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Space Data Storage Systems and Technologies

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Abstract—A central aspect of most space missions is the acquisition from space of unique, mission-specific data and the subsequent return of these data to Earth. Because of technological requirements and constraints and the related *design* of the mission, a data storage subsystem, based on a data storage technology, is typically used to buffer data from the spacecraft and its instruments before raw or processed data are returned to Earth. The selection of the appropriate data storage technology for this function is based on a variety of considerations, including reliability, capacity, readiness, availability, mass, volume, power consumption, data rate, radiation insensitivity, nonvolatility, environmental stability, vibration insensitivity, data management flexibility, and cost, among other issues. Here, data storage technology selection, ranging from magnetic tape recording to solid-state memories, for past, present, and future missions, such as Voyager, Cassini, and Pluto Flyby, will be reviewed as mission requirements evolve, mission needs and designs become more complex, and progress is made in data storage technology.

I. INTRODUCTION

The acquisition and return of unique data from space to Earth is typically the central aspect of space missions. The data of interest typically include visual image data; other science and environmental data including data from particle, field, radiation, and other detectors; and engineering and telemetry data which provide information on the state and location of the spacecraft for control purposes. Since most missions have instruments which acquire data at different rates and times, and since playback typically occurs at yet other rates and times, a data storage subsystem is typically used to buffer the data acquired by instruments prior to transmission to Earth.

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At present, many space missions are planned as one-of-a-kind, first-of-a-kind projects. As such, realizing a successful mission is usually very important. Space missions are typically designed to obtain data in locations either near the Earth or in the solar system and beyond. The ability to effect repairs during a mission can be limited, impractical, or impossible. Technological performance at a system level is governed first by the amount of performance that can be obtained from the components in each of the subsystems. Thus, both near-Earth and planetary missions, by their very nature, have constrains in which technological performance is ultimately linked to mass, power, and volume. Second, limits exist on the amount of hardware and resources that can be brought to bear in a mission because of launch and ground system constraints. These constraints include limits on the performance of subsystems including data-gathering instruments, propulsion, telecommunications, and spacecraft control. Constraints from the launch and space environments as well as the space data channel enforce these constraints. Definition of the data storage subsystem is therefore affected by technological performance of data storage technology as well as the other technology elements which are used to generate data and to relay data to Earth. These combined effects dictate that data storage technology selection is the result either of optimization or compromise between a variety of constraints. Data storage technology selection is therefore driven by a combination of technological capability, technological reliability, performance at a system level, and practicality of implementation and risk aversiveness at a project level.

II. SPACE MISSION REQUIREMENTS

Most space missions essentially can be categorized either into earth-orbiting missions, in which spacecraft are operated near Earth; or planetary missions, in which spacecraft venture away from Earth into the solar system and beyond. While both types of missions have launch and environmental constraints, categorical differences in performance and technological implementation can be made which are linked to the distance between the spacecraft and Earth during operation. Shown in Figure 1 is a graph of the functional storage and data rate requirements for a variety of past and current missions and future mssion concepts whose requirements are deterined by year. [1-35] These missions include the well-known planetary Mariner, Viking. Voyager, Mars Observer, Magellan, and Galileo missions which have been launched over the past thirty years. Also included are missions such as Cassini which are planned for launch over the next few years as well as projected missions, for example, to Mars and Plum which are being studied for launch over the next decade.

Figure 1 shows that data storage and data rate requirements have been gradually increasing. Trends for data storage capacity requirements are growing by one order of magnitude approximately every twenty-four years, and data rate requirements are growing by one order of magnitude approximately every fourteen years. It is also observed that absolute values of storage are only now beginning to exceed one gigabyte, while data rate requirements are approaching one megabyte per second for planetary missions.

Figure 2 shows the dependence of resource consumption requirements [1-35] as a function of space mission. Power consumption and mass allocations are both observed to decrease with time, both at a rate of approximately one order of magnitude every thirty years. Volume allocations are observed to decrease at a rate of approximately one order of magnitude every twenty-two years. Bit-error rate requirements are also seen to improve, such that the number of bits in error per number of bits transferred is expected to reduce by one order of magnitude every decade.

The data shown in Figure 3 provide normalized performance metrics [1-36] which provide a measure of performance efficiency and technological advancement. First, the performance efficiency of storage capacity and data rate per unit resource is seen to increase uniformly. The first of these metrics is the peak data transfer rate normalized to the peak consumed power. Data transfer rate and power are related; and it is observed that the data rate supported per unit of power increases by one order of magnitude per decade.

The second metric, which is the product of the data transfer rate and the bit-error rate, is decreasing at a rate of approximately one order of magnitude every twenty years. Thus, the bit-error rate requirement is decreasing at faster rate than the data transfer rate is increasing, so that the reliability requirements appear to be more stringent as time advances.

The normalized metrics in Figure 3 which relate to the storage requirement per unit mass and volume are increasing at a rate of one order of magnitude per fourteen years and twelve years, respectively. A more detailed look at those metrics indicate rapid increases in storage efficiency in the, 1960's and early 1970's, steady growth in the 1970's and 1980's, and a range of values including an increase storage efficiency requirements for the next decade. While storage requirements are growing, the need to store additional data in less mass and volume is growing more rapidly.

The second type of trend shown in Figure 3 is based on the fact that magnetic tape recorders have historically been the technology of choice for space data storage applications. For tape recording, linear density becomes a measure of technological performance. The linear storage density that has been achieved in space tape recorder systems in the 1970's and 1980's is comparable to those achieved with commercial tape and disk products. However, as shown through the 1980's, the. rate at which commercial linear storage densities [37-39] are increasing, at approximately an order of magnitude. per decade, is greater than that sustained in space tape recorder systems, which show an increase of an order of magnitude every twenty years.

Figure 1. Storage capacity and data transfer rate requirements as a function of the selected space missions' functional requirements date.

Figure 3. Normalized data transfer rate and storage requirements metrics as a function of the selected space missions' functional requirements date.

Environmental requirements are important to space data storage systems in addition to absolute performance and performance efficiency. Selected launch and spaceflight environmental requirements [40-42] are shown in Table I. These requirements provide a general indication of the environmental constraints data storage technologies and subsystems must satisfy.

Parameter	Range
Temperature	27810318 K [5 to45 "C]
Temperature change rate	-2.8 to 2.8 mK/s
pressure	10^{-12} to 10^{5} N/m^2
	[10-14 to 760 torr]
Pressure change rate	6 kN/m^2
	[45 torr/s]
Relative humidity	01070%
Radiated emission:	
Broadband	<0.316 V/m/MHz
Narrowband	<3.16 mV/m
Solar pressure	$<10^{-5}$ N/m^2
Magnetic field emissions:	
Subsystem production	<2 nT/kg @ 1 m
Demagnetization exposure	<5 mT
DC from launch vehicle	<320 μT
AC from launch vehicle	<10 μT @ >30 Hz
From planetary objects	0.025 to 50 μT
From lightning	<75 A/m
Vibration:	
Sinusoidal	20 $G_{0\text{-pk}}$ @ 23-60 Hz
Random, RMS	17.2 g_{rms}
Random, spectral density	0.2 g^2/Hz @ 20-1000 Hz
Acoustic level	<400 N/m^2
Launch acceleration	<6.75 G
Meteoroid interception:	
Averaged product-of mass and fluence	2 μg-impacts/cm^2
Mean density	0.5 g/cm^3
Mean penetration velocity	17 km/s

Table I. Sample selected launch and spaceflight environmental requirements relevant 10 a space data storage system. [40-42]

As shown in Table 1, a number of parameters are specified since a spacecraft is subjected to environments on earth, during launch, and in space. First, the temperature and pressure ranges and the maximum allowed rate of change in temperature and pressure are limited. Since solar radiation is not negligible when matter is present, controlled heating is feasible, and electronics and materials selections are simplified because of experience on Earth at Earth's temperatures, a relatively warm temperature range is required as opposed to a cryogenic space environment. The pressure change range spans many orders of magnitude, ranging from Earth's atmospheric pressure to the vacuum in space. This range is allowed since most materials and coatings can tolerate large quasistatic changes in pressure, and localized coatings and seals canal be used for sensitive elements. Second, limits are provided on the radiated electrical, solar, and magnetic emissions which any subsystem must accommodate and will be allowed to generate. These limits are placed to accommodate launch and space environmental effects, and to mitigate the production of electromagnetic noise which would affect the data from science instruments. Third, vibration, acoustical, and acceleration limits are provided which spacecraft subsystems must be designed to withstand. Most of these limits are associated with propulsion, during either launch from Earth or midflight trajectory changes. Fourth, spacecraft subsystems must be prepared to withstand certain levels of bombardment from small particles that the spacecraft may see as it travels through space. Physical shielding and coatings are nominally used to protect components and subsystems from damage.

III. TECHNOLOGY SELECTION: MAGNETIC TAPE

The data storage technology of choice for space applications from the 1960's through the 1980's has typically been magnetic tape recording. Tape recording is a usable and useful storage technology for buffering and transmitting images and science and engineering data, Tape recording has been selected because of technological availability, and capability to provide satisfactory performance through necessary engineering. Tape recorders to create data storage subsystems that provided very effective means for returning space data to Earth.

In order to satisfy environmental constraints, engineering and operational adjustments have been made. To satisfy temperature range, first, electronic component fabrication, selection, and testing was performed. Extensive tape testing, tape certification, and head-medium interface testing was performed to select the head-tape combinations and humidity and pressure conditions that maximized lifetime, and minimized wear, stiction, shedding, and dropouts. Tape replacement from controlled lots was also performed if lifetime limits were being approached based on ground tests. Second, because the tape and transport, as well as the electronics, have temperature limits, the temperature ranges, gradients, and fluctuations to which a tape recorder are subjected are limited. The temperature ranges of the data storage subsystem bays are regulated, using sensors, heaters, vents, louvers, and radiative and conductive cooling.

The wide pressure range, as shown in Table 1, is accomodated by the data storage system by encasing the tape recorder in a hermetically sealed unit. O-ring sealed and welded stainless steel enclosures are used to maintain pressure within the tape recorder transport Within a tape recorder, gas pressurization and humidity are controlled to keep the tape from disintegrating. Procedures to minimize contamination as well as to remove fungi and inhibit fungal growth were also implemented.

Insensitivity to vibration is achieved through spring mounting of the recorder's chassis, bearing selection, and design of a transport which keeps the tape under tension.

During periods when vibration is expected, such as during launch, trajectory changes, or pyro events: the tape transport is operated to reduce localized stresses on the bearings which could cause cracking and chipping. The induced rotation of the reels also serves to keep the tape from unraveling or slipping from the reels, which itself could serve as a catastrophic failure or induce long dropouts caused by gaps in head-to-medium compliance.

Rotation of the reels and transport elements in a tape recorder is a source of torque within a spacecraft, Since maintaining the attitude and articulation of a spacecraft is important for maintaining communication with and power to the spacecraft, since the amount of propellant onboard a spacecraft is limited, and since the firing of thrusters during data acquisition is usually not desired, minimizing the angular momentum produced by the recorder onto the spacecraft is important. Counter-rotating reels are typically used to satisfy this criterion.

Because the electronics are typically exposed to the very low pressures of space, precautions need to be taken to avoid electrical discharge and arcing between components. Polymeric coatings are usually placed on electronic boards around connecting pins to increase the dielectric breakdown voltage.

As tape recorders are used, tape passes are viewed as consumables since tape tensioning mechanisms, and media expansion, and media and head wear are life-limiting features. While the number of tape passes are limited, it has been possible to increase the number of tape passes that are specified. For example, 2400 tape passes were specified for the Mariner Venus/Mercury mission in 1973, while 14950 tape passes were specified for the Galileo mission to Jupiter in 1979. The number of start and stop cycles, head-to-tape velocity changes, and tape reversals also affect lifetime. While 300 such cycles were specified for the Mariner Venus/Mercury mission, 23,000 cycles were specified for Galileo.

The linear densities achieved in space tape recorders have been comparable to those achieved in commercial tape and disk systems, though the rate of growth has been higher for commercial systems. The linear bit density baselined for the Voyager mission in 1976 was approximately 210 kb/m, while that for the Magellan mission of 1989 was approximately 827 kb/m.

Bit-error rate (BER) specifications have also been improving. While the BER specifications ranged from 10-3 to 10-5 for missions through the early 1970's, typical BER values improved from 10^{-5} to 5×10^{-6} for missions from the late 1970's through the 1980's.

Since most missions were concerned with buffering science data from one or more instruments along with low date rate engineering data, tape recorders provided effective means for buffering streams of data at one rate and playing back data to Earth, when ready, at other data rates. Bulk memories, initially based on core and plated wire technologies and more recently based on CMOS technology, were used to help organize data to reduce data fragmentation; place time stamps, markers, and headers; and minimize needed tape velocity changes. The transport, the head-medium channel bandwidth, and selectable signal preamplifiers allowed supporting changes in data rate by more than two orders of magnitude between either the high or low record and playback rates.

progress in transport technology is also evident. Peripheral drive transports with a single hysteresis motor were initially used, until replaced by multispeed, bidirectional, co-planar reel-to-reel transports using peripheral belt/capstan differential drives. By the late 1970's, multispeed, co-axial, reel-to-reel transports using negator spring/capstan differential drives were in use.

Detecting the end of the tape in a reel-to-reel system is necessary to avoid the loss of data and loss of the recorder. Inductively-detected splices were used initially, until replaced by optical detection using sections of transparent tape.

However, as electronic technology, including memory and storage technology, advanced, the limitations of tape became a greater concern. Since basic operations for storing and accessing data, such as tape usage and Skirt and stop cycles, became linked to recorder lifetime, tape recorders effectively offered limited cyclability. Motor operation becomes a reliability concern, which also consumes power and affects attitude and articulation of the spacecraft. Tape and recorder testing become significant issues. Tape recorder operations therfore become more of a concern with added risk. In tape, data fragmentation becomes a concern. As data storage requirements evolve, from more simple data buffering scenarios to more complex, computationally-based scenarios, tape begins to offer more and more constraints.

IV. TECHNOLOGY EVOLUTION SOLID STATE RECORDING

In the 1990's, space data storage technology selection is going through a transition. Some of the limitations associated with tape technology and tape recorder system architectures are motivating the use of solid-state technologies. In particular, silicon-based semiconductor memory, typically implemented as dynamic random access memory (DRAM), is being baselined as the storage technology of choice. While semiconductor technology offers its share of limitations and concerns, and while it is not necessarily ideally suited for space applications, semiconductor memories are showing a capability, through technology development, engineering, and systems methodologies, for being usable in data storage applications in the same way that tape recording was applied. Table II provides a space systems viewpoint that compares magnetic tape recording with semiconductor solid-state recording. The space applications environment also provides insight into the nature of the technological crossover [44] that occurred between semiconductor memories and magnetic core.

This crossover is analogous to the crossover that is projected to occur between semiconductor memory and magnetic disk storage commercially.

Parameter	Magnetic tape recorders	Semiconductor RAM-based recorders
Technology readiness	Good	Good
Technology growth potential	Fair	Excellent
Storage expandability	Good	Good
Data rate flexibility	Poor	Excellent
Implementation modularity	Poor	Excellent
Random access Capability	Poor	Excellent
Storage nonvolatility	Excellent	Fair
Radiation hardness	Excellent	Good
Bit-error immunity	Good	Excellent
Reliability	Fair	Good
Mass	Fair	Good
Volume	Fair	Good
Power	Fair	Good
Cost	Good	Good

Table 11. Subjective performance comparison between tape and semiconductor memory-based .solid-state recorders.[19-28]

Several reasons exist which justify the use of semiconductor memories for space data storage. Progress in semiconductor memory technology and packaging make 10 GByte data storage systems feasible and cost-effective from a space data storage technology standpoint. DRAM characteristics are similar to the electronics in the. rest of the spacecraft so that system design, fabrication, testing, and integration are simplified. Since semiconductor memories have already been used successfully, albeit with care, in space applications as processor and bulk memories, the progression to expanding the application of semiconductor memory into the storage function is not unnatural. Solid-state components offer vibration insensitivity and environmental compatibility. Semiconductor memories can provide sufficient radiation insensitivity, through design, fabrication, selection, and operational control. DRAM -based data storage systems do not require pressurization.

Some of the limitations of semiconductor memory technology can be controlled through system design. If the system can guarantee that power interruptions are not a factor, then the problem of inherent volatility of semiconductor memory technology can be dismissed.

Radiation limitations are an important factor. Semiconductor memories can be made to work by offering sufficient radiation insensitivity [43] through technology and part selection and shielding, as indicated in Figure 4. In addition, constant monitoring of the memories can be performed. Codes in the data can be incorporated which assist in detecting and correcting bit-errors. Spare memory can be used to mask out failed memory areas. Self-annealing properties of radiation-damaged memories can be used to return previously error-prone memory pages back to service. Many of these functions can be performed autonomously; in a manner transparent from an operational view.

Figure 4. Radiation sensitivities for total dose, single-event upsets, and neutron fluence in Si for electronic technologies.

V. DISCUSSION

As mission requirements have grown, data storage capabilities have also grown, as shown in Figure 1. However, technological limits in space and ground-based telecommunications technologies, including transmission power density, antennae sizes and sensitivity, and bandwidth constraints; noise in the relatively low capacity space channel; and the trajectories and distances for a given mission; ultimately limit the data rate and hence capacity needed in a data storage subsystem. Thus, if the planetary missions, with low data rates and long data acquisition times, are compared to earth-orbiting missions, which feature high data rates and low acquisition times, the total storage capacity required can be seen to be fixed. The value of this storage capacity is currently seen to be near 10 Gbytes. In addition, it is noted that if system requirements become too ambitious, then either requirements can often be lessened to reduce the stress on the data storage subsystem, or requirements can be distributed across more than one platform or into a mission series,

Hence, as indicated as well in Figures 2 and 3, the perceived limit of required data storage capacity supports the use of technological improvements to improve normalized performance. Resource consumption should reduce and reliability should increase in time per unit of storage and accessed storage. It is noted that launch constraints place limits on injectable mass, volume, and power. This serves to motivate the use of smaller spacecraft and even microspacecraft if possible.

The trends of linear storage density performance for commercial and space applications is shown in Figure 3.

Initially, the linear densities for space tape, commercial tape, and commercial disk are comparable, suggesting that the levels of technology were comparable. In time, differences in technological performance are observed so that extrapolated rates of progress show that commercial systems were advancing at a rate greater than that for space systems, This is consistent with the levels of investment in the two technologies. This slower rate of progress for space tape recording with respect to commercial semiconductor memories indicates that a technological crossover was imminent. [44]

Given that a technology shift was made from magnetic tape to semiconductor memories, the question exists as to why alternative technologies were not considered. Given that missions could be designed to succeed with either magnetic tape or semiconductor memory, existing alternative technologies offered performance which was inferior to either magnetic tape or semiconductor memory. Technologies such as magnetic core, plated wire, and magnetic bubbles tended not to provide sufficient capacity and data rate perform for the same mass, volume, and power. While magnetic disk technology offers a number of good attributes, the perceived complexities of limits on issues such as mechanical reliability, bearing wear, pressurization, head crashes, vibration, induced torque affecting spacecraft control, electromagnetic noise, and potential electronics incompatibilities, tends to affect its selection with respect to solid-state technology. technologies such as magneto.optical tape, optical tape are typically not considered as desirable because of similarities to issues which limit performance in magnetic tape recorders coupled with limited technology experience.

Since, there was interest in making a technological shift from magnetic tape, the attributes of solid-state recorders were seen as desirable as indicated in Table 11. Because of solid-state reliability, modularity, scalability, data management, and technology base issues; and the desire to plan for few paradigm shifts in the long run, it was decided to accept the risk of making a significant but broad-based technology change. The use of dynamic random access memories, for example, to achieve this goal was accepted. Technological, system, and operational adjustments were made to attain sufficient radiation, environmental, and data retention performance through the use of methods such as memory monitoring, scrubbing, sparing, part selection, shielding, selective memory usage, and the provision of keep-alive power. [16, 42, 43]

As space data storage systems look to the future, the matter arises regarding how to attain greater performance per unit resource for a given mission. [36,44-45]. *First,* will the current technology of choice evolve in this way, or will a technology shift again be necessary? As semiconductor memory cell sizes diminish, interrelated concerns of reliability arise, with respect to radiation, signal levels, signal-to-noise levels, and timing. This concern serves to help motivate, in part, the investigation of alternative technologies [45] such as Vertical Bloch Line (VBL) storage devices [46,47] and memories such as magnetoresistive random access memories

[48]. Alternative technologies are expected to have a place in spaceflight applications if technological maturity and superior performance with respect to existing technologies can be achieved.

VI. CONCLUSION

Data storage technology evaluation and selection has been governed by a combination of technological capability, technological reliability, performance at a system level, and practicality of implementation and risk aversiveness at a project level. Historically, magnetic tape recording has been the technology of choice because, when compared to alternative technologies at the time, it provided sufficient volumetric storage density, nonvolatile and radiation-insensitive storage capacity, and data transfer rate in a reasonable form factor at reasonable power levels; provided reasonable data buffering characteristics; was supported by a stable technology base and was available at reasonable cost; and was capable of being engineered to satisfy known spacecraft requirements. By bolstering a tape recorder's inherent attributes with appropriate engineering, the tape recorder offered functionally acceptable performance for spaceflight applications.

As semiconductor memories and control electronics advanced, it became desirable to use these technologies, with appropriate system control to mitigate some of the disadvantages, in order to overcome some of the limitations present in tape recorders. Alternative existing nonvolatile technologies of the time, such as magnetic cores, bubbles, and plated wire, did not appear to offer sufficient storage performance and additional reliability with respect to mass, volume, power consumption, and system support. Data storage technologies for the future which hold promise for future spaceflight applications are expected to be evaluated with respect to the relative performance and reliability characteristics of semiconductor memory technology.

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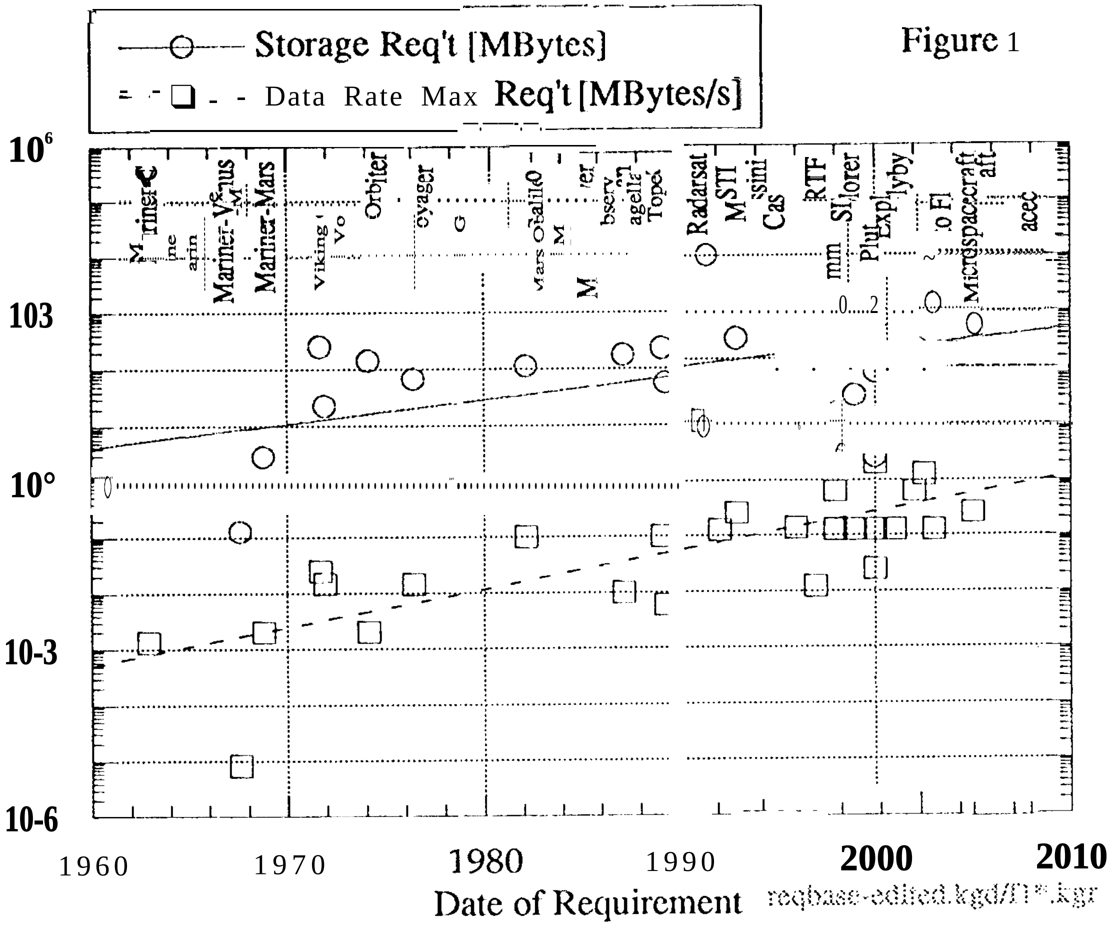
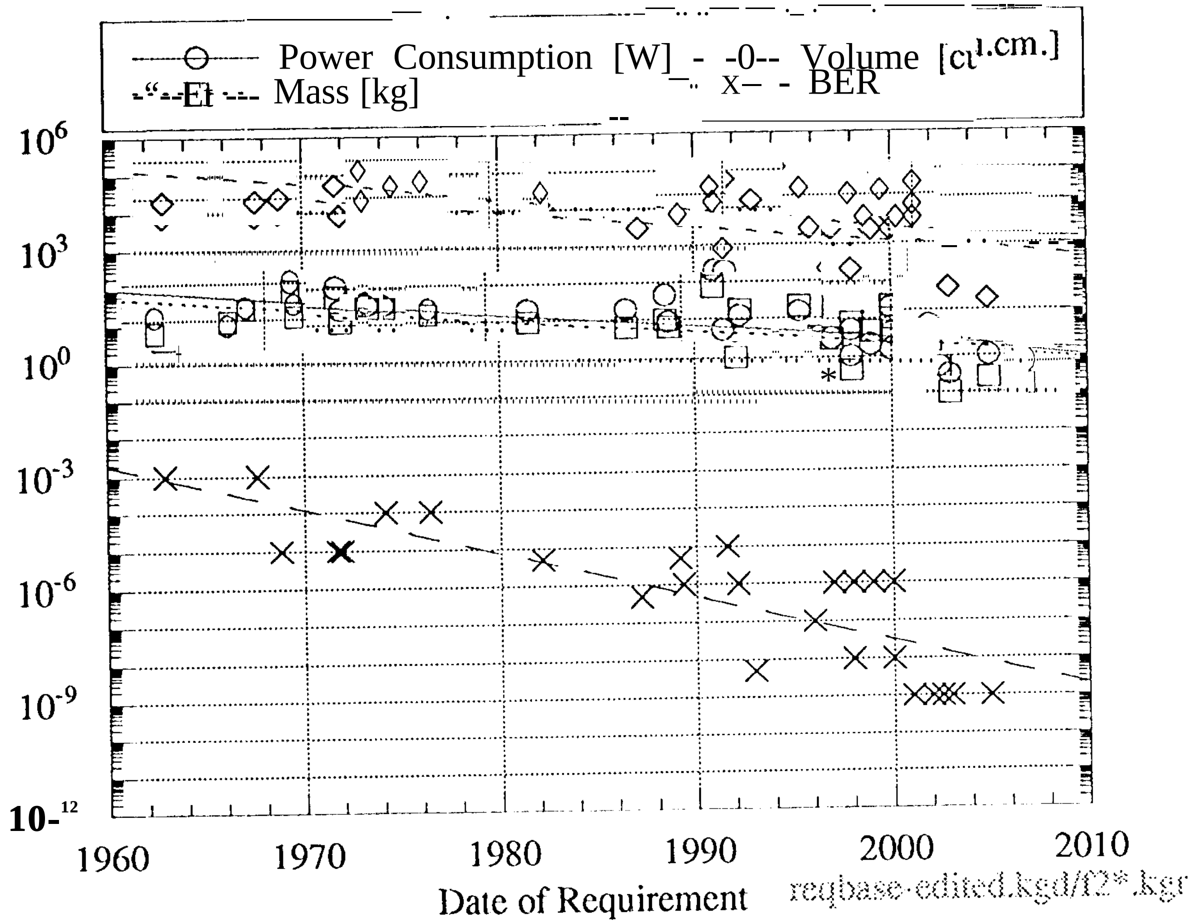
Figure 1



Storage Req't [MBytes]
Data Rate Max Req't [MBytes/s]
10^6
10^3
10^0
10^-3
10^-6
1960
1970
1980
1990
2000
2010
Date of Requirement
reqbase-edited.kgd/f1*.kgr
Mariner-Venus
Mariner-Mars
Viking
Orbiter
Voyager
Galileo
Mars Observer
Magellan
Topex
Radarsat
MSTI
Cassini
Pluto Express Flyby
Microspacecraft

Figure 2



Power Consumption [W]
Volume [cu.cm.]
Mass [kg]
BER
10^6
10^3
10^0
10^-3
10^-6
10^-9
10^-12
1960
1970
1980
1990
2000
2010
Date of Requirement
reqbase-edited.kgd/f2*.kgr

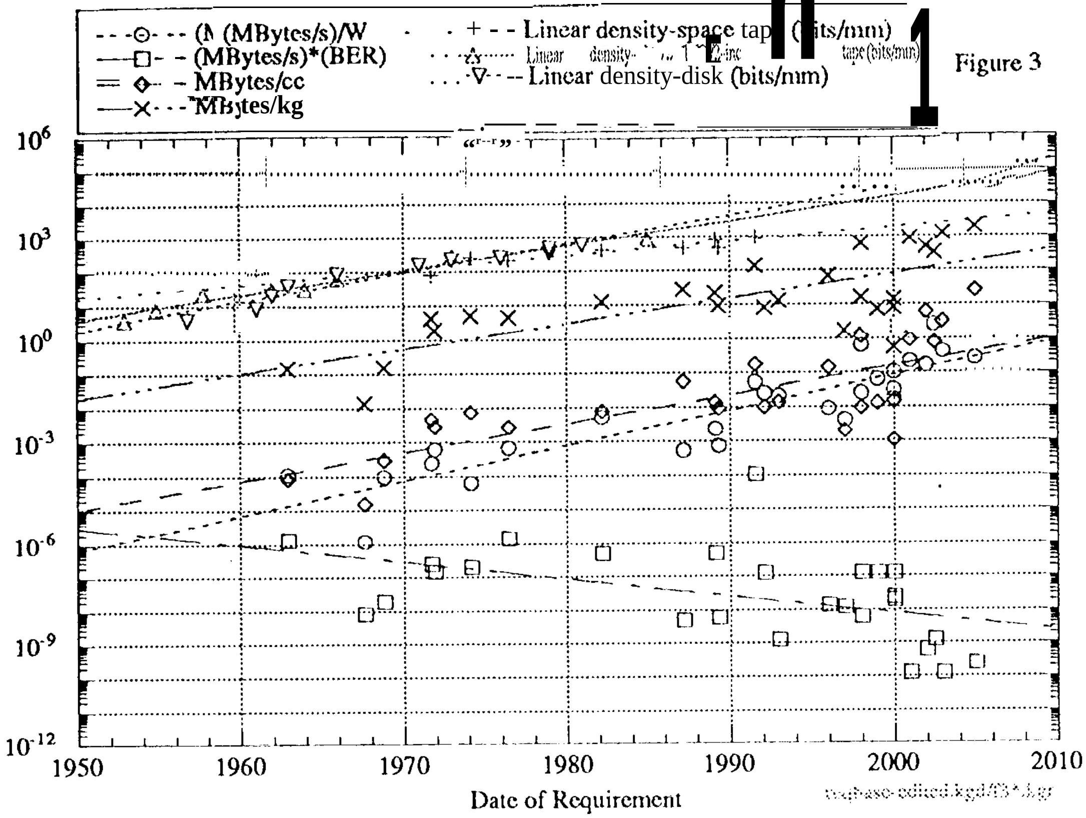

(M (MBytes/s)/W
(MBytes/s)*(BER)
MBytes/cc
MBytes/kg
Linear density-space tape (bits/mm)
Linear density-
tape (bits/mm)
Linear density-disk (bits/mm)
10^6
10^3
10^0
10^-3
10^-6
10^-9
10^-12
1950
1960
1970
1980
1990
2000
2010
Date of Requirement

Figure 3

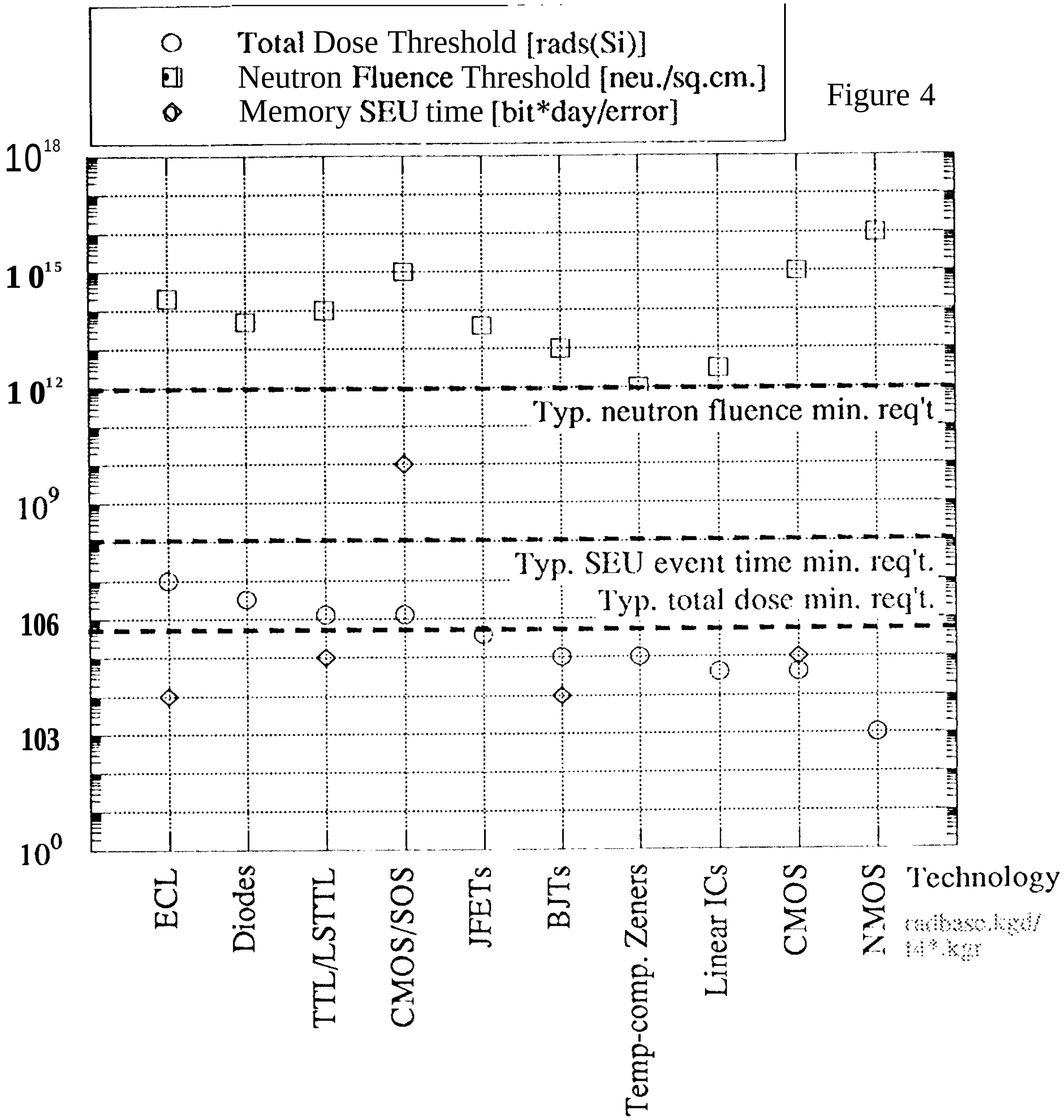


Figure 4

○ Total Dose Threshold [rads(Si)]
□ Neutron Fluence Threshold [neu./sq.cm.]
◇ Memory SEU time [bit*day/error]
10^{18}
10^{15}
10^{12}
10^{9}
106
103
10^{0}
Typ. neutron fluence min. req't
Typ. SEU event time min. req't.
Typ. total dose min. req't.
ECL
Diodes
TTL/LSTTL
CMOS/SOS
JFETs
BJTs
Temp-comp. Zeners
Linear ICs
CMOