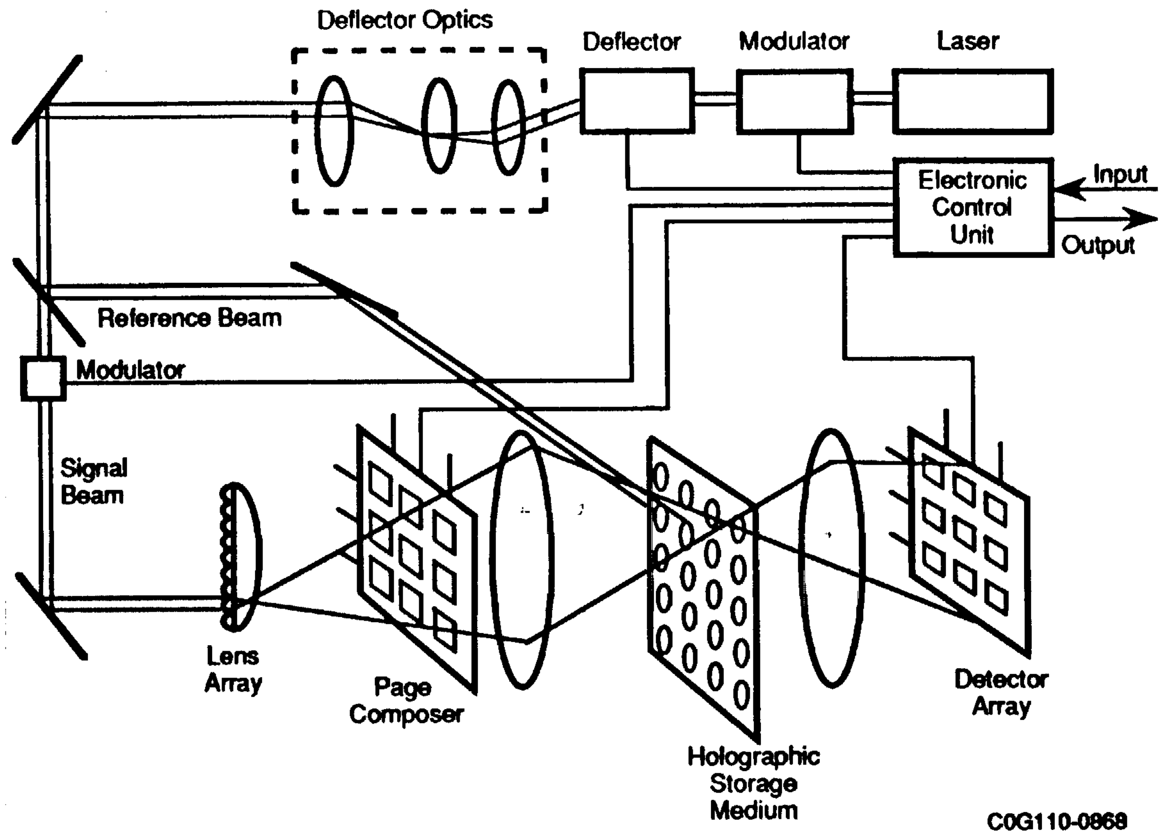


Figure 4. Schematic Diagram of a Holographic Optical Memory System

a holographic recording arrangement, with a reference beam and a signal beam. The object of which a hologram is to be formed is a two-dimensional array of bits. This array is constructed by a device called a page composer (or spatial light modulator). A page composer can be considered as an array of light valves, some of which are open and some closed. The opening and closing may be activated by light, by an electric field or by a combination of both. The open valves will correspond to ones, and the closed valves to zeros. These light valves are arranged in a pattern to represent an array of ones and zeros. This array of ones and zeros is then stored at one time in the holographic memory medium. Because the hologram contains a large number of bits, one has simultaneous storage of this large number of bits at one time.

The beam passes through the beam splitter and is divided into two parts, the reference beam and the signal beam. The signal beam goes through an optical train and arrives at the page composer where an electronically composed data pattern is set up. This data pattern is imposed on the signal beam. When the signal beam combines with the reference beam to form a hologram on the recording medium, the resulting hologram represents the entire array of bits. The hologram is formed on one particular small area of the storage medium. The area is selected by the light beam deflector. During recording, the modulators allow maximum light intensity in both the signal and reference beams.

In order to store a different hologram in another location on the storage medium, the deflector moves the beam to that location. Movement of the object from one lens to another lens in the lens array changes the position of the hologram on the storage medium. At the same time the reference beam tracks the signal beam, so that both beams reach the same spot in the storage medium. If one changes the angle between the signal and reference beams it is also possible to store multiple holograms in the same area of the memory material.

Readout of data occurs when the hologram is addressed with only the reference beam. The deflector directs the beam to the hologram to be read out. An image which represents the array of ones and zeros is produced. This image is focused by the lens next to the recording medium. An image of the data array is projected onto the photodetector array, which has the same relative dimensions as the elements of the page composer. Each bit originally stored in the page composer is incident on one photodetector in the array. The data thus are converted back to an electrical signal. If a particular area in the page composer corresponded to a one, there will be light on the photodetector in that position in the detector array. Thus, the array of bits can be reconstructed and converted to an electrical signal in parallel, with all the bits on the page being recovered at the same time. This feature allows the data readout rate to be high.

Storage of data in holographic form in an optical computer memory offers several advantages compared to a bit-oriented memory. The information about the original array of bits is distributed in a holographic fringe pattern and covers the entire hologram. Therefore, the hologram is not sensitive to small imperfections such as dust particles or scratches. Such imperfections could cause the loss of a bit in a bit-oriented memory, but their only effect on the hologram is to reduce resolution slightly.

A second advantage of holographic storage is that the information is essentially recovered in parallel. A large number of bits are all read out at the same time by the projection of the image of the array of bits directly onto the array of photodetectors. This recovery of a large number of bits at the same time offers possibilities for very high readout rates.

The requirements on light beam deflection are reduced in holographic memories. Each position to which the beam is deflected represents a page of data containing many bits. Thus, for a 10^9 bit memory (10^4 pages of 10^5 bits each) one requires only 10^4 separate locations. This figure lies within the capability of inertialess light beam deflectors. Addressing can be done entirely with nonmechanical light beam deflectors which have random access time less than 10 μsec. Such a holographic optical computer memory could be constructed with no moving parts and since 10^5 bits are stored (and read) in parallel, one could have data rates of 10^{10} bits/second, although system complexity would be high.

Still another advantage is that the holographic recording and reconstruction is insensitive to the exact positions of the reference or reading beam on the hologram. This is not the case with the bit-oriented memory, for which the beams must be positioned very exactly. This means that the holographic system will be less subject to problems of vibration.

The holographic approach to optical data storage was followed, along with the bit-oriented optical disk approach, for a number of years, through the early 1970's[4-13]. By the late 1970's, the optical disk approach had clearly pulled ahead. At the same time, there had been little progress in the two most difficult aspects of holographic recording, the page composer and the recording medium itself. Therefore, interest in holographic optical data recording waned, and there was little research done and no papers published throughout the 1980's.

Recently there has been a revival of interest in holographic optical data recording. Although there still have been no papers published, at least three research organizations are actively pursuing holographic optical mass data storage.

- Georgia Tech University
- University of Alabama - Huntsville
- Physical Optics Corporation, Torrance, California

These organizations feel that advances in materials technology now offer the possibility of solving the problems associated with the page composer and the recording media. The University of Alabama and Georgia Tech are using ferroelectric liquid crystal page composers and a photopolymer recording media. Physical Optics is using a magneto optic page composer and a dye polymer media. None of the organizations were willing to identify their materials exactly.

A diagram of the Physical Optics system is shown in Figure 5. This system has the following characteristics currently:

Bit density	$5 \times 10^7/cm^2$
Page size	512 x 512
Page rate	100 Hz
Bit rate	26 Mbit/sec

The requirements for the current flight system could thus easily be met by a system with a reasonable area of storage medium. Since the page rate is limited by page composer set up time, rather than by recording time, the requirements for the test stand application could be met by adding several stages of page composer plus storage media, with electro-optic beam deflectors to switch between page composers.

The main drawback involves the fact that one would be doing holographic recording in an environment with substantial vibration. In holographic recording, one requires all the components to remain stationary relative to each other to within less than 0.1 wavelength. This makes the vibration requirement more stringent for a holographic system than for the other candidate technologies.

We have defined a vibration isolation approach which we believe could provide the required degree of isolation. The approach uses active vibration damping, in which the isolation is provided by

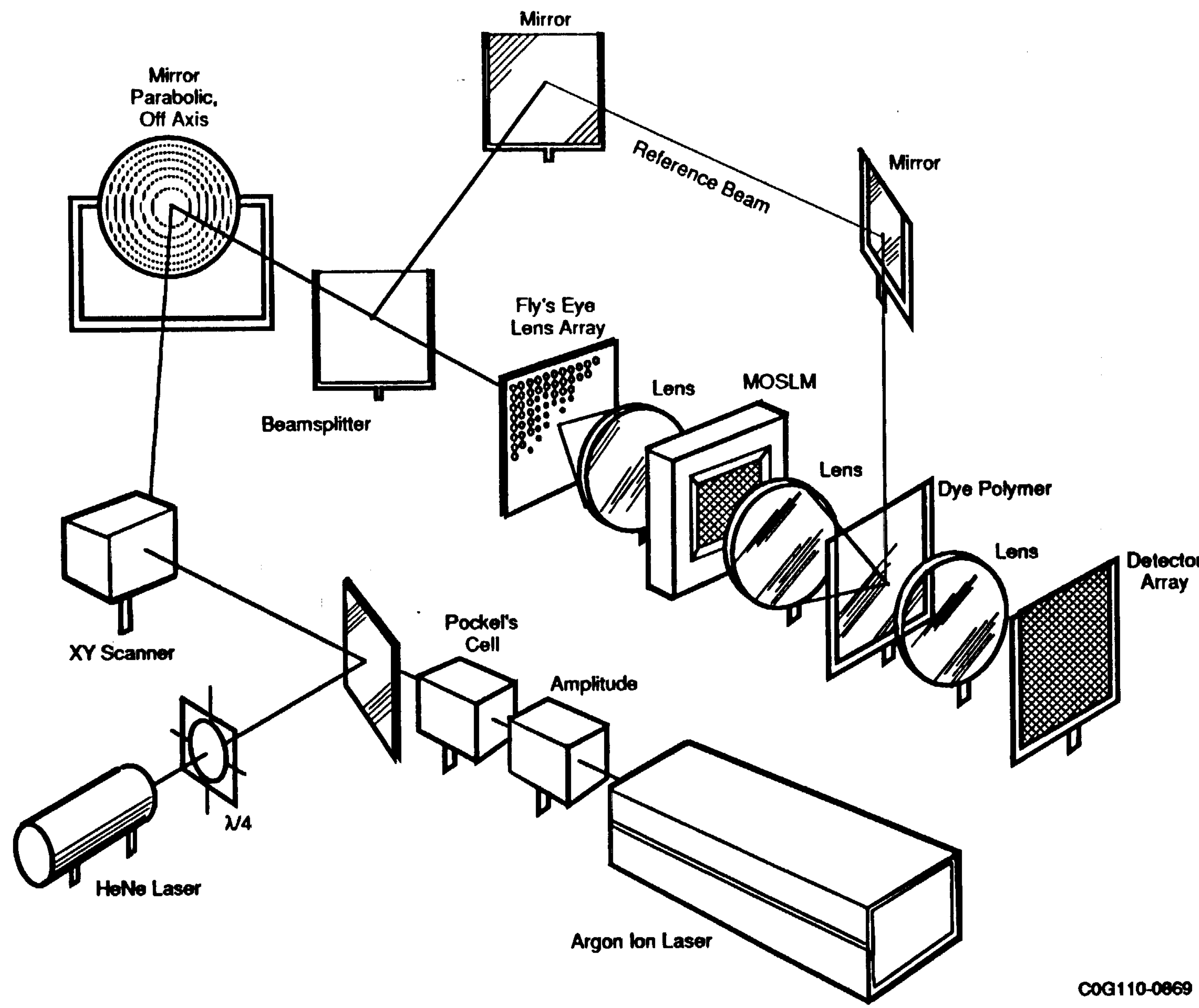


Figure 5. A Holographic Memory Based on Organic Polymer Dye Media (Drawing from Physical Optics Corporation)

accelerometers and electromechanical servocircuits which actively cancel any time varying forces. It should be possible to provide adequate vibration isolation for holographic recording by using two such stages in series.

However, the vibration isolation comes at a high price in resource usage, especially size and weight. These factors reduce the attractiveness of the holographic approach.

c. Optical Card Concept

This concept for MDS technology for rocket engine HMC is based on the rapidly emerging optical card technology being developed by a variety of vendors. This technology is technically related to the compact audio disc and CD-ROM technologies but offers a more compact and inexpensive digital memory system for small memory storage uses.

The optical card concept is based on present day optical card systems which utilize an optical recording stripe encapsulated between multiple protective transparent card layers. Data bits in the form of microscopic sized spots of 3 to 10 micrometers in diameter are recorded on and read from the optical recording stripe. A high speed laser recording system can be used to provide up to 150 kilobits per second write speed per writing channel. Several different types of cards are available including WORM, ROM (read only memory) and a hybrid card offering a combination of both WORM and ROM features.

To read the data light from an incandescent bulb, a LED (light-emitting diode) or laser illuminates the data bits contained on the optical stripe located beneath the protective transparent surface of the card. A CCD (charge coupled device) array measures the intensity of the light reflected back from the stripe. Recorded data spots have a reduced reflectivity compared to that from unrecorded areas and these reflectivity differences are read by the equipment as digital bits.This technology is relatively impervious to strong electric or magnetic fields, EMP, EMI, X-rays, ultraviolet light or electrostatic discharge.

Error rates for this technology are very small at less than 10^{-12}. The media is quite permanent and should retain data for at least 10 years. The media is write once and therefore would be replaced after every mission. The media should allow well in excess of 200 read cycles, exceeding any MDS requirements.

Present day cards hold up to 2.8 Mbytes of data within a 35mm stripe of about 2 inches in length. When extrapolated to account for the MDS storage requirements the area of card material grows substantially, to the values listed below:

Flight System	9,910	in^2
Test Stand	36,400	in^2
Advanced System	33,300	in^2

When we assume a maximum area per card of 100 in^2, a 0.25 in spacing between cards for the read/write head travel and 1 inch peripheral volume for environmental isolation the following volume requirements are derived.

Flight System	3,146	in^3
Test Stand	11,132	in^3
Advanced System	10,164	in^3

Mass estimates were derived using standard card reader densities and the volumes listed above.

Flight System	72	lbs.
Test Stand	256	lbs.
Advanced System	233	lbs.

The power consumption was determined by assuming 10W of writing power per card (150 kbits/second) and scaling upward to reach our requirements.

Flight System	1000	W
Test Stand	5000	W
Advanced System	1000	W

Development and recurring costs were assessed through discussions with SRC personnel familiar with the development of hardened optical card readers.

Development Costs

Flight System	2000	$k
Test Stand	500	$k
Advanced System	5000	$k

Recurring Costs

Flight System	300	$k
Test Stand	150	$k
Advanced System	500	$k

It is expected that there is little growth potential for this concept and that the volatility of the card media makes this concept not very survivable. The access time for reusability is estimated at 1 day.

After this analysis it became clear that the optical card concept would be highly aligned with the optical tape concept and that the differences in the two concepts were mainly in the implementation of the media/head geometries.

d. Optical Tape Concept

The optical tape concept relies on a new recording medium, which is sometimes called "optical paper" or "digital paper", because it feels like paper. It may be used either in as a disk or as a tape.(14)

Digital paper is a new recording medium developed by ICI Imagedata, Wilmington, Del. It is a high density flexible optical data storage media that can be made into tape or disk form. Digital paper is a WORM media based on dye polymer layer sandwich between a metal reflective layer and an overcoat layer. A reflectivity sensing system similar to that of optical disk systems would be used with this media. Figure 6 shows the structure of the paper.

The optical paper can be employed either in a tape recorder format or in a disk format. In the disk format, one can take advantage of the flexibility of the paper by using the Bernoulli effect to position the paper. See Figure 7. The Bernoulli effect produces lift when air flows faster over the upper surface of the disk than under it. The lift makes the disk "fly" at a close and constant distance from the Bernoulli plate and record head. This is a very advantageous feature. The disk format may be considered to be a subset of optical disk technology.

Creo Products Inc. of Vancouver, British Columbia is working on an optical tape recorder system with a 12 inch reel of 35 mm wide optical digital paper tape that is 3 mils thick. A tape 880 meters long can store 1 Tbyte of data with an average access time of 28 secs. The data rate of this system is 24 Mbits/sec.

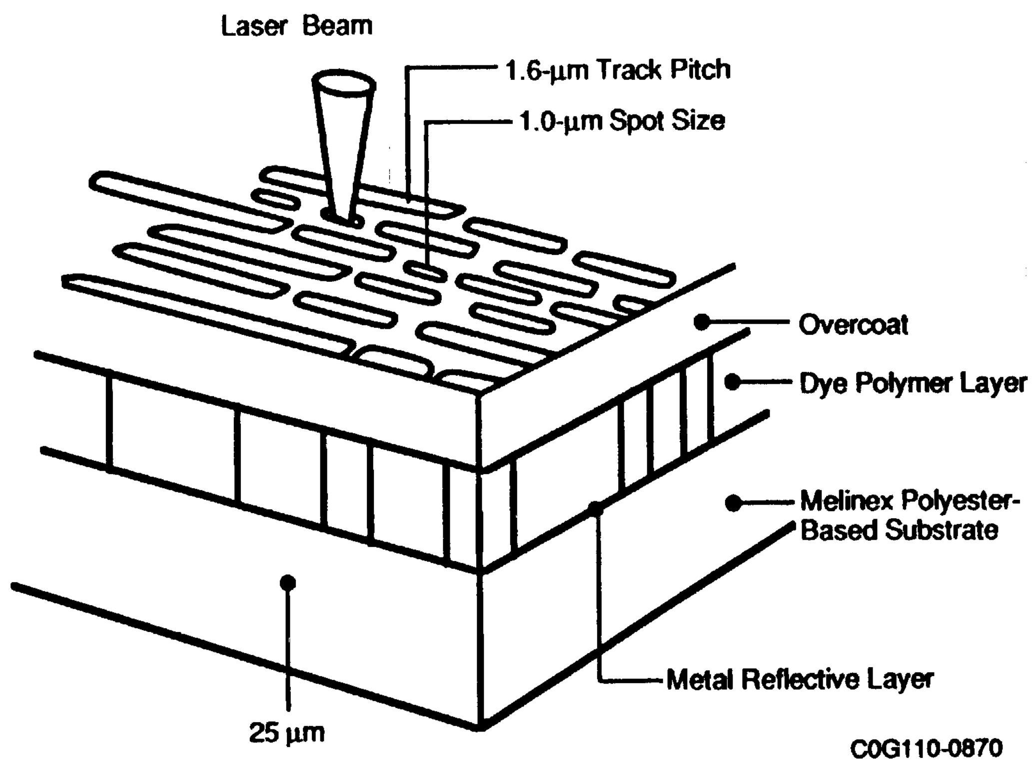


Figure 6. Digital Paper is a Flexible Optical Recording Medium Made from a "Sandwich" of Thin Polymer Films. This Cross Section Shows the Various Functional Layers and the Approximate Dimensions.

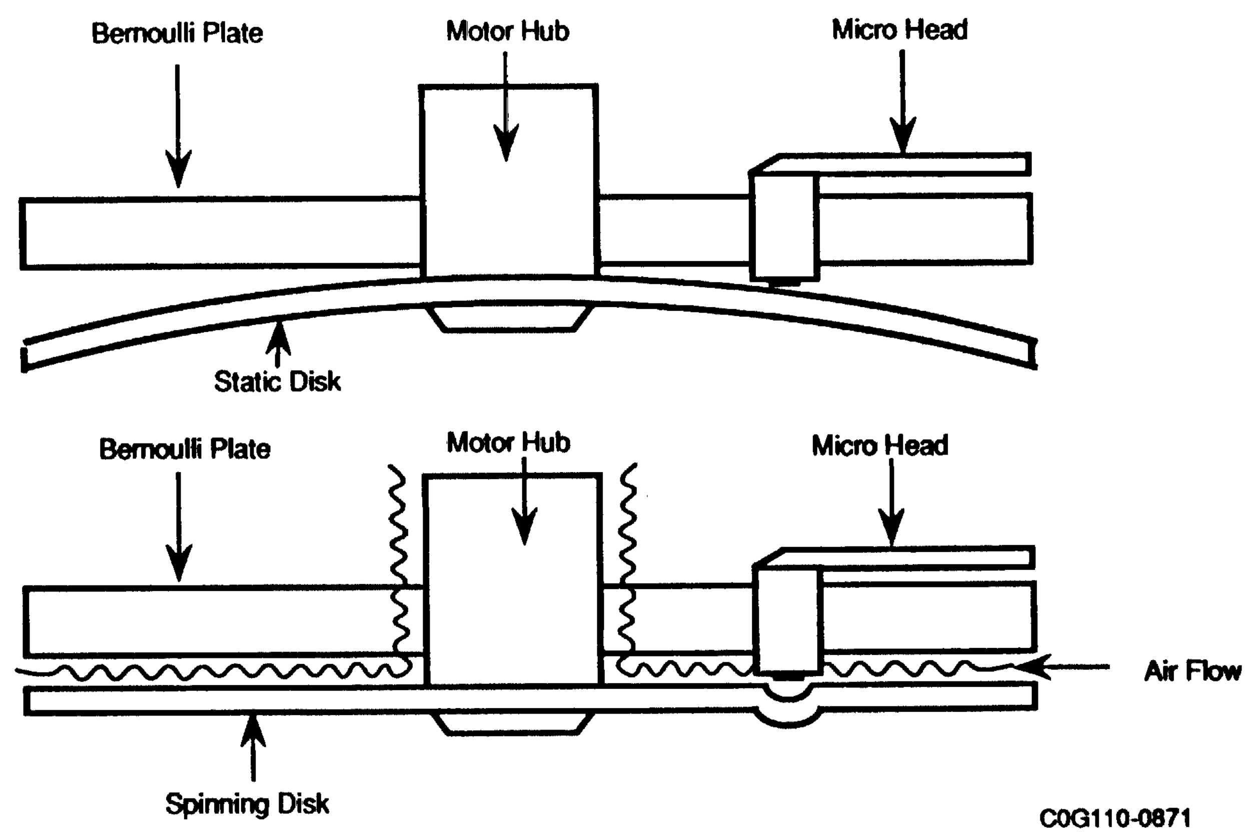


Figure 7. Operation of the Bernoulli Effect on an Optical Paper Disk

An optical disk system using the flexible digital paper made into disks as removable media is being developed by Bernoulli Optical Storage CO. (Boulder, CO). The same principle they use in their well known magnetic disk drives, the Bernoulli Box, will exploit the mechanical flexibility of the digital paper media. A system with 5.25 inch 1.2 Gbyte data cartridges, 30 milliseconds access times and 6 Mbits/sec data rate is planned.

Lasertape Systems Inc. of Campbell, California, is developing a high capacity, cartridge based digital optical tape system. The system is to be compatible with the IBM 3480 magnetic tape cartridge. A single cartridge is to have 50 Gbytes capacity with a data rate of 24 mbits/size, expandable to 40 mbits/sec. Access time to any 200 Mbyte segement is 15 sec and within a 200 mbyte segment is 2.5 seconds. The scanning system to be used on the optical tape system is an acousto-optic scanner which will allow for an inheritly rugged design. Increase of data rates of up to 100 mbits/sec are possible by increasing the tape speed.

Both of these approaches will have the same inherit ruggedness as the optical disk that include unlimited number of read cycles, a permanent nonalterable record, long archival life of the media (>10 years), and freedom from worrying about head crashes and castastrophic damage to the data. The Bernoulli system in fact is less complex then that of the standard optical disk system because it does not need to have a focus servo system since the head rides on a cushion of moving air a few micro inches from the media. Presently no company is working on developing rugged military units using either of these approaches.

Because of the decreased distance from the media to the outer protective layer, dust and dirt particles become a more serious issue than for optical disks, because they will obscure much more of the converging cone of light. Cleanliness will thus be an extremely important factor for the optical tape.

The flight system strawman data recording system could be accomplished by an optical digital paper tape system. The system being developed by Creo would need be reduced in physical size due to its Terabyte data capacity. A system based on the digital paper disk would need multiple 5.25 inch drives to obtain the 3.2 Gbyte data capacity and 23.2 Mbits/sec data rate or larger diameter media with multiple laser diodes in the optical head.

For both the test stand and advanced system strawman systems the required data capacity of 12 Gbytes and data rate of 85 Mbits/sec would require a multiple drive multiplexed system if the digital paper disk system was to be used. The digital paper tape system could meet the data capacity easily but would have problems with the required data rate. Increasing the number of write and read laser diodes in the system could possibly solve this problem.

e. Fiber Optic Memory

Considerable investigations have been done on the use of optical fibers as dynamic digital memory. Most of this use has been for buffer storage as part of code generation, or serial to parallel conversion. The extremely high bandwidth of optical fibers supports a very high bit rate. Potentially a delay line could support mass data storage, but the use of this technology for rocket engine health monitoring appears to offer little feasibility.

Delay lines as a storage medium were used as digital memory storage in some of the earliest digital computers. In one early computer a mercury delay line storing sonic pulses acted as storage, such technology being borrowed from methods of storing analog signals in radar sets of the day. In such a delay line memory, the pulse sequence is re-injected into the input of the delay line after being detected at the output. Thus, such a memory is a dynamic memory, and stores data only so long as power is applied to the support circuitry. Dynamic memory is not desirable for archival storage as even short power disruptions can degrade data.

The use of tapped fiber optics delay lines for signal processing at rates up to 1 Gbit/sec. has been demonstrated by Jackson and co-workers[15-17]. Such programmable delay line buffers may well be effective in Gbit/sec correlation computers, and may have use in mass data storage if large factors of data compression are desired. In this case real time correlation of incoming engine data is compared with signal profiles consistent with known operating conditions. Such signal processing is probably more consistent with control and crew warning functions than archival storage, however.

Goutzoulis and Davies have demonstrated programmable fiber optic delay generators at bit rates of 3.85 Gbits per second[18,19]. This work used fiber delay lines as serial to parallel multiplexers. Such high speed multiplexing may well be useful as an adjunct to high speed mass storage. If serial bitstreams have a higher bit rate than can be supported by an otherwise desirable mass storage technology, fiber optic multiplexers could be used to convert the single bit stream to a number of parallel channels, so that, for instance a sixteen bit word protocol could be recorded in parallel on sixteen channels.

The design of a fiber optic delay line memory for a bit serial optical computer has been reported by Sarazin, Jordan, and Heuring[20]. In keeping with its use with a demonstration optical computer, the researchers from University of Colorado desired to keep electronic components to a minimum, and optical components to a maximum. This forced the use of very expensive optical switches, and prevented the use of as many repeaters as might otherwise be desired.

Further, the design called for synchronous operation. In a synchronous delay line the uncertainty in propagation time limits the length of the delay line, since the pulse must exit the line within a tight tolerance of the timing of clock pulses. The investigators found that changes in refractive index due to temperature limited the maximum length of the fiber, and hence the number of bits stored. Increasing the write frequency does not help in this case, since the higher bit rate decreases the tolerance of timing. Still, the design, which is to be built, represents the first actual design of a fiber optic delay line to serve principally as a computer memory.

As a preliminary concept, a single fiber could be used to store the 1140 seconds of data. A laser diode driven by the 8.5 Mbps bitstream writes information into the fiber. The length of the fiber is long enough so that all the bits are written during data taking in one cycle. A receiver at the end of the fiber detects the bit pattern, and rewrites the signal through the laser. The delay line would operate asynchronously, overcoming the problem of refractive index changes mentioned above. An asynchronous delay line has more overhead bit structure due to sync pulses and other frame defining codes, but we feel this is more than compensated for by the longer fiber lengths allowed.

This concept does require a very long fiber, 2.28×10^{11} m in order to hold the 26 gigabits of data. A fiber this long will obviously require a large number of repeaters to regenerate the pulses within the line. We have used a value of one thousand kilometers between repeaters. Although this is long compared to present communications systems, such a length may become practical with future advances in fibers. Further, the size, weight, and cost of the memory system is dominated by the fiber, and relatively insensitive to the number of repeaters. The only system resource highly dependent on the number of repeaters is power consumption.

Figure 8 illustrates such a memory storage device. Such a memory unit is patently impractical for shuttle (or almost anything else), with a volume of 760 million cubic inches, a weight of 70 million pounds, and an estimated recurring cost of 57 billion dollars.

The very high bandwidth of fiber can be used in multiplexing schemes to reduce the fiber length. The two major techniques are time division multiplexing (TDM) and wavelength division

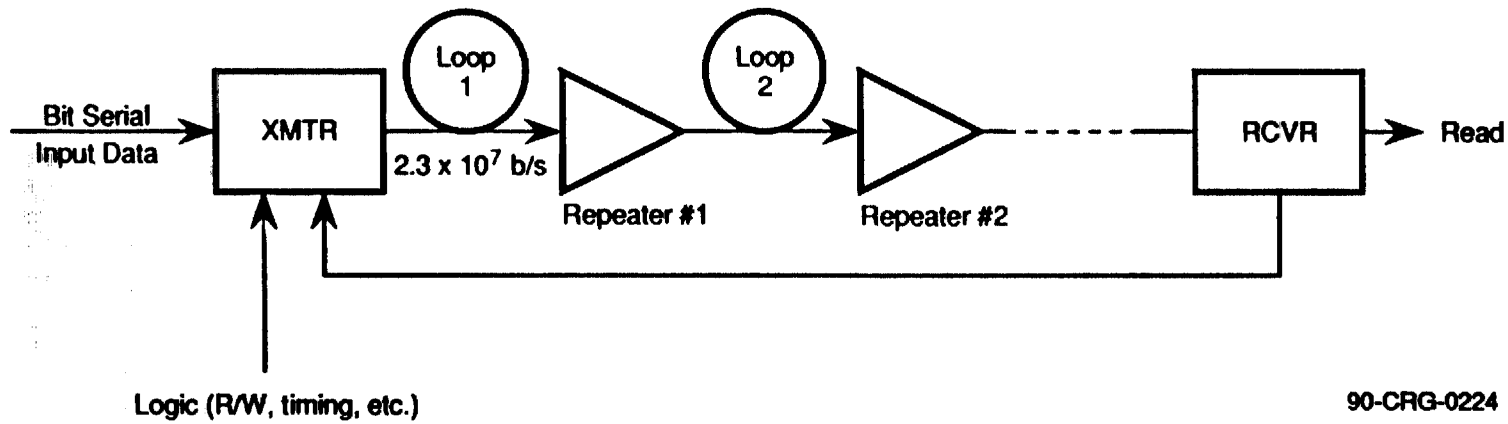


Figure 8. Simple Fiber Optic Delay Line Memory

multiplexing (WDM). If sixteen discrete laser wavelengths can be found, with a separation of wavelength adequate to remain separated considering dispersion in the fiber, the data words could be read in parallel. This WDM scheme would reduce the fiber length by a factor of sixteen. System complexity would be substantially increased, and the repeaters would be much more expensive. Still, the number of repeaters would likely be reduced by the same factor of sixteen.

System costs may not be substantially reduced, because of the complexity of the repeaters. Still, size and weight of the system would definitely be reduced. Figure 9 is an illustration of such a wavelength multiplexed scheme.

Time division multiplexing is feasible because optical fibers can support a much higher bit rate than what is called for in STS MDS requirements. Figures 9 and 10 illustrate a time division multiplex, or "packet" scheme.

The TDM memory of Figure 9 looks quite similar to Figure 8. Not visible in the figures is the fact that Figure 9 contains an order of magnitude fewer loops and repeaters than Figure 2-8. It also contains the data buffer and frame formatters. These additional blocks do increase the complexity of the system, but this additional complexity does not add much to resource utilization, so that most resources are reduced by an order of magnitude.

The data buffer is a key concept that allows the TDM system to operate with a steady bitstream of data to archive, and works because the incoming data rate is considerably less than can be handled by state of the art digital circuits. In fact, a fiber optic buffer may well be used here. In operation a normal input data word takes 0.69 microseconds. This data is stored for a short time, and written to the transmitter upon command of the formatter logic in 0.065 microseconds. The write word time is more than an order of magnitude shorter than the incoming data word time in order to allow packet sync and ID bits to be added.

As can be seen in Figure 10, a frame of data contains 10 data words plus frame and packet sync/ID pulses. This overhead is not a problem considering the rates at which data has already been demonstrated in fiber optic delay lines. The system operates asynchronously, and hence uncertainties in exact propagation time of a frame are of no importance.

In operation the data is always written into packet 1. The storage time of the loop is 114 seconds, one tenth of the engine operation time. At the end of the first cycle, at 114 seconds, the data from the receiver is rewritten into the delay line, but now in packet 2. Incoming data is still written into

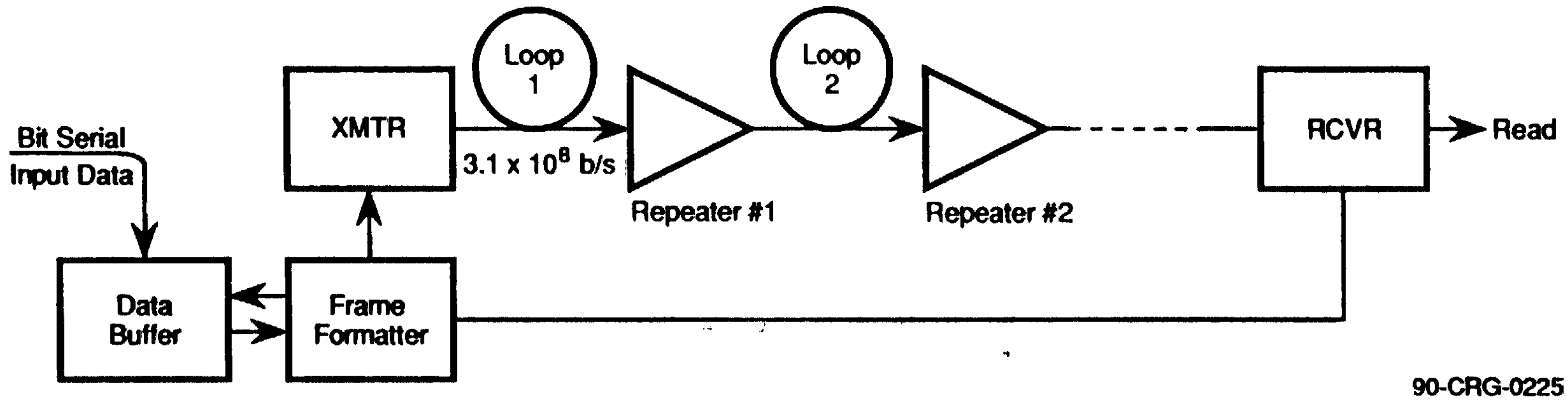
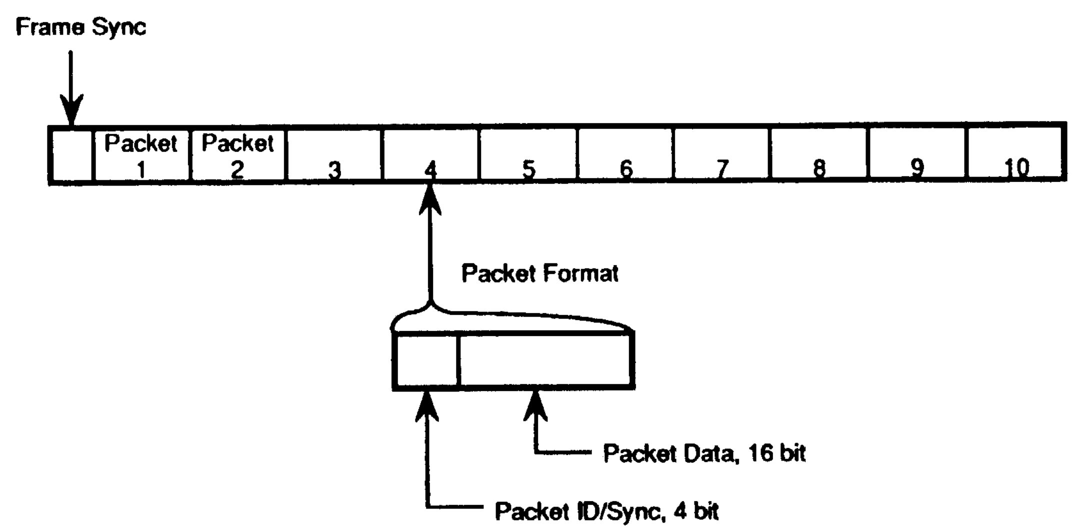


Figure 9. Time Delay Multiplexed Fiber Optic Memory



Formatter Algorithm

Write: Packet 2 from Packet 1
Packet 3 from Packet 2
•
•
•
Packet 10 from Packet 9

Packet 1 from;
Data if Data Write High
Packet 10 if Data Write Low

90-CRG-0223

Figure 10. Packet Frame

packet 1. At the end of each cycle the old data is shifted into the next higher packet. Packet 10 only contains data during the last write cycle. Beyond this point, data from packet 10 is now written into packet 1, and the loop will continue to recirculate as long as power is available.

Table 9 shows the parameters estimated for a fiber optic delay line memory using ten TDM packets for the flight system. The total delay needed is 1/10 of the write time or engine operation. An approximate value for speed of light in a typical fiber results in a propagation speed of about 2×10^8 m/s. This results in a fiber length of 23 million km. An estimated 22,800 repeaters would be required even for the best low attenuation fibers and most sensitive detectors anticipated in the near future. Even so, the resource usage shown on Table 9 is totally dominated by the fiber. Resources for the repeaters, buffers, and other functions alter the system costs by less than 1 part in 1000, below the accuracy we can estimate to. The size, weight, and cost shown do not include structure. The tremendous size of the device led to a feeling that further conceptual design to refine structural contributions to resources would not be warranted. Things could only get worse.

Table 9
Resource Usage
Fiber Optic Delay Line Memory

Total fiber length = 2.28×10^{10} (1)

Fiber volume = 8.7×10^7 in^3 (2)

Fiber weight = 7.8×10^6 (3)

Fiber cost = $\$5.7 \times 10^9$ (4)

Total system;

Volume, weight, and cost essentially as above

Power = 4.5×10^4 (5)

Error rate = 1×10^{-6}

Permanence = 1000 hr.

Write cycles = 10^6

Read cycles = 4×10^5

Reusability = .1 hr.

Estimated development cost = $20 M

(1) 114 seconds, n = 1.5 (v = 2e8)
(2) 250 μm diameter fiber
(3) density 2.5 g/cc
(4) $0.25 /m
(5) 22,800 repeaters at 2W each

f. Optical Heterodyne

Optical heterodyne techniques are not, in themselves, a mass storage technique. Rather, optical heterodyne technology can be applied to other mass data storage techniques, primarily optical disk and holographic memories. This section will include brief discussions of how optical heterodyne may be applied to these technologies. There will be no evaluation of the technique against the requirements for HMC, however. The advantages of heterodyne operation will be considered as part of optical disk and holographic techniques, and the evaluation included as part of these technologies.

Optical Heterodyne in Disk Memory- The technique of persistent spectral hole burning allows the storage of more than one bit of information in a given location on an optical disk medium, the information being separated by spectral wavelength. In a sense, the storage location is a color center, the color of absorption being determined by the writing laser. The bit position is defined by color or wavelength, and the presence or absence of absorption at that wavelength determines whether a one or a zero is present for that bit position. The color absorption bands are extremely narrow, and it is estimated that the use of wavelength as an added dimension with this technique could increase optical disk storage area density by as much as three orders of magnitude(21) The read laser power must be kept low in use of this technique to prevent spectral broadening of the absorption lines. This limits the signal to noise ratio obtainable.

One technique for obtaining optimum read signal to noise is to use heterodyne detection, modulating the read laser at microwave frequencies, and beating the received signal with the modulating signal, a homodyne approach, with coherent detection the result(19). While the long term potential of this technique does promise increased data storage density, the technique is still at a very early stage of development. Further, to date all research on the phenomena of spectral hole burning has been limited to materials at cryogenic temperatures, limiting the utility of mass data storage techniques using this technique in space vehicles.

Heterodyning in Holographic Readout- Mezrich and Stewart have described a heterodyne readout for read-write holographic memories which improves the signal to noise ratio of the readout process(22). The technique uses a conventional write process. For readout, however, two beams are used. One is a modified object wave created by illuminating the page composer with all the bit locations open. A second reference beam simultaneously illuminates the hologram. Either of the beams or both are modulated (if both beams are modulated the modulation frequencies are different). The received readout signal then contains modulation beat frequency that is processed with the appropriate filter circuitry. This work was funded by NASA under contract NAS8-26808.

The experimenters found that phase modulation of the reference beam contributed signal to noise enhancement without contributing unreasonably to the complexity of the setup or the need for extreme structural rigidity (needed for amplitude modulated readout). This enhancement technique would be a variant of holographic storage technology, and hence no evaluation of the technique will be done in this section.

2. Magnetic Technologies

Magnetic technologies, particularly magnetic disks and tapes, represent established technology. Magnetic tapes, in particular, are used for HMC MDS for the current SSME. These technologies have to be considered as the baseline of well developed approaches.

a. Magnetic Hard Disc

Magnetic hard discs represent a mature data storage technology. A magnetic field confining head is flown over a spinning platter coated with a thin magnetic media. Bits are written by applying a focused magnetic field which orients magnetic domains within the media. The state of the bit is read by measuring the magnetic field created by the orientation of the domains. Storage density is dictated ultimately by the domain size of the thin film material on the platter, but in practice rotation speed, coercivity of the media, closeness of the magnetic head, and head field confinement combine to limit storage density. The storage densities of the present state of the art, ≈ 7Mbits/ cm^2, are expected to be improved by another factor of two before media limitations are reached.

The magnetic hard disc system used to evaluate the technology in this report is made up of four commercial 5 1/4" commercial drives installed in a ruggedized chassis. The final system has a total capacity of 4 times the capacity of an individual drive with a data rate equal to the data rate of the individual drives. The present maximum capacity of a single chassis is roughly 4 Gbytes with a data rate of 15 Mbits/sec. Very large capacity storage systems will require either increased drive capacity, an increase of a factor of 2 may be possible, or a combination of multiple chassis. The data rate of the system can be increased by a combination of buffering and multiplexing or parallel bus architecture. This would be required to meet the 85 Mbit/sec rates needed for the Test Stand system. The buffer/MUX controller is not presently available and would have to be designed and built for this application.

The environmental limitations of magnetic hard drive systems are primarily due to head-media spacing restrictions and the susceptibility of the media to moisture and thermal variations. Vibration and shock dampening must be performed in order to keep the read/write heads properly spaced from the media. The ruggedized chassis system does this for the drive unit as a whole as opposed to ruggedizing each drive. Moisture and temperature are controlled with a combination of cavity sealing and air flow.

The commercial drives/ruggedized chassis system has the advantages of low cost an high capacity since commercial drives are used. The limitation of the system is that the ruggedization can only go so far. This system could not, for example, be engine mounted without extensive additional ruggedization. The other potential limitation of the system is the relatively low data rates, but the buffer/MUX system described above should solve this problem.

b. Magnetic Tape Drive

Digital magnetic tape storage is also a very mature data storage technology. The present mass data storage system on the shuttle uses this technology. Magnetic tape systems have the advantage of very large capacities, bigger tapes equate directly with more storage capacity, and very high data rates due the the multiple scanning record head technologies used for writing the data. Data rates can be increased by increasing the tape speed or the scanning speed of the head. The primary disadvantages of tape systems is data access, since the data is stored sequentially on the tapes and the tapes are typically thousands of feet long access times are measured in minutes, and power consumption, which is large due to the mass and speed of the tape. Since this application is primarily archival in nature, and thus does not have severe access requirements, the access time limitation is not significant.

The tape drive system baselined for the technology analysis is a ruggedized 42 Gbyte tape system which can store data at rates up to 107 Mbits/sec. The environmental issues which strongly impact magnetic tape systems are the same as for the magnetic hard drives. Vibration restrictions are not quite as stringent because magnetic tapes record heads are actually held in contact with the tape and therefore the head-to-media spacing is more easily controlled. The contact also reduces the life of both the tapes and the record head, however. Humidity and temperature control are again handled with air flow and sealed chambers.

The magnetic tape systems do not offer technology development, storage densities are again within about a factor of 2 of the theoretical limit and the recording technology is very mature, but they do offer well understood and tested systems.

3. Solid State Memories

Solid state memory technologies are memory systems which have no moving parts and typically take are manifested as electronic devices. Solid state memory units are monolithic and are fabricated using VLSI fabrication technology. These memory technologies are characterized by very fast access times (on the order of 1 μsec to 100 nsec), high densities (10^5-10^6 bits/cm^2), very low power requirements, and 2-dimensional structure. Although 16 Mbit RAM chips presently exist, the packaging problems involved in putting together mass storage systems with Gbyte capacities is not trivial. A 4 Gbyte system, for example, would require 1000 16 Mbit RAM chips. The size and weight of the resulting system may not be prohibitive to this application, but the present cost of solid state memory systems very quickly becomes excessive when compared to the costs of the the magnetic and optical systems. Further, the archival nature of this application fails to use one of the biggest assets of the solid state systems, the short access times.

Since solid state memory systems have no moving parts, the vibration and shock requirements of the environment are typically not a significant problem. The shock and vibration will impact packaging, however. Shear forces will restrict methods such as die stacking and multi-chip modules. Unlike magnetic and optical memory technologies, solid state memory technologies may be subject to radiation damage. Since this application is space based some of the solid state memories may require additional hardening to cosmic radiation.

The paragraphs below describe the basic concept of each solid state memory technology analyzed and gives the product information upon which the technology system data was extrapolated for the technology review.

a. RAM

RAM is the acronym for Random Access Memory. Most solid state memories are random access, but in this case RAM will refer to solid state memory which will retain its information only as long as power is supplied. This of course is a severe restriction with significant implications to system reliability and survivability. Figure 11 shows schematic and cross-sectional diagrams of a dynamic-RAM storage cell. Charge is stored in the capacitor etched in to the glass substrate. The glass capacitor is leaky so the charge must be refreshed by application of voltage. At present one can buy 20 Mbits of RAM on a single 6" wafer. This product was used to extrapolate the size, weight, power, and costs of the Gbyte systems required for the mass data storage unit. RAM a.

b.

c.

d.

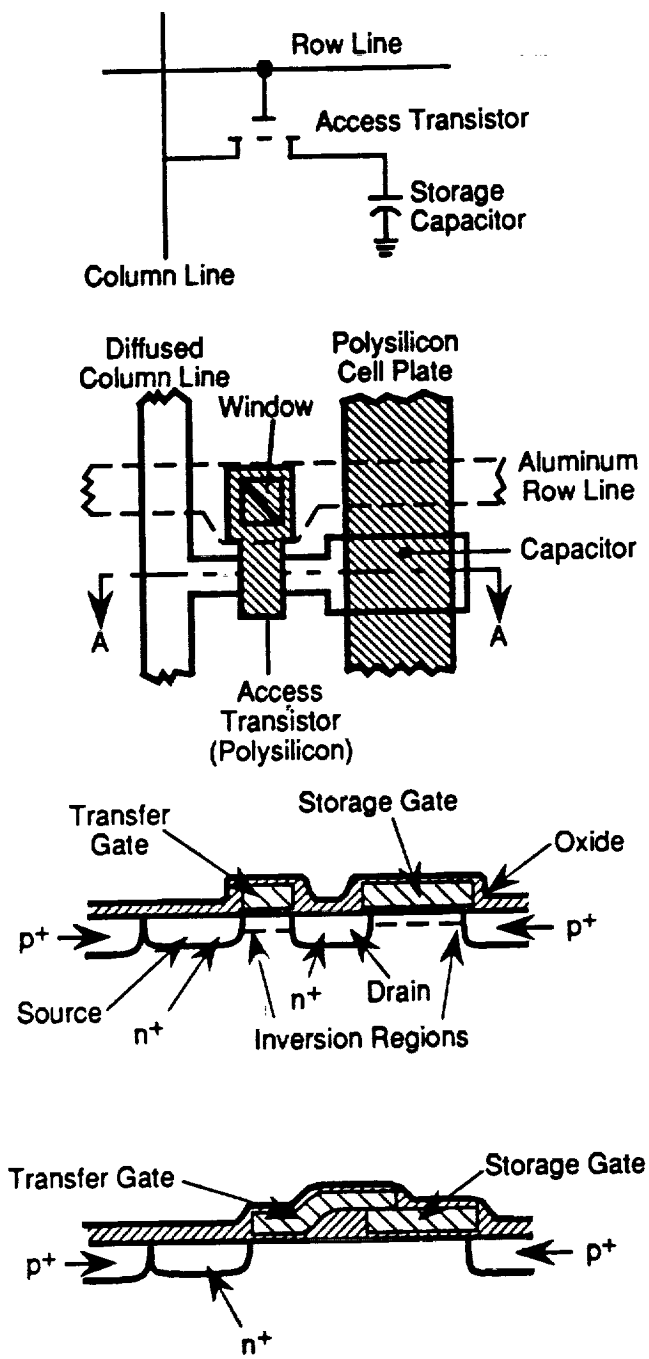


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Figure 11. Single-Transistor Dynamic-RAM Cell with a Storage Capacitor
(a) Circuit Diagram Schematic
(b) Cell Layout
(c) Cross Section Through A-A
(d) Double-Level Polysilicon Cell

systems are one of the solid state memory technologies which will be subject to radiation damage and should therefore be hardened.

As an example of the current state of the art in space-qualified semiconductor RAMs, Seakr Engineering, Inc., Torrance, CA, offers recorders with 4-32 Mbytes of data storage. The 8 Mbyte unit has dimensions 3.4 x 6.4 x 7.5 inches and weights 9.2 lbs. Its maximum continuous data rate is 4 Mbits/sec. It should be possible to expand these memory units to the 128 Mbyte region easily.

b. EEPROM

Electrically Erasable Programmable Read Only Memory (EEPROM) is a solid state memory which will retain the bit information after power loss. EEPROM's store the bit information in the form of stored charge in the memory cell and, like RAM, they are susceptible to radiation damage. Figure 12 shows a cross-section diagram of an EEPROM memory cell. EEPROM's can be written and erased many times, although the number of write cycles is 8-10 orders of magnitude lower than bubble memory or FRAM technology. Presently 1 Mbit EEPROM's are available and this chip size was used to extrapolate the resource usage of the EEPROM mass storage system.

Although the access times for EEPROM's can be as low as 150 nsec, the write times for a 16 bit word are on the order of milliseconds. These write times translate to data storage rates of only 10^4 bits/sec and therefore EEPROM is not a candidate technology for any of the applications reviewed here unless very extensive and sophisticated buffering and multiplexing is performed. Such buffering and multiplexing is possible, but the complexity of the storage system will become unwieldy.

c. FRAM

Ferroelectric Random Access Memories (FRAM) are a hybrid of ferroelectric materials and silicon based RAM technologies[23]. The bit information is stored in the electronic polarization of the memory cell. The cell contains a thin ferroelectric film like KNO_3 or PZT (see Figure 13). The individual crystals of the ferroelectric films have two polarization states which can be toggled with the application of an electric field. Once the polarization of the crystals/film has been set it will remain polarized until another electric field is applied. The state of the bit is read by applying an electric field and measuring the transient current response. The polarization of the crystals will dictate the size of the resulting current transient and thus the state of the cell. The cell is re-written to restore its original state.

The big advantages of the FRAM technology is that the information is stored as crystal polarization, not a charge configuration, and is inherently radiation hardened and the read/write times are on the order of 10 nsec giving the devices extremely high bandwidth. Like magnetic memory technologies, FRAM systems are temperature sensitive. Present products are limited a range of 0-70°C but are expected to have full Mil-Spec temperature ranges, -55 - 125°C, soon.

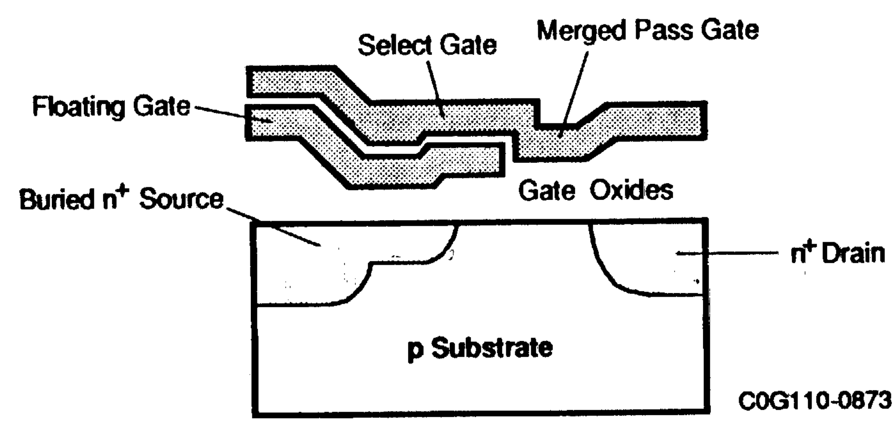

Figure 12. Sketch of EEPROM Cell

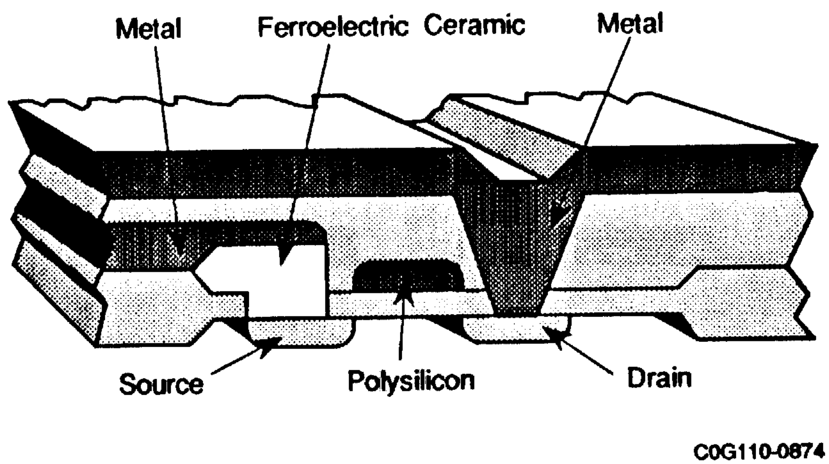

Figure 13. Sketch of FRAM Cell

FRAM technology is relatively new and is only available in 8Kbit chip at this time, although 1 Mbit chips are expected by the end of 1991. The extrapolated resource usage reflects this minimal state of development.

d. Magnetic Bubble Memory

Magnetic bubble memory has been cited as a potential rugged replacement for magnetic disc and tape systems since its conception at Bell Labs in the early 1960's. Magnetic bubble memory is a solid state memory in which localized regions of oriented magnetic domains are formed in a thin magnetic film, typically garnet or permalloy (see Figure 14). The oriented domains repel or attract each other, depending upon the orientation of the neighboring domains, and will try to expand or contract a given oriented bubble until the bubble disappears. If an external magnetic field is applied, a minimum bubble size becomes thermodynamically preferred and single bit storage bubbles result. In thin garnet films the bubble diameter is on the order of .0001 in. Presently 1 Mbit/cm^2 storage densities are achieved in bubble memory systems.

The bubbles are written and read by moving them around the chip in sequence with a rotating magnetic field (see Figure 15). As a given bubble passes the magnetic read/write location in the chip the appropriate function is performed. Because the system has no movable read/write head the entire string of bubbles must be moved with respect to the read/write location. Large capacity systems could have access times on the order of seconds. Advanced chip design and bubble string management have resolved this problem, however, and 1 Mbit bubble memories can have access times on the order of 15 msec with proper string management.

The biggest advantage of bubble memories when compared to magnetic disc and tape systems is ruggedness and reliability. Like all of the solid state memory technologies the lack of moving parts make the memory technology inherently more robust. When compared to other solid state memory technologies, bubble memories have the advantage of not being susceptible to radiation. Bubble memories are more susceptible to shock and temperature variation than FRAM because of the properties of magnetic thin films, but are still more robust than the mechanical system. The biggest disadvantage of bubble memory systems is their limited data rates. The sequential accessing makes the bubble systems inherently slower than the random access solid state memories. Present systems can achieve 1 Mbit/sec data rates but only with significant power consumption. Further increases in data rates will require linear increases in power consumption. A 1.2 Mbyte bubble memory cartridge product used in a buffered/multiplexed system was used as the baseline for the Flight System and Test Stand technology comparisons.

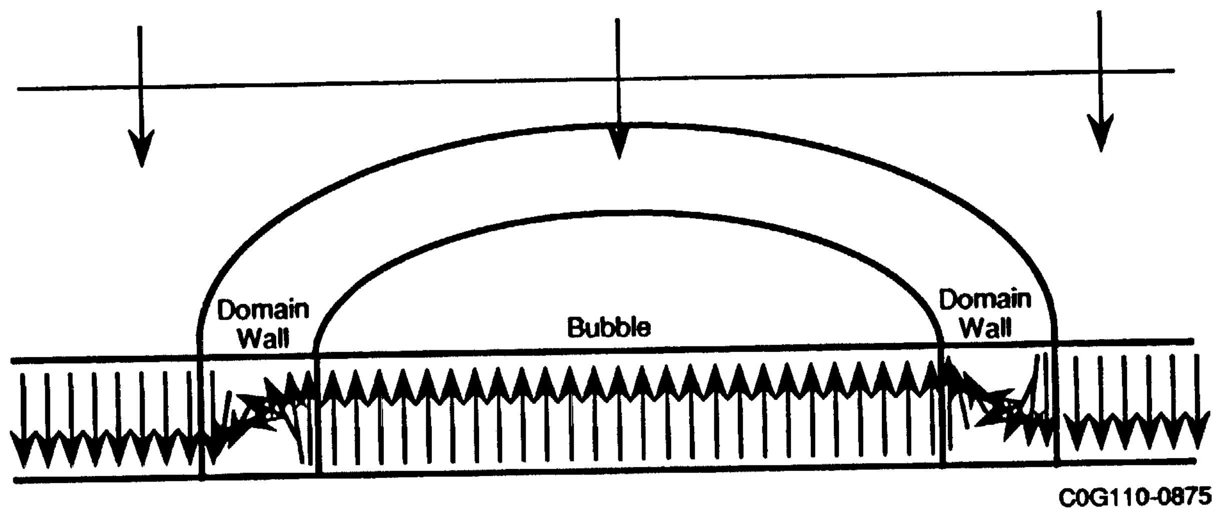

Figure 14. In a Bubble Memory, the Magnetic Force Exerted by the Domain Wall Combines with the Force of the External Magnetic Field (Arrows) to Reduce the Bubble's Growth

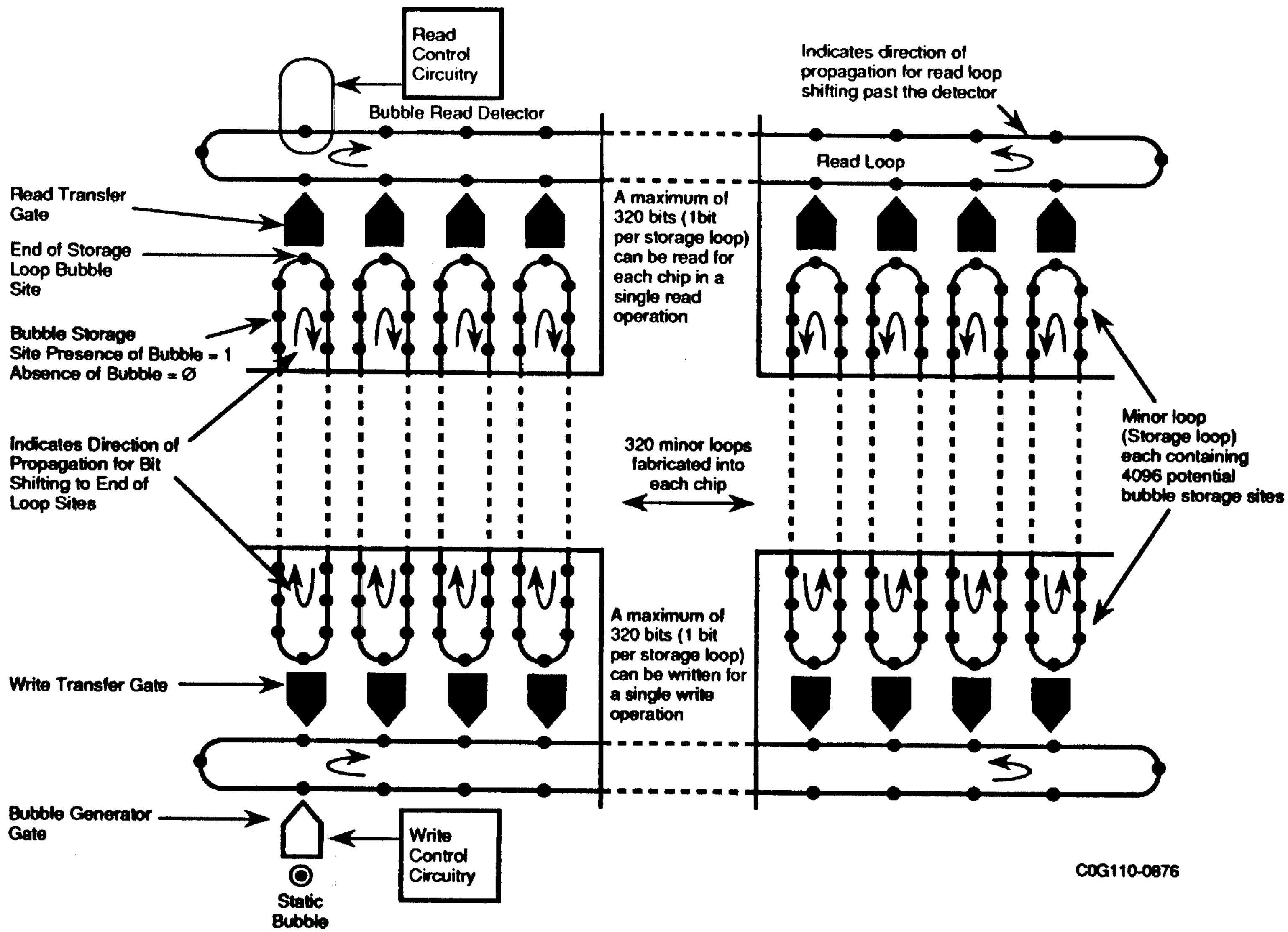

Figure 15. Block Diagram of a Bubble Memory Chip

The most recent development in bubble memory technology is a new way of storing bit information called Vertical Bloch Line memory (VBL). VBL stores bit information around the walls of the bubbles in the form of Bloch Lines of polarization. Storage densities of 0.5 -1 Gbit/cm2 are expected to be achieved with VBL technology. Very high data rates will still be a problem for these systems, however. VBL technology was used as the baseline bubble technology for the Advanced Vehicle portion of the Technology Review.

Bubble memory technology has the potential as a high density, inherently rugged mass data storage technology. However, a lack of development resources and advances in conventional magnetic, optical, and solid state memory technologies like ferroelectric RAM have slowed the development of bubble memory technology. Consequently the costs of the bubble systems and their further development are very high.

C-26. The Rating Process

In our evaluation of the candidate technologies, we adopted the following approach, in order to account for the tradeoffs that can be made between various relevant factors. (For example, the capacity of an MDS system can be increased by adding more units, but at a cost in resource usage, e.g. increased size, weight, etc. Or, in order to meet environmental specifications, a memory unit could be enclosed in an elaborate temperature-controlled vibration-isolated package, but this package could be unacceptable from the standpoint of size or cost.) The total required data capacity and data rate and the environmental factors are to be treated as requirements that must be met, i.e. the system must have enough total capacity to perform its task and it must operate in the prescribed environment. A technology that cannot meet the total capacity, data rate, or environmental requirements under any conditions will be rejected. During Task III, we defined specific systems using the various candidate technologies, so as to meet these minimal requirements. Then the distinguishing factors were issues such as the resource usage and risk associated with the development of the technologies.

The weighting factors for each parameter defined in Task II, the definition of requirements for MDS technology, were presented in Table 8. They were presented for three scenarios:

- Current flight vehicle (the space shuttle) (we evaluated this on the basis of three engines)
- Ground test stand
- Advanced launch vehicle (we assumed 10 engines for this scenario)

The categories of data storage and environmental catability are treated as binary go/no go requirements, i.e. a candidate technology which cannot meet the minimal requirements was not considered further.

The other categories have their individual factors weighted in importance according to a scale of weighting factors defined by Table 8. This table represents our considered judgement about the relative importance of the various factors. These factors were used in Task III as weighting factors, w_i. For a candidate technology, we defined a system configuration which could meet the data capacity and environmental requirements.

The performance of a given system was evaluated and given a score, s_i, relative to the minimum requirements. The scoring system and the scores, s_i, are defined in Table 10. We then evaluated the various candidate technologies by forming the sums $s_i w_i$ for each specified system.

Table 10 represents the scoring system on a scale of 0 through 5 for each of the relevant parameters. The table was generated by starting with the requirements derived in Task II, and assigning the minimum acceptable value a low score (usually 0, but 2 in the case of resource usage, because the system is reuqired to have increased capacity, so some increase in parameters like size could be allowed). The scoring range was spread over what we judged to be a reasonable range that could be accomplished for the particular factor, usually one order of magnitude. A few factors (survivability and growth potential) have scores described in qualitative terms, rather than quantitative.

Table 10. Summary of Scoring Ranges

Category	Requirement	Minimum Value	Weight	Score Ranges 0	1	2	3	4	5
Data Storage									
	Total Capacity	3.3 Gbytes	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Data Rate	23.2 Mbits/sec	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Architecture	digital	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Environment									
	Op. Temp.	35-105°F	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Vibration	8g RMS	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Shock	20g	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Pressure	0-1000 Torr	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Humidity	0-95%	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Acceleration	0-5g	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Survivability	100g,salt water	3	None	Nominal Fire	Explosion	Challenger	Worse/Challe	Nuclear
Reliability									
	Error Rate	0.000001	3	0.000001	3.1623E-07	0.0000001	3.1623E-08	0.00000001	3.1623E-09
	Permanence(hrs)	1000 hrs	5	1000	3874.67512	15013.1073	58170.9133	225393.39	873326.162
	Maintainability (MTBS)	no periodic	5	Period. Req.	<10 flights	10 to 20	20 to 50	50 to 100	>100 flights
	Read Cycles	20000	5	2000					20000
	Write Cycles	100(non-removable)	4	<100					1000
Resource Usage									
	Size (cu. in.)	3000 in3	8	5000					300
	Power(W)	150 W	3	250					30
	Weight(lbs.)	100 lbs	10	200					20
	Cost($k)	$300K	8	400					30
Access Time									
	Access Time	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A
Reusability									
	Reusability(hrs)	1 day maximum	5	>1 day	12-24 hr	8 - 12 hr	4 - 8 hr	1 - 4 hr	< 1 hr
Risk									
	Cost of Development ($M)		3	>$10M	5M-10M	2M-5M	500K-2M	100k-500k	<$100k
	Growth Potential		6	none	poor	fair	good	very good	excellent
	Readiness (1991)	Ready in 1991	Binary	N/A	N/A	N/A	N/A	N/A	N/A

Table 10. (continued)

Category	Requirement	Minimum Value	Weight	Score Ranges 0	1	2	3	4	5
Data Storage									
	Total Capacity	12.1 Gbytes	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Data Rate	85 Mbits/sec	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Architecture	digital/flexible	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Environment									
	Op. Temp.	0-100°F w/Solar	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Vibration	Commercial	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Shock	Commercial	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Pressure	760 torr	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Humidity	0-95%	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Acceleration	1g	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Survivability	N/A	1	None	Nominal Fire	Explosion	Challenger	Worse/Challer	Nuclear
Reliability									
	Error Rate	0.000001	5	0.000001	3.1623E-07	0.0000001	3.1623E-08	0.00000001	3.1623E-09
	Permanence(hrs)	1000 hrs	4	3000	9486.83298	30000	94868.3298	300000	948683.298
	Maintainability (MTBS)	no periodic	5	Periodic Requ	<1 tests	1 to 2	2 to 5	5 to 20	>20
	Read Cycles	20000	4	2000					20000
	Write Cycles	100(non-removable)	4	<100	5				1000
Resource Usage									
	Size (cu. in.)	1000 cu. ft.	3	1000000					1700
	Power(W)	1500W.	3	1500					150
	Weight(lbs.)	1000 lbs	3	5000					100
	Cost($k)	$300K	10	400					30
Access Time									
	Access Time	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A
Reusability									
	Reusability(hrs)	1 day maximum	5	>1 day	12-24 hr	8 - 12 hr	4 - 8 hr	1 - 4 hr	<1 hr
Risk									
	Cost of Development ($M)		3	>$10M	5M-10M	2M-5M	500K-2M	100k-500k	<$100k
	Growth Potential		6	none	poor	fair	good	very good	excellent
	Readiness (1991)	Ready in 1991	Binary	N/A	N/A	N/A	N/A	N/A	N/A

Table 10. (continued)

Category	Requirement	Minimum Value	Weight	Score Ranges 0	1	2	3	4	5
Data Storage		(10 Engines)							
	Total Capacity	12 Gbytes	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Data Rate	85 Mbits/sec	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Architecture	digital	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Environment									
	Op. Temp.	-65 - 160°F	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Vibration	8g RMS	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Shock	20g	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Pressure	0-1000 Torr	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Humidity	0-95%	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Acceleration	0-5g	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Survivability	100g salt water	3	None	Nominal Fire	Explosion	Challenger	Worse/Challei	Nuclear
Reliability									
	Error Rate	0.000001	3	0.000001	3.1623E-07	0.0000001	3.1623E-08	0.00000001	3.1623E-09
	Permanence(hrs)	3000 hrs	5	3000	9486.83298	30000	94868.3298	300000	948683.298
	Maintainability (MTBS)	no periodic	5	Periodic Requ	<10 flights	10 to 20	20 to 50	50 to 100	>100 flights
	Read Cycles	200000	5	20000					200000
	Write Cycles	1000(non-remove)	4	1000					10000
Resource Usage									
	Size (cu. in.)	1500 in3	8	3000					300
	Power(W)	75 W	3	150					15
	Weight(lbs.)	50 lbs	10	100					10
	Cost($k)	$150K	8	300					30
Access Time									
	Access Time	100 seconds	3	>100s	10 to 100s	1 to 10s	0.1 to 1.0s	20-100ms	<20 ms
Reusability									
	Reusability(hrs)	1 day maximum	5	>1 day	12-24 hr	8 - 12 hr	4 - 8 hr	1 - 4 hr	< 1 hr
Risk									
	Cost of Development ($M)		6	>$10M	5M-10M	2M-5M	500K-2M	100k-500k	<$100k
	Growth Potential		8	none	poor	fair	good	very good	excellent
	Readiness		2	2020	2010	2000	1996	1993	1992

The results of the evaluation for each candidate technology are presented in Tables 11, 12 and 13 for the three scenarios.

In Tables 11 through 13, the left column names the parameter consideration and the second column gives the values desired for that parameter. These are the values that were derived during Task II. The third column presents the weighting factor associated with the parameter, also as derived in Task II. Then, for each technology candidate, named at the top of the page, there are three clumns, which give our considered opinion for the vlaue of the parameter in the given scenario, its score according to the scoring ranges established in Table 10, and then the weighted score (the score multiplied by the weighting factor). The total score is listed at the bottom, for the particular technology.

In order to allow easier comparison of the results, Table 14 compiles the total scores for each of the three scenarios, in decreasing order for each scenario.

The results in this table show that the scoring values for different technologies change substantially according to the scenario which is being considered. In addition, candidates from each of the three different areas (optical, magnetic and electronic) ranked high in each scenario.

Table 14 represents the outcome of our formal numerical scoring process. It is apparent that there is not a single absolutely clear "winner" in this process. It is necessary to evaluate and interpret the meaning of this table critically in order to derive a recommendation. In the next section we describe the interpretation and the evolution of a recommendation for a candidate for technology development.

Table 11. Scoring Summary for Flight System

Flight System Compare

Category	Requirement	Minimum Value	Weight	Magnetic Disk Values	Magnetic Disk Score	Magnetic Disk Weighted Score	Magnetic Tape Values	Magnetic Tape Score	Magnetic Tape Weighted Score	Magnetic Bubble Values	Magnetic Bubble Score	Magnetic Bubble Weighted Score
Data Storage												
	Total Capacity	3.3 Gbytes	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Data Rate	23.2 Mbits/sec	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Architecture	digital	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Environment												
	Op. Temp.	35-105°F	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Vibration	8g RMS	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Shock	20g	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Pressure	0-1000 Torr	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Humidity	0-95%	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Acceleration	0-5g	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Survivability	100g,salt water	3	Enter score->	3	9	Enter score->	3	9	Enter score->	3	9
Reliability												
	Error Rate	0.000001	3	1E-10	5	15	0.00000001	4	12	1E-15	5	15
	Permanence(hrs)	1000 hrs	5	100000	3	15	100000	3	15	350000	4	20
	Maintainability (MTBS)	no periodic	5	30	3	15	20	3	15	200	5	25
	Read Cycles	20000	5	20000	5	25	10000	2	10	1E+12	5	25
	Write Cycles	100(non-removable)	4	10000	5	20	240000	5	20	1E+12	5	20
Resource Usage												
	Size (cu. in.)	3000 in3	8	3500	2	16	5000	0	0	55000	0	0
	Power(W)	150 W	3	50	4	12	450	0	0	400	0	0
	Weight(lbs.)	100 lbs	10	90	3	30	160	1	10	500	0	0
	Cost($k)	$300K	8	50	4	32	160	3	24	9625	0	0
Access Time												
	Access Time	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Reusability												
	Reusability(hrs)	1 day maximum	5	1	4	20	1	4	20	0.1	5	25
Risk												
	Cost of Development ($M)		3	0.5	4	12	0.5	4	12	7.5	1	3
	Growth Potential		6	Enter score->	1	6	Enter score->	1	6	Enter score->	2	12
	Readiness (1991)	Ready in 1991	Binary	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
					Total Score	227		Total Score	153		Total Score	154

Table 11. (continued)

Flight System Compare

EEPROM			RAM			Ferro Electric			Holographic			Optical Card			
Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Enter score->	3	9	Enter score->	0	0	Enter score->	4	12	Enter score->	3	9	Enter score->	0	0	Enter score->
1E-10	5	15	1E-10	5	15	1E-10	5	15	0.00001	0	0	1E-12	5	15	1E-12
20000	2	10	1000	0	0	50000	2	10	100000	3	15	100000	3	15	100000
10	2	10	10	2	10	1000	5	25	1	1	5	2	1	5	50
1E+15	5	25	1E+12	5	25	1E+12	5	25	1000000	5	25	20000	5	25	10000000
10000	5	20	1E+12	5	20	1E+12	5	20	100	0	0	100	0	0	1000000
10000	0	0	1000	4	32	1000	4	32	11000	0	0	3146	2	16	5000
150	2	6	5	5	15	5	5	15	50	4	12	1000	0	0	100
800	0	0	80	4	40	80	4	40	700	0	0	72	4	40	150
15000	0	0	800	0	0	20000	0	0	300	1	8	300	1	8	50
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
0.1	5	25	0.1	5	25	0.1	5	25	2	4	20	24	1	5	0.3
3	2	6	3	2	6	10	1	3	2	3	9	2	3	9	0.5
Enter score->	3	18	Enter score->	2	12	Enter score->	3	18	Enter score->	3	18	Enter score->	0	0	Enter score->
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total Score	144		Total Score	200		Total Score	240		Total Score	121		Total Score	138	

Table 11. (continued)

Flight System Compare

Optical Disk		Optical Tape			Fiber Optic			Com. Optical Disc In Chassis		
Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
3	9	Enter score->	3	9	Enter score->	0	0	Enter score->	3	9
5	15	1E-12	5	15	0.000001	0	0	1E-12	5	15
3	15	150000	3	15	1000	0	0	100000	3	15
4	20	20	3	15	1	1	5	50	4	20
5	25	60000	5	25	400000	5	25	10000000	5	25
5	20	60000	5	20	1000000	5	20	1000000	5	20
0	0	3650	1	8	87000000	0	0	7000	0	0
4	12	450	0	0	45000	0	0	240	0	0
1	10	160	1	10	8000000	0	0	180	0	0
4	32	50	4	32	5700000	0	0	100	4	32
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	25	0.3	5	25	0.1	5	25	1	4	20
4	12	0.5	4	12	20	0	0	0.5	4	12
5	30	Enter score->	5	30	Enter score->	1	6	Enter score->	4	24
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total Score	225		Total Score	216		Total Score	81		Total Score	192

Table 12. Scoring Summary for Ground Test Stand

Test Stand Compare

Category	Requirement	Minimum Value	Weight	Magnetic Disk Values	Magnetic Disk Score	Magnetic Disk Weighted Score	Magnetic Tape Values	Magnetic Tape Score	Magnetic Tape Weighted Score	Magnetic Bubble Values	Magnetic Bubble Score	Magnetic Bubble Weighted Score
Data Storage												
	Total Capacity	12.1 Gbytes	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Data Rate	85 Mbits/sec	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Architecture	digital/flexible	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Environment												
	Op. Temp.	0-100°F w/Solar	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Vibration	Commercial	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Shock	Commercial	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Pressure	760 torr	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Humidity	0-95%	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Acceleration	1g	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Survivability	N/A	1	Enter score->	3	3	Enter score->	3	3	Enter score->	3	3
Reliability												
	Error Rate	0.000001	5	1E-10	5	25	0.00000001	4	20	1E-15	5	25
	Permanence(hrs)	1000 hrs	4	100000	3	12	100000	3	12	350000	4	16
	Maintainability (MTBS)	no periodic	5	30	5	25	20	4	20	200	5	25
	Read Cycles	20000	4	20000	5	20	10000	2	8	1E+12	5	20
	Write Cycles	100(non-removable)	4	10000	5	20	24000	5	20	1E+12	5	20
Resource Usage												
	Size (cu. in.)	1000 cu. ft.	3	10500	4	12	5000	4	12	165000	4	12
	Power(W)	1500W.	3	150	5	15	450	4	12	1200	1	3
	Weight(lbs.)	1000 lbs	3	270	4	12	160	4	12	1500	4	12
	Cost($k)	$300K	10	150	4	40	160	3	30	28875	0	0
Access Time												
	Access Time	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Reusability												
	Reusability(hrs)	1 day maximum	5	1	4	20	1	4	20	0.1	5	25
Risk												
	Cost of Development ($M)		3	1	3	9	0	5	15	10	1	3
	Growth Potential		6	Enter score->	1	6	Enter score->	1	6	Enter score->	2	12
	Readiness (1991)	Ready in 1991	Binary	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
					Total Score	219		Total Score	190		Total Score	176

Table 12. (continued)

Test Stand Compare

EEPROM			RAM			Ferro Electric			Holographic			Optical Card		
Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Enter score->	3	3	Enter score->	0	0	Enter score->	3	3	Enter score->	3	3	Enter score->	0	0
1E-10	5	25	1E-10	5	25	1E-10	5	25	0.00001	0	0	1E-12	5	25
20000	1	4	1000	0	0	50000	2	8	100000	3	12	100000	3	12
10	4	20	10	4	20	1000	5	25	1	2	10	2	3	15
1E+15	5	20	1E+12	5	20	1E+12	5	20	1000000	5	20	20000	5	20
10000	5	20	1E+12	5	20	1E+12	5	20	100	0	0	100	0	0
10000	4	12	10000	4	12	10000	4	12	3670	4	12	11132	4	12
50	5	15	50	5	15	50	5	15	50	5	15	5000	0	0
800	4	12	800	4	12	800	4	12	233	4	12	256	4	12
10000	0	0	8000	0	0	6000	0	0	210	3	30	150	4	40
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
0.1	5	25	0.1	5	25	0.1	5	25	2	4	20	1	4	20
3	2	6	3	2	6	10	1	3	2	3	9	0.5	4	12
Enter score->	3	18	Enter score->	2	12	Enter score->	3	18	Enter score->	3	18	Enter score->	0	0
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total Score	180		Total Score	167		Total Score	186		Total Score	161		Total Score	168

Table 12. (continued)

Test Stand Compare

Optical Disk			Optical Tape			Fiber Optic			Com. Optical Disk in Chassis		
Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Enter score->	3	3	Enter score->	3	3	Enter score->	0	0	Enter score->	3	3
1E-12	5	25	1E-12	5	25	0.000001	0	0	1E-12	5	25
100000	3	12	150000	3	12	1000	0	0	100000	3	12
50	5	25	20	4	20	1	2	10	50	5	25
10000000	5	20	60000	5	20	400000	5	20	10000000	5	20
1000000	5	20	60000	5	20	1000000	5	20	1000000	5	20
50000	4	12	3650	4	12	87000000	0	0	21000	4	12
1000	2	6	450	4	12	45000	0	0	7200	0	0
1500	4	12	160	4	12	8000000	0	0	540	4	12
500	0	0	50	4	40	5700000	0	0	400	0	0
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
0.3	5	25	0.3	5	25	0.1	5	25	1	4	20
0.5	4	12	0.1	4	12	10	1	3	1	3	9
Enter score->	5	30	Enter score->	5	30	Enter score->	1	6	Enter score->	4	24
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total Score	202		Total Score	243		Total Score	84		Total Score	182

Table 13. Scoring Summary for Advanced Vehicle

Advanced System Compare

Category	Requirement	Minimum Value	Weight	Magnetic Disk Values	Magnetic Disk Score	Magnetic Disk Weighted Score	Magnetic Tape Values	Magnetic Tape Score	Magnetic Tape Weighted Score	Magnetic Bubble (VBL) Values	Magnetic Bubble (VBL) Score	Magnetic Bubble (VBL) Weighted Score
Data Storage		(10 Engines)										
	Total Capacity	12 Gbytes	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Data Rate	85 Mbits/sec	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Architecture	digital	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Environment												
	Op. Temp.	-65 - 160°F	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Vibration	8g RMS	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Shock	20g	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Pressure	0-1000 Torr	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Humidity	0-95%	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Acceleration	0-5g	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
	Survivability	100g,salt water	3	Enter score->	3	9	Enter score->	3	9	Enter score->	3	9
Reliability												
	Error Rate	0.000001	3	1E-10	5	15	0.00000001	4	12	1E-15	5	15
	Permanence(hrs)	3000 hrs	5	100000	3	15	100000	3	15	350000	4	20
	Maintainability (MTBS)	no periodic	5	30	3	15	20	3	15	200	5	25
	Read Cycles	200000	5	20000	0	0	10000	0	0	1E+12	5	25
	Write Cycles	1000(non-remove)	4	10000	5	20	24000	5	20	1E+12	5	20
Resource Usage												
	Size (cu. in.)	1500 in3	8	10500	0	0	5000	0	0	1000	4	32
	Power(W)	75 W	3	150	0	0	450	0	0	1600	0	0
	Weight(lbs.)	50 lbs	10	270	0	0	160	0	0	100	0	0
	Cost($k)	$150K	8	150	3	24	160	3	24	2000	0	0
Access Time												
	Access Time	100 seconds	3	0.02	4	12	3	2	6	0.01	5	15
Reusability												
	Reusability(hrs)	1 day maximum	5	1	4	20	1	4	20	0.1	5	25
Risk												
	Cost of Development ($M)		6	1	3	18	0.5	4	24	20	0	0
	Growth Potential		8	Enter score->	1	8	Enter score->	1	8	Enter score->	3	24
	Readiness		2	1991	5	10	1991	5	10	2000	2	4
					Total Score	166		Total Score	163		Total Score	214

Table 13. (continued)

Advanced System Compare

EEPROM			RAM			Ferro Electric			Holographic			Optical Card		
Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Enter score->	3	9	Enter score->	0	0	Enter score->	3	9	Enter score->	3	9	Enter score->	0	0
1E-10	5	15	1E-10	5	15	1E-10	5	15	0.00001	0	0	1E-12	5	15
20000	1	5	1000	0	0	100000	3	15	100000	3	15	100000	3	15
10	2	10	10	2	10	1000	5	25	1	1	5	2	1	5
1E+15	5	25	1E+12	5	25	1E+12	5	25	1000000	5	25	200000	5	25
10000	5	20	1E+12	5	20	1E+12	5	20	100	0	0	1000	5	20
625	4	32	625	4	32	625	4	32	11000	0	0	10164	0	0
50	4	12	50	4	12	50	4	12	50	4	12	1000	0	0
50	3	30	50	3	30	50	3	30	700	0	0	233	0	0
1000	0	0	500	0	0	3000	0	0	300	0	0	500	0	0
0.000001	5	15	0.000001	5	15	0.000001	5	15	0.000001	5	15	1	3	9
0.1	5	25	0.1	5	25	0.1	5	25	2	4	20	24	1	5
10	1	6	5	2	12	15	0	0	2	3	18	5	2	12
Enter score->	3	24	Enter score->	3	24	Enter score->	3	24	Enter score->	3	24	Enter score->	0	0
1994	4	8	1994	4	8	1997	3	6	1991	5	10	1991	5	10
	Total Score	236		Total Score	228		Total Score	253		Total Score	153		Total Score	116

Table 13. (continued)

Advanced System Compare

Optical Disk			Optical Tape			Fiber Optic			Com. Optical Disk in Chassis		
Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score	Values	Score	Weighted Score
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary	Binary
Enter score->	3	9	Enter score->	3	9	Enter score->	0	0	Enter score->	3	9
1E-12	5	15	1E-12	5	15	0.000001	0	0	1E-12	5	15
100000	3	15	150000	3	15	1000	0	0	100000	3	15
50	4	20	20	3	15	1	1	5	50	4	20
10000000	5	25	60000	1	5	400000	5	25	10000000	5	25
1000000	5	20	60000	5	20	1000000	5	20	1000000	5	20
25000	0	0	3650	0	0	87000000	0	0	10500	0	0
500	0	0	450	0	0	45000	0	0	3600	0	0
750	0	0	160	0	0	8000000	0	0	270	0	0
500	0	0	50	4	32	5700000	0	0	200	2	16
0.1	4	12	10	2	6	114	0	0	0.1	4	12
0.3	5	25	0.3	5	25	0.1	5	25	1	4	20
4	2	12	1	3	18	20	0	0	1	3	18
Enter score->	5	40	Enter score->	5	40	Enter score->	1	8	Enter score->	4	32
1994	4	8	1994	4	8	1996	3	6	1994	4	8
	Total Score	201		Total Score	208		Total Score	89		Total Score	210

Table 14. Ordered Scoring Ranks

Flight System	
FRAM	240
Magnetic Disk	227
Optical Disk	225
Optical Tape	216
RAM	200
Commercial Optical Disk	192
Magnetic Bubble	154
Magnetic Tape	153
EEPROM	144
Optical Card	138
Holographic	121
Fiber Optic	81
Ground Test System	
Optical Tape	243
Magnetic Disk	219
Optical Disk	202
Magnetic Tape	190
FRAM	186
Commercial Optical Disk	182
EEPROM	180
Magnetic Bubble	176
Optical Card	168
RAM	167
Holographic	161
Fiber Optic	84
Advanced Vehicle	
FRAM	253
EEPROM	236
RAM	228
Magnetic Bubble	214
Commercial Optical Disk	210
Optical Tape	208
Optical Disk	201
Magnetic Disk	166
Magnetic Tape	163
Holographic	153
Optical Card	116
Fiber Optic	89

C-2c. Recommendation for Technology Development

The central objective of this study program on MDS technology for rocket engine HMC is to develop a recommendation for the best candidate(s) for technology development. In this section, we describe the development of the recommendation, based on the requirements defined in Task II and on the technology survey and evaluation described in the previous section.

The rankings for the different technology candidates vary from one application scenario to another, and there is no single top candidate that emerges clearly ahead of all others. Thus, it is necessary to perform a critical evaluation of the ranking system in order to develop a recommendation.

First, we note that within a particular scenario, two technologies which differ in total score by a small number of points cannot clearly be differentiated with respect to one being better than the other. The assignment of scores for particular parameters is a matter of judgement, and the range of error for a particular score could reasonably be estimated as 10% of its value. Thus, the rankings are probably accurate with respect to the identification of leading candidates and poorest candidates, but one cannot distinguish clearly the exact order of two adjacent rankings.

Second, the technology development recommendation probably should not give great weight to the ground test scenario. This is an application for which the storage needs can be met with existing technology, simply by adding additional magnetic recording devices. The technology development recommendation should be driven by the requirements of a flight system.

Of the two flight systems, the requirements for the current flight system are by far the better defined. There are no firm specifications for the advanced vehicle, and although we have developed working values for parameters such as the total capacity and data rate, these values were derived from generalized arguments, whereas for the current flight system, the values come from a much better defined analysis of the specific sensors characteristics that are employed. Although it may be argued that the recommended technology may not be developed and space qualified in time to become the HMC MDS on the space shuttle during its remaining life, the quantitative requirements of that system are on a much firmer basis than for the advanced vehicle.

The rankings for the current system indicate a group of 6 top technologies, ranked fairly closely, within about $\pm 10\%$ of their average value. These are the FRAM, the magnetic disk, the optical disk, the RAM, the optical tape and the commercial optical disk in a chassis. Below that there is a substantial gap, large enough to be considered real, before the next candidate (magnetic bubble).

The recommendation should come from the top group of six. Thus, the scoring process has identified a group of technologies which are significantly poorer than the leading group and which may be dropped. The tradeoffs between positive and negative features in the group of six leading candidates are summarized in Table 15.

One may make the argument that the evaluation process, as we have defined it, may have allowed unsuitable candidates to be included in the final ranking. In order to handle the question of how to achieve the required capacity, we used the procedure that the number of units could be multiplied by as large an amount as needed to achieve the required capacity. Then the resource requirements for that technology would increase. This would cause the technology to receive low rankings in requirements such a size, weight, etc.

In inspecting the results closely, we see that the electronic technologies (RAM, FRAM, EEPROM, and magnetic bubble) generally scored well in the areas of size, power and weight. This is despite the fact that many units had to be multiplexed in order to achieve the capacity. But the cost of the total package has become very high, up to $20M per unit for the FRAM. This means that the FRAM scored a zero in cost. But any technology judged to cost over $400K received a zero, and the scoring system, as set up, did not punish the excessively high costs adequately.

Thus, among the differing basic technologies, the electronic technologies are judged to be unacceptable because of their very high cost, both development cost and the recurring cost per unit.

One might argue even that the EEPROM should not have been one of the surviving candidates, in that its intrinsic 1 millisecond write time makes it unsuitable. In order to achieve the data rate, it was necessary to link 23000 devices via a parallel buffer which would probably be an unworkable solution.

With respect to the comparison between magnetic technology and optical technology, the magnetic technology (disks and tapes) is extremely mature. Magnetic technology derives its relatively high scores at least partly because it has been worked extensively over a period of decades. Thus, a technology development phase as envisioned for the next stage of this program would have relatively little effect. A larger advance at the cutting edge of technology would be achieved by an investment in optical technology.

Table 15

Trade Offs Among Leading Candidates

	Pros	Cons
Optical Disk	High capacity, good match between current status and required development	Relatively high resource usage, need more speed
Optical Tape	Excellent match to program requirements	Immaturity
Commercial Optical Disks	Low risk, readiness	No growth potential
Magnetic Disk	High capacity, realiability, readiness	No growth potential
RAM	Small and light, reliable	Much multiplexing, to get capacity, high cost
FRAM	Small and light, reliable	Much multiplexing, high unit cost, large development

Among the 6 optical candidates evaluated, the ordering was:

Optical disk
Optical tape
Commercial optical disk in chassis
Holographic
Optical card
Fiber optic

The optical disk and tape were fairly close at the top, followed by commercial optical disk with a small gap, followed by optical card and holographic with a large gap and with fiber optic ranked last. Possibly, because of its unreasonable weight and cost, fiber optic systems should not have reached the final ranking process.

We feel that this rank ordering among the optical technologies is realistic and accurately reflects their relative attractiveness. The bottom three may be ruled out on the basis of the scoring; the commercial optical disk in a multiple platter chassis does not represent substantial technology development and may also be eliminated.

The choice between the final two candidates is difficult. They rank very closely in scoring, too closely to distinguish clearly between them. They both exhibit extremely attractive potential for technology development. For the optical disk, the issues would be increased capacity, attainable via multiple heads, increased disk diameter and increased recording speed. For the optical tape, the main issues would be ruggedization and technology maturation.

For a series of follow on programs leading to an actual ground test in 1993, we judge the state of development and readiness of the optical disk to be superior. We recommend this as the best candidate for HMC MDS technology development.

The optical tape is an extremely close and extremely attractive second place candidate. If a second development program can be funded, we recommend this as a subject for that program.

In summary then, our recommendation for the best technology for development as a proof of concept demonstration for MDS for HMC is an optical disk approach, emphasizing those factors required to increase total data storage capacity and writing rate above the current state of the art. Optical tape would be a close second choice.

C-3. Project Plan and Specification

The recommendation formulated by Honeywell for the best candidate for technology development for MDS for rocket engine HMC was optical disk technology. The purpose of this subsection is to make the recommendation more specific so as to form the basis for a mission-focused demonstration and test model of an MDS unit which can be constructed over a 20 month period beginning around January 1, 1991.

The most significant issues which must be addressed in such a proof-of-concept demonstration are total data capacity and data rate. Requirements for these two parameters for a mission similar to a space shuttle flight have been defined as:

Total capacity: 3.3 G bytes
Data rate: 23.2 M bits/second

Note that these two requirements are relevant to the useful sensor-generated data that must be stored. Requirements for formatting, tracking, error correction, etc. increase the total storage required, probably by an additional 30% or so in typical systems.

The current state of the art for capacity and data rate in ruggedized optical disks is 0.26 gigabytes at a writing rate around 3 megabits/second. Both these numbers refer to the useful data storage, after the overhead is subtracted. They are referenced to a single-sided, 5.25 inch diameter disk. It is apparent that increases by about one order of magnitude in both these parameters are required.

The main technology developments that will be required to achieve these increases include increases in the disk size (while retaining the ruggedness), increases in packing density on the disk, increased rotation speed for the disk and use of multiple writing heads.

C-3a. CONCEPT DEFINITION

- Short Wavelength Alternative

One approach that could be envisioned involves the use of shorter wavelength laser diodes to perform the writing function. If one used a blue (or violet) laser wavelength, instead of the present 780 nm infrared wavelength, the diffraction-limited focal area of the beam would be reduced by a factor of two and the linear spacing of the bits could be increased by a factor of two. With a concomitant increase by a factor of two in the track packing density, the areal bit packing density would increase by a factor of 4, and a single two-sided 5.25 inch disk would hold about 2.08 gigabytes. Thus, a two platter system could meet the capacity requirement. Because of the increased bit density, the writing speed would increase by a factor of two for a single writing head. If one envisions two independent writing heads for each side of each disk, with the data properly interleaved, the writing rate would increase by a factor of 8, to approximately 24 megabits/second, close to the requirement.

This appears to be an attractive approach in that the required capacity and data rate could be met with the same size disks that are already in use, and which have already been ruggedized.

Probably currently available recording media could continue to be used at the shorter wavelength. The absorption coefficient of the tellurium based alloys that are used as the media in current write-once-read-mainly (WORM) optical disks is approximately as large in the blue portion of the spectrum as it is in the near infrared. The issues of ruggedization to meet vibration and shock requirements would be minimized. The system development would be substantially simplified.

The drawback to this approach is the current status of laser technology, suitable for use as a pump source. There are no blue diode lasers available, nor do there appear to be any near term prospects for development of such lasers. There are some prospects, within a period of several years, for compact, efficient blue solid state lasers, which could be coupled to the medium via optical fibers.

There are other requirements for small blue lasers, including projection scanning, high definition TV, and underwater communications. There is enough research interest driving the development of blue laser sources that good devices probably will become available at some point in the future.

The blue line could be achieved via frequency doubling of semiconductor lasers operating near 900 nm. Frequency doubled semiconductor lasers with outputs in excess of 40 mW at 428 nm have been reported. The packages to date have been very elaborate and cumbersome, and it will require extensive development over a period of years to develop effective sources via this approach. Frequency doubling of Ti:sapphire lasers will also yield sufficient power but the package will be large. Intracavity frequency doubling of diode pumped Nd:YAG operating at 946 nm has been demonstrated, yielding 473 nm light, but only at a level of a few mw.

As a dark-horse suggestion, frequency doubling of Cr:LCAF (chromium doped lithium calcium aluminum fluoride) is a prospect. LCAF is tunable over the range 800-950 nm, and is experiencing growth as a result of extensive research interest. This system could be made compact. Thus, the blue line could be provided by several developing systems.

It is our judgement that a suitable blue laser would not be available until three to five years from now. Thus, an approach that requires such a laser for a demonstration unit that is to be delivered in 1992 is not appropriate.

Thus, we are led to technology developments in the form of increased disk size or packing density, while continuing to use infrared diode lasers operating near 780 nm.

- Impact of System Requirements

Let us consider the required size of a single large disk with the required capacity, which we will assume to be about 4.3 gigabytes, including 30% overhead for formatting, etc. Assuming 8 bit bytes, this means that the total capacity is 3.4×10^{10} bits (1.7×10^{10} bits/side). If we assume a bit spacing of 1.3 μm center-to-center along the track and a track-to-track spacing of 1.6 μm, then each bit requires an area around 2.08×10^{-8} cm^2. Within a 3 inch wide band around the edge of a 10" diameter disk, one could store 2.04×10^{10} bits per side. Thus, a 10" two sided disk would have adequate capacity. There are, however, several issues that arise in the use of a disk packed completely with data.

We must consider the issue of variable or constant rotation speed. Several possible formats are possible, as illustrated in Figure 16. The left side of the figure shows the case of constant angular velocity (CAV), with the bits arranged in concentric circular tracks. At the center of the recorded area, the spacing of the bits is 1.3μm. But as one goes toward the edge of the disk, the linear velocity increases and the bit spacing also increases, so that the total storage capacity decreases. One may increase the capacity by modifying the format. If one divides the recorded area into bands (say 6-10), with the bits in the innermost track of each band spaced at 1.3μm, the capacity is

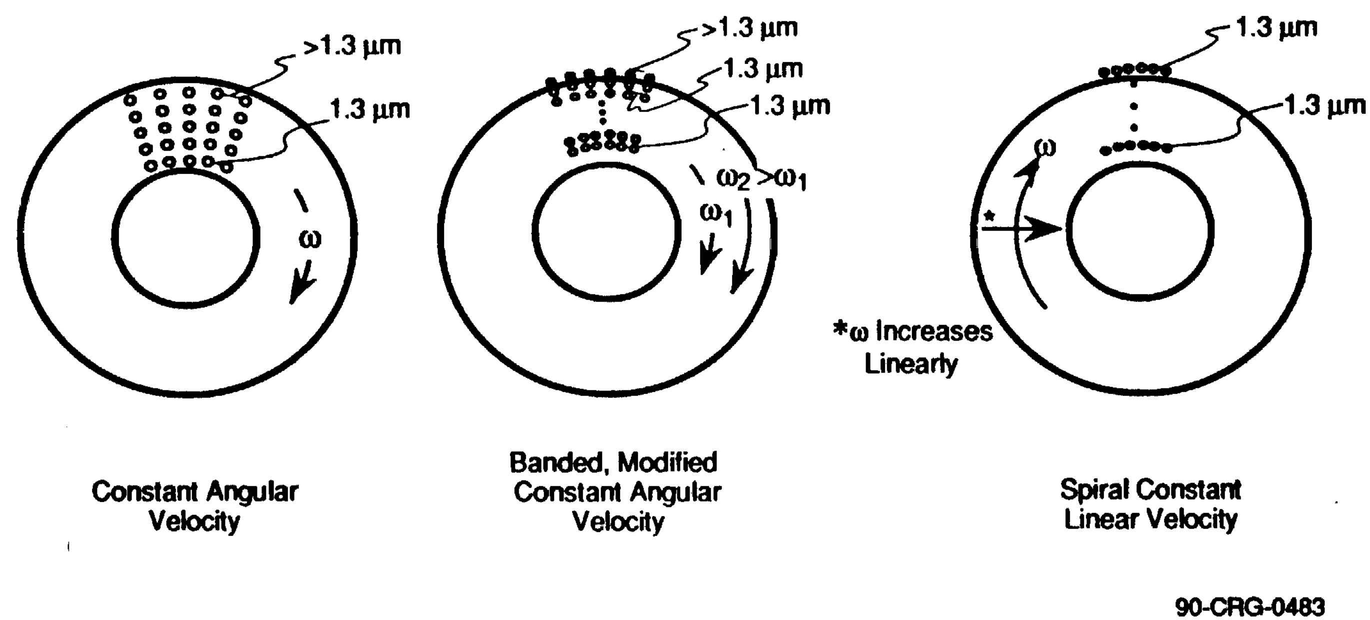

Figure 16. Illustration of Data Formatting and Banding

increased. This case is illustrated in the center portion of the figure. A third possibility is constant linear velocity (CLV), with the bit spacing held at 1.3μm along all the tracks. This case is shown in the right portion of the figure. The rotation rate is decreased as one goes from the center of the disk toward the edge.

If we were choose to have the rotation speed constant, then the bits become more widely spaced along the track near the periphery of the disk, and the total capacity of the disk decreases, to 1.2×10^{10} bits/side if no banding is used. If one does use banding and discontinuously variable rotation speed between bands, the capacity increases to 1.9×10^{10} bits per side (for six equal bands). Thus with a ten inch diameter disk, the required capacity may be obtained with either a constant linear velocity format or a banded format with constant angular velocity within each band.

The alternatives thus appear to be either using a disk with diameter greater than 10 inches (with attendant problems in ruggedization) or using a banded system or a linear velocity system (which necessitate a variable rotation speed). The linear velocity alternative appears to be compatible with the NASA mission requirements.The bits could be configured in a single spiral track. The data flow would be in the form of a continuous bit stream, and there will be no need to jump between tracks. Thus, the control system could be substantially simplified, because it would only have to follow a single spiral track from the center of the band to the edge (or vice versa).

A second issue is that one must allow for the fact that the write head can jump tracks, perhaps a number of tracks at a time, in response to a shock. Thus, each track must have an identifying code which enables the system to determine which track it is following and allows the fine tracking system to make the necessary corrections. This issue would favor the use of a banded system, with constant velocity within each band.

- Constant Linear Velocity (CLV) Alternative

We first examine the characteristics of the CLV alternative, with the single spiral track of data. Let us consider the questions of data rate. In the single spiral track system described above, with the bit spacing along the track equal to 1.3 μm, at the outer edge of the disk, the length of the track would be 79.8 cm and the number of bits around the track would be 6.14×10^5. To achieve the required data rate of 1.16×10^7 bits per second (per side) would require a rotation rate of 18.9 revolutions per second (1134 RPM), a reasonable rate. (This approach assumes that the bits are interleaved or "daisy chained" between the two sides of the disk in some fashion, perhaps using a buffer to store blocks of some size.)

At the inner edge of the band, the rotation rate would have to be 2.5 times higher (2835 RPM) in order to achieve the required bit rate. This rotation rate will represent a substantial challenge. It is substantially above the 1800 RPM currently used. We judge that there would be no substantial issues of mateial deformation or material strength for a glass disk, but it will be difficult to make the tracking servos and controls operate fast enough.

The issue of the constancy of the rotation rate is also important. The timing of the system can become subject to error if the rotation rate varies. The tracking system requires the reading of prerecorded track identification, with the bits being read at a specified rate. If the rotation rate varies, at random, the bits will not appear in the correct temporal time slots in which they are expected, and the track identification system could become confused. But with monitoring of the bit rate, feedback and closed loop control, we judge that the rotation rate can be held constant to within 0.1% and that this would not be a problem.

A suitable form for a 10 inch disk which could be quite rugged could involve a lead screw format. The runout of the lead screw would provide the coarse tracking. The head would be capable of fine tracking, over a range of perhaps 25 tracks. The rotation rate of the disk would vary linearly as the head moves outward (or inward) along a radius of the disk. This configuration is sketched in Figure 17. Such a system can provide stability to within 0.001 inch even in an environment with shock and vibration. The corresponds to a maximum error around 16 tracks, which is within the capacity of the fine tracking system to correct.

We also see the desirability of using a direct-read-after-write (DRAW) approach to check the recorded bits for accuracy. It allows for instant checking of the accuracy of a recorded bit immediately after recording, and will aid in keeping data rate high. This will require that the head incorporate two sources.

Thus, one possible system concept is a single 10 inch diameter two sided WORM disk, using currently available tellurium alloy recording media. It will require two independent heads, one per side, with two light sources per head, and using DRAW. The total capacity would be 4 gigabytes, but it is possible that the technology demo would require only one side. The diode lasers would be conventional AlGaAs lasers, operating near 780 nm. The disk would be formatted in a single spiral track in a band covering the outer three inches of its diameter. The rotation rate would be continuously variable from around 2800 RPM near the center of the band to about 1200 RPM near the edge. The runout would be controlled by a lead screw.

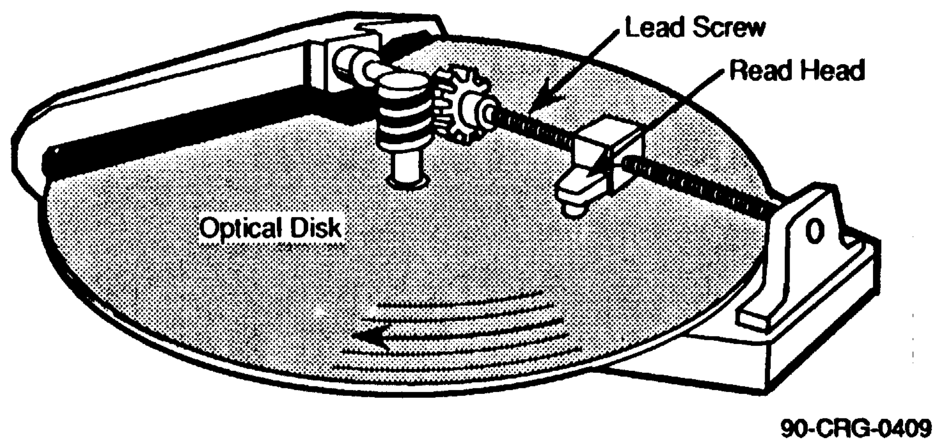

Figure 17. Configuration for Optical Disk with Lead Screw and Continuous Runout to Follow a Spiral Track at Constant Linear Velocity

The approach has several conservative features, including:

- Use of currently available recording media
- Use of currently available lasers
- Simple control, with no motion between tracks required
- No significant increases in bit density

It does represent some challenges including areas which require technology development.

- Use of a large (10 inch) disk which will be difficult to ruggedize for vibration stability
- Development of configurations for multiple lasers per head
- Daisy chaining and buffering to allow the data to be written from a single stream via two write heads
- Use of a relatively high rotation rate (up to 2800 RPM, substantially higher than what has been used before)
- Development of a continuously variable rotation rate drive and concomitant controls

Although this is an attractive embodiment from a technical point of view, it does suffer from a drawback from another aspect. It is designed fairly specifically for this one application, of archival mass data storage. It is not readily adaptable to other applications because it is uncompatible with any random access. It is essentially a mastering system, aimed at a niche market. Thus, it may be difficult to find organizations willing to invest the required development effort to product this system. We judge that these issues are very significant and that the system defined above will not be an acceptable choice.

- Banded System

Therefore, we define a second system which will have more versatility. Necessarily, this will require either a storage media larger than 10 inch diameter as described above, or a banded format, rather than a single spiral track. These features will make the memory more versatile and more compatible with conventional memory requirements.

We judge that requirements of ruggedization will increase rapidly with disk diameter, and thus prefer to work with the minimum possible disk diameter. As we saw before, a ten-inch disk, with data stored on the outer three inches of its perimeter, in a banded system with six bands and constant angular velocity within each band could store 1.9×10^{10} bits on each side. This would be adequate storage capacity. Within each band the track could be a spiral. This would be compatible with the incoming data stream and would eliminate the need to step tracks each revolution.

Let us consider the writing rate for such a system. We require 23.2 megabits/second of data, or about 30.2 megabits/second if one includes the requirements for overhead. In the center of the innermost band, where the data rate will be lowest, we have a total of 2.45×10^5 bits in the innermost track. At a conservative rotation rate of 1800 RPM, a single head would read 7.35×10^6 bits/second.

If the data are stored in an edge-detection format, as illustrated in Figure 18, the bit rate may be increased. The bits are stored as grooves, rather than individual pits, one pit per bit. The presences of "1" bits is denoted by either the start or the end of a groove. This format in principle could increase the writing rate by a factor of 2, but there are some limitations. For example, one cannot have too many zeros in a row. Thus, we conservatively estimate the increase in data rate associated with edge detection to be a factor of 1.5. With edge detection, we thus could have a data rate of 1.10×10^7 bits/second.

In order to reach the required data rate, we postulate the use of writing heads with more than one write source. If we assume two writing sources per head, and two relatively independent heads (one per side), the writing rate would increase to 4.4×10^7 bits/second, enough to provide the necessary data rate.

We envision that an efficient manner to use two writing sources on a single head would be to write on two adjacent tracks, with suitable interleaving of the data. Thus, the concept envisions meeting the data rate requirements with a head containing two writing sources, writing on two adjacent tracks concurrently. The head would contain four laser sources, two for writing and two for DRAW. There would be one head for each side of the disk. The heads would be constrained to work within the same band because of the angular rotation rate requirements, but otherwise would be relatively independent.

The coarse and fine tracking would be very similar to present ruggedized WORM optical memories.

The disk will require preformatting, which is an operation that will be performed on the entire disk before any data is written on it. The preformatting will include track identification, which will

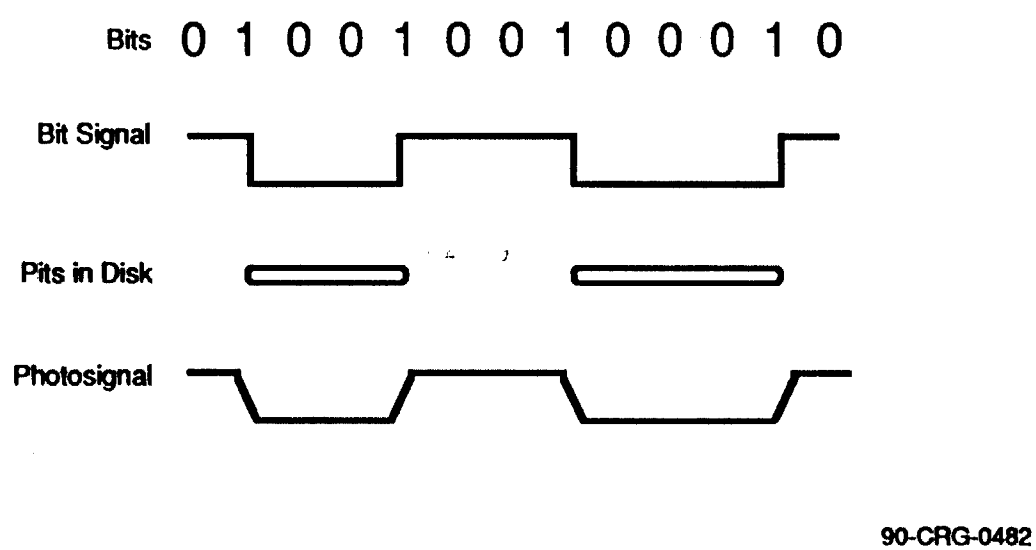

Figure 18. Illustration of Data Format for Edge Detection

identify the track periodically to the read portion of the head and will allow correction of any errors in track position by the fine adjustment system. It will also include clocking information which will allow adjustment of rotation rate to the correct value within each band. This preformatted information would come at predetermined positions in the rotation along each track. It is part of the overhead information, assumed to be about 30% of the available data capacity.

As the system fills the capacity of one band and moves to the next band, there will be some dead time required, for head movement and for the rotation rate to accelerate and stabilize at its new value. We estimate that this total time may be around 150ms, based on the parameters of current magnetic disk systems. Thus one would require (at at data rate of 23.2 M bits/sec) an auxiliary buffer memory with capacity around 4 M bits to store temporarily the data coming in during the band change.

In summary, this concept would use a two-sided 10-inch WORM media, banded into six bands with constant angular rotation rate in each band. The writing head contains 780 nm sources, two for writing on two adjacent tracks and two for DRAW. There would be a separate head for each side.

This approach is more like current optical memories in its format, and would be better adapted to a variety of applications. In particular it would be better suited for applications which would require random access to the data. It would probably be better accepted by the organizations who would have to produce it.

In some ways it is more conservative than the first approach defined, particularly in its use of bands of data with constant angular rotation rate in each band. Also the maximum rotation rate has been reduced to a conservative 1800 RPM.

The technology development challenges in this design include:

- Ruggedization of a 10-inch disk system
- Development of heads with four very closely spaced sources per head
- Development of optics to focus two sources in a head on adjacent tracks
- Daisy chaining and multiplexing to allow data to be written from a single data stream via two different heads and four sources
- Development of 10-inch glass disks with WORM recording media

We note explicitly that this technology development is compatible with real time access, although that was not one of the requirements for the HMC application. But the availability of real time access would provide more versatility and would allow the system to be used in other applications.

Also, despite the fact that the recommended technology emphasizes use of WORM media, it would be compatible with rewritable media as they become more available. It is, in fact, a development that would enhance the use of rewritable media systems.

This banded system represents our recommendation to be developed for the proof of concept demonstration. In this technology development, the critical feature is the increase of the data rate by about one order of magnitude above what is now available.

- Reduced Scope Alternative

In our analysis of the tasks required to develop the recommended proof of concept demonstration, and the level of effort required to perform them, we have defined a substantial program (see next section). Therefore, we have also defined a smaller, lower-cost alternative program. This program envisions that the main emphasis would be development of the four-source head (two for writing and two for DRAW) which would be required in the recommended program. However, the other development tasks would not be undertaken. This reduced-scope program would employ an existing 5-1/4 inch WORM optical memory unit, and would replace the current head with the four-source head. The emphasis would be to show that the new four-source head could perform the recommended writing and DRAW functions, multiplexing the data from the single data stream between the two writing sources. In particular, there would be no development of focusing and tracking controls.

The essential portion of this demonstration would be to show that the writing rate, which is one of the limiting factors in current WORM technology for the HMC application, could be doubled by use of the dual writing sources in a single head.

C-3b. TASKS FOR DEVELOPMENT

- Recommended Program

In a proof of concept demonstration, expected to extend over a 20 month period beginning near the end of 1990, we consider that the main development tasks would involve development of the four-source head, a rotational drive, and a focus/tracking servo control. In addition, the electronic interfacing, buffering and control necessary to split the single data stream between two writing sources would be developed.

Table 16 shows elements of a work breakdown structure necessary to accomplish this. It also includes a judgment about the number of person hours necessary to accomplish each task, laid out by month. The staffing includes several labor grades, including program managers, senior engineers, junior engineers and technicians. Design tasks would require a preponderance of engineering talent, whereas fabrication tasks would require more technicians.

The table also includes a list of the necessary materials and their estimated costs (including cost of acquisition). The total comes to 13058 person hours plus $174K of materials. The estimate of prices for materials includes an allowance for acquisition cost. A nominal amount is also included for travel to attend technical reviews, assumed to include a kick-off meeting and a final review. At a nominal NASA rate of $150K per person year (2000 hours), this program would be priced around $1.15 million.

The outcome of this program would be technology development, resulting in an operating MDS unit with adequate capacity and writing speed to perform the HMC task. This unit could later be employed in ground tests with rocket engines. The main technological development would be an increase by about one order of magnitude in the recording rate above what is now available.

The most important feature would be the development of the four-source head, which will allow a substantial increase in writing rate. This is one of the serious limiting factors in current state-of-the-art optical MDS technology.

The testing would not include testing over the full range of environmental specifications, but would include some limited environmental testing, including low-level shock and vibration and testing to show that it operates in all orientational attitudes.

- Lower Cost Alternative

We recognize that the level of effort required for the recommended program may be high. Therefore, we have defined a program with reduced scope, which emphasizes only development of the four-source head, the essential component for increased writing speed. The source would be integrated into an existing commercial 5-1/4 inch optical MDS unit and would take advantage of the predeveloped rotational drives, focus/tracking controls, etc.

Table 16. Tasks and Level of Effort for Recommended Program

MDST Optical Disk Proof of Concept Program

Task	Sub-Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Task Sub-Totals
		Months ARO																						
1.0 Requirements Review																								
	1.1 Environmental Requirements	80																						80
	1.2 Data Rate/Capacity Requirements	80																						80
	1.3 System Implementation Requirements	120																						120
2.0 System Design																								
	2.1 Media Definition/Formatting		160	160																				320
	2.2 Dual DRAW Head Design		320	320																				640
	2.3 Tracking/Focus Servo Design		320	320																				640
	2.4 Rotational Drive Design		320	240																				560
	2.5 Package Design					320	320																	640
	2.6 Thermal Design			80	160	160																		400
	2.7 Electronic Interface Design		240	240																				480
	2.8 System Design		80	80	80	80	80																	400
3.0 System Fabrication																								
	3.1 Procurement		40	80	40	40	80	40																320
	3.2 Dual DRAW Head Fabrication							200	200	200	200													800
	3.3 Tracking/Focus Servo Fabrication							240	240	240	240													960
	3.4 Drive/Disk Fabrication							160	160	160	160													640
	3.5 Interface Electronics Fabrication								160	160	160													480
	3.6 System Assembly										160	160	160											480
4.0 Sub-System Testing																								
	4.1 Laser Head Read/Write Testing									80	160	80	80	80	80									560
	4.2 Dual DRAW Head Testing									80	160	80	80	80	80									560
	4.3 Rotational Drive Testing									40	80	40	80	80	80									400
	4.4 Tracking/Focus Servo Testing									80	160	80	80	80	80									560
	4.5 Electronics Testing										40	80	80	80	80									360
5.0 System Test																								
	5.1 Test Plan Development														80									80
	5.2 Functional Testing - Data Rate/Capacity															160	160	160						480
	5.3 Limited Environmental Test																		80	80				160
6.0 Flight System Design																								
	N/A																			160	160			320
7.0 Program Management																								
	7.1 Management	80	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40			840
	7.2 Administration	24	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	234
	7.3 Reviews	48											48										48	144
	7.4 Reporting	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	80	80	320
	Monthly Totals	440	1538	1578	338	658	538	698	818	1098	1578	578	666	458	538	218	218	218	138	298	218	90	138	

Program Total (Person Hours)	13058

Travel	$7
Materials	$174

Bill of Materials	QTY	$K Ea.	Total
DRAW Head Lasers	10	0.33	3.30
Detectors	10	0.27	2.66
DRAW Head Optics	1	67.00	67.00
Servo Actuators	2	13.30	26.60
Electronics	1	20.00	20.00
Media	12	1.40	16.80
Drive Motor/Assembly	1	27.00	27.00
Power Supply	2	0.67	1.34
Thermal Controls	1	2.70	2.70
Raw Stock	1	6.70	6.70
TOTAL $K			174.1

This demonstration would not be able to meet the full capacity and speed requirements for HMC, but would serve as a demonstration of technology advancement in one critical area.

A work breakdown structure and schedule, along with estimated level of effort by month for each task, is given in Table 17. The person hours are reduced substantially, from 13058 to 8036. The materials have increased slightly, to $201K, because of the need to acquire a current operating optical MDS unit. At the assumed NASA rate of $150,000 per person year, this program would be priced around $0.80 million.

C-3a. Test Plan

The test program for the demonstration program would include a test plan defining the system test program. Based on the demonstration program defined above, we envision the test program defined below. System test activity would start with a well defined test plan. The test plan would define:

- Objectives
- Performance goals
- Setup and required test equipment
- Test procedures

The test objectives would be to demonstrate mass stoarge performance through a functional test, and confidence in ruggedness through limited environmental testing.

The functional test would demonstrate read and write rates (Mbits/sec) and the read and write error rates. Total capacity would not be demonstrated. Capacity can be verified to a high degree of confidence by writing to a number of successive tracks, and scaling the results to the total number of tracks on the system. The rate tests would require writing to a number of successive tracks, and across band boundaries.

The environmental tests would not be a full qualification test, as the demonstration unit will only be a brassboard. However, we recommend limited environmental testing consisting of high temperature, operating shock, and operating vibration. A full functional test procedure would be performed while the unit is undergoing environmental stress.

Table 17. Tasks and Level of Effort for Alternate Program

MDST Optical Disk Proof of Concept Program

Months ARO

Task	Sub-Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Task Sub-Totals
1.0 Requirements Review																								
	1.1 Environmental Requirements	20																						20
	1.2 Data Rate/Capacity Requirements	80																						80
	1.3 System Implementation Requirements	60																						60
2.0 System Design																								
	2.1 Media Definition/Formatting		20	20																				40
	2.2 Dual DRAW Head Design		320	320																				640
	2.3 Tracking/Focus Servo Design		320	320																				640
	2.4 Rotational Drive Design		0	0																				0
	2.5 Package Design					0	0																	0
	2.6 Thermal Design			40	80	80																		200
	2.7 Electronic Interface Design		80	80																				160
	2.8 System Design		40	40	40	40	40																	200
3.0 System Fabrication																								
	3.1 Procurement		40	40	40	40	40	40																240
	3.2 Dual DRAW Head Fabrication							200	200	200	200													800
	3.3 Tracking/Focus Servo Fabrication							240	240	240	240													960
	3.4 Drive/Disk Fabrication							0	0	0	0													0
	3.5 Interface Electronics Fabrication								40	40	40													120
	3.6 System Assembly										160	160	160											480
4.0 Sub-System Testing																								
	4.1 Laser Head Read/Write Testing									80	160	80	80	80	80									560
	4.2 Dual DRAW Head Testing									80	160	80	80	80	80									560
	4.3 Rotational Drive Testing									0	0	0	0	0	0									0
	4.4 Tracking/Focus Servo Testing									80	160	80	80	80	80									560
	4.5 Electronics Testing										40	40	40	40	40									200
5.0 System Test																								
	5.1 Test Plan Development														80									80
	5.2 Functional Testing-Data Rate/Capacity															120	120	120						360
	5.3 Limited Environmental Test																		20	20				40
6.0 Flight System Design																								
	N/A																			0	0			0
7.0 Program Management																								
	7.1 Management	40	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20			420
	7.2 Administration	24	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	192
	7.3 Reviews	48											48										48	144
	7.4 Reporting	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	40	80	280
	Monthly Totals	280	856	896	196	196	116	516	516	756	1196	476	524	316	396	156	156	156	56	56	36	48	136	

Program Total (Person Hours)	8036

Travel	$7
Materials	$201

Bill of Materials

	QTY	$K Ea.	Total
DRAW Head Lasers	10	0.33	3.30
Detectors	10	0.27	2.70
DRAW Head Optics	1	67.00	67.00
Servo Actuators	2	13.30	26.60
Electronics	1	20.00	20.00
Media	6	1.33	7.98
Optical Drive	1	67.00	67.00
Power Supply	0	6.67	0.00
Thermal Controls	0	2.70	0.00
Raw Stock	1	6.70	6.70
TOTAL $K			201.3

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The test setup is shown in Figure 19. A minicomputer with a fast magnetic hard disk is used as a data file source, test data acquisition and analysis computer, and test controller. The computer must be able to access the data file on the hard disk and supply it to an output port to the item under test at a rate higher than the write rate to be examined. This rate capability must be a sustained rate, not a peak rate. This involves access time of the hard drive. Read signals would also be examined with a transient recorder or storage oscilliscope.

The test procedure for the functional test involves first generating a test data file. This test file can be generated by pseudorandom methods, or from an old word processing text file. The file is then dumped to the unit under test. Subsequently the data is then read from the disk. This read procedure should be done several times, with the read output read to a different file each time. A statistical analysis will then determine whether errors are read or write errors. Write errors will show consistancy from file to file for a given byte. Bytes in error only in one of the files can be considered read errors. The read and write error rates are then determined.

This test will then be repeated under high temperature, shock and vibration. For the alternate program the functional tests would be the same as for the baseline recommended program. The environmental test, however, would consist of only a simplified operating shock test.

C-3d. SUMMARY

This document has described a recommended proof of concept demonstration for optical MDS technology development. It is based on the use of two heads, each containing four laser sources (either integrally or coupled through optical fibers), along with a two-sided banded 10-inch WORM media. The most significant portion of the technology development is the head design and fabrication, which will allow increase in writing rates above the current state of the art. This program will yield an operating optical MDS unit with the required capacity and speed.

A work breakdown structure and estimate of required effort for this development are included.

Also, a program of reduced content and scope, at lowered cost is also presented. This unit would emphasize only the head development, integrating it into a current 5-1/4" WORM system. It would not provide the total capacity nor data rate required, but would represent a substantial technology development and would require fewer program resources.

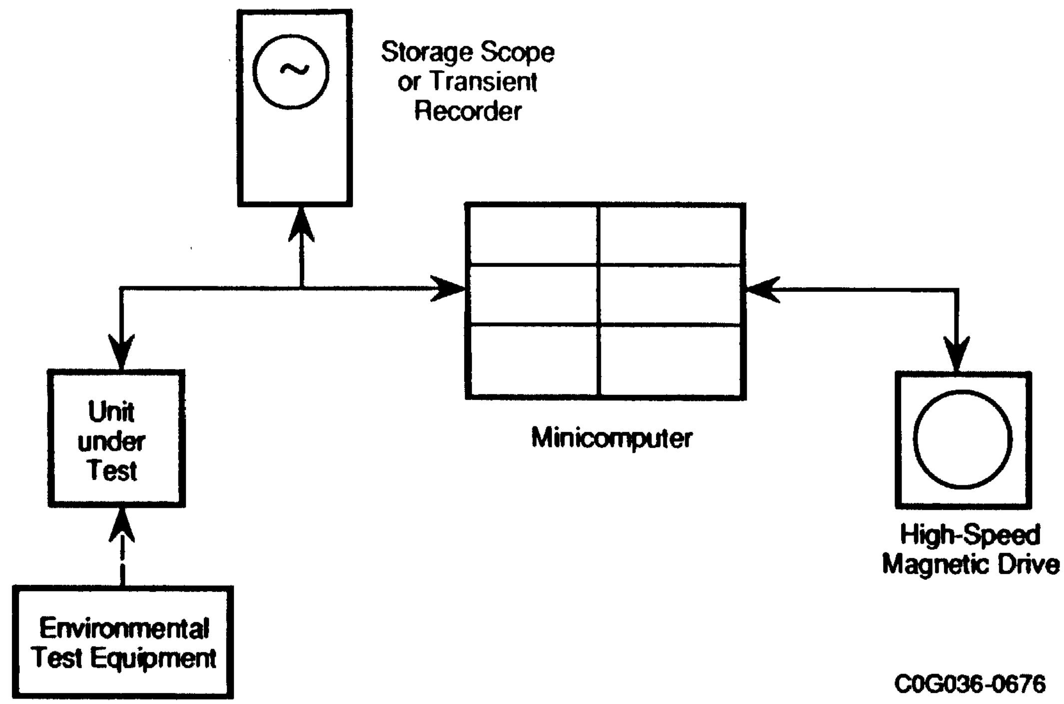

Figure 19. Test Setup

D. DISCUSSION OF RESULTS

We have generated a recommendation for optical disk technology as the best candidate for technology development for HMC and MDS have generated a specific concept and approach for a project to develop the technology. In this section we examine some of the issues that arise as a result of these recommendations.

The first issue involves resources required for generation of a completely new optical disk memory unit. The development of new optical disk technology requires a major long term investment. Typically companies which have brought new optical disks to market as commercial products have invested many years and multiple millions of dollars. The program that we have recommended for a proof-of-concept demonstration requires 20 months and slightly over $1 million, but it is intended to demonstrate a single key advance in recording rate. It will definitely not yield a completed, space-qualified MDS system. NASA should recognize that the total path to an operating MDS system for use in a flight vehicle will be much longer and more expensive than the project plan and specification for technology development, as outlined in this report.

A second issue involves the fact that the application of MDS for rocket engine health monitoring and control is a somewhat specialized application. It requires very large amounts of data storage (3.3 G bytes), whereas the market defined for most ruggedized optical mass memory units for use in aerospace environments has envisioned systems with total capacity around 1 G byte. Moreover, the lack of a significant driving force for rapid access is a signficant departure from the requirements of most mass memories. These factors combine to make this application rather different from the mainstream of optical disk applications.

Thus, when the time comes to purchase memory systems of this type for actual space missions, the unit cost may be high. The potential manufacturers may view these requirements as very specialized and may perceive that the total number of units that can be sold will be small. Thus, the development costs would have to be spread over a relatively small number of units, driving the unit cost up.

We have attempted to minimize the effect of this issue by defining a technology development with increased versatility and wider applicability. Specifically, we rejected the CLV system with a single spiral track as being of very narrow application. We defined a system which could be adapted so as to meet requirements for reasonably short access time. Finally, we proposed a recommended technology develpment which emphasizes increased data rate. This technology will be of use in a variety of applications in addition to HMC.

A third issue involves the fact that the recommended technology development leads in a direction different from the main thrust of the momentum in optical disk technology. The directions in which most research and development in optical disk technology is moving are toward rewritability (perhaps at most, 1 year away, with some products already reaching the market) and toward higher packing density made possible by use of blue laser sources (perhaps 3-5 years away, depending on developments in laser technology).

We have judged rewritability to be of minor importance for the HMC application. It would be desirable in that it could aid the resetting of the memory after a mission. There would be no physical removal of the media after a mission. One could simply erase the memory, probably in a time of the order of 20 minutes, and be ready to begin again. Although this feature would be desirable, it was not judged to be a critical factor, and in fact in Task II received a weighting factor of 5.

We believe that the shift to a shorter laser wavelength will come in time. It will increase packing density, total capacity and data rate. But it awaits the development of advances in laser technology, either in blue semiconductor lasers, frequency-doubled semiconductor lasers or blue diode-pumped solid state lasers. This is a development that is driven by other requirements also (for example, high definition TV) and will probably occur over a period of several years. But it is not available for a 1991 program and the large size of the investment that would be required makes unattractive for this project.

Despite the fact that there are good reasons for our choice of the specific technology development; it does mean that the recommended program is not along the main direction that optical disk manufacturers are moving. We have minimized the impact of this factor by recommending a technology development which will be useful in any case. The writing head development with increased data rate will be useful for either rewritable or unalterable otpical disks, and it will also be compatible with systems incorporating shorter wavelength lasers.

E. CONCLUSIONS

This program on MDS technology for rocket engine HMC applications had the objective of developing a recommendation and a program plan and specification for the best candidate(s) for technology development for mass data storage for rocket engine health monitoring and control.

The program had four main tasks:

- Program management to ensure successful completion within cost and schedule constraints\
- A review of current data storage technology leading to development and prioritization of mass data storage requirements
- A survey and analysis of current and new mass data storage technologies, leading to a recommendation for technology development
- Generation of a program plan and specification for the recommendation concept

This section will summarize the most important conclusions and recommendations of the program.

With respect to the requirements, we estimate that MDS for HMC on a flight system like the space shuttle would reuqire a total capacity of 3.3 G bytes (user available) and a recording rate of 23.2 M bits/second. These numbers refer to a three engine vehicle. For an advanced vehicle with a different number of engines, these numbers would scale linearly with the number of engines.

The recommendation for the best candidate for technology development is optical disk technology, with emphasis on increasing the recording rate by about one order of magnitude above the current state of the art. If sufficient funding is available, we recommend also an investment in the development of digital paper technology.

As a specific recommendation for the technology development, we recommend a proof of concept demonstration that would have the following features:

- Banded WORM-type, two sided, 10 inch diameter media on glass substrate
- 780 nanometer laser diodes
- Spacing 1.3μm along track, 1.6μm between tracks
- Current SOA focus/tracking servo control
- 4 source heads (2 for writing, 2 for DRAW)

This system would provide a proof of concept demonstration encompassing both the required capacity and data rate.

We estimate that this development could be carried out over a 20 month period, with an investment of 13058 person-hours of labor and $174K of materials.

As a lower cost alternative development, we suggest emphasizing the head development and installing the head on a currently available optical disk memory unit. This would provide a demonstration of technology for the required data rate, but not for the required total data capacity.

This development would require 8036 person-hours of labor and $201K of materials.

APPENDIX - LIST OF ACRONYMS

Acronyms used in this report have been defined at the first place where they are encountered. For reference, a list of the acronyms is compiled in this appendix.

ALS	-	Advanced launch system
CAV	-	Constant angular velocity
CCD	-	Charge-coupled device
CD-ROM	-	Compact disk read only memory
CLV	-	Constant linear velocity
DRAW	-	Direct read after write
EEPROM	-	Electrically erasable programmable read only memory
EIU	-	Engine interface unit
FDM	-	Frequency division multiplexer
FRAM	-	Ferroelectric random access memory
HMC	-	Health monitoring and control
LED	-	Light emitting didoe
M-O	-	Magneto-optical
MADS	-	Modular auxiliary data system
MDS	-	Mass data storage
MMU	-	Mass memory unit
POC	-	Proof of concept
PPS	-	Project plan and specification
RAM	-	Random access memory
ROM	-	Ready only memory
SSME	-	Space shuttle main engine
TDM	-	Time division multiplexing
VCO	-	Voltage controlled oscillator
VDL	-	Vertical Bloch line
WDM	-	Wavelength division multiplexing
WORM	-	Write once read mainly

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Report Documentation Page

1. Report No. NASA CR 185272	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Study of Mass Data Storage Technology for Rocket Engine Data		5. Report Date June, 1990
		6. Performing Organization Code
7. Author(s) John F. Ready, Earl T. Benser, Bernard S. Fritz, Scott A. Nelson Donald R. Stauffer and William M. Volna		8. Performing Organization Report No. None
		10. Work Unit No. 582-01-11
9. Performing Organization Name and Address Honeywell Inc. Systems and Research Center 3660 Technology Drive Minneapolis, MN 55418		11. Contract or Grant No. NAS3-25714
		13. Type of Report and Period Covered Contractor Report Final
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

This report summarizes the results of a nine month study program on mass data storage technology for rocket engine health monitoring and control. The program had the objective of recommending a candidate mass data storage technology development for rocket engine health monitoring and control and of formulating a project plan and specification for that technology development. The work was divided into three major technical tasks: (a) Development of Requirements, (b) Survey of Mass Data Storage Technologies and (c) Definition of a Project Plan and Specification for Technology Development. The first of these tasks reviewed current data storage technology and developed a prioritized set of requirements for the health monitoring and control application. The second task included a survey of state-of-the-art and newly developing technologies and a matrix-based ranking of the technologies. It culminated in a recommendation of optical disk technology as the best candidate for technology development. The final task defined a proof-of-concept demonstration, including tasks required to develop, test, analyze and demonstrate the technology advancement, plus an estimate of the level of effort required. The recommended demonstration emphasizes development of an optical disk system which incorporates an order-of-magnitude increase in writing speed above the current state of the art.

17. Key Words (Suggested by Author(s)) Mass data storage Rocket engines Optical disks Health monitoring and control	18. Distribution Statement Unclassified - Unlimited Subject Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	119	A06

COG035-0675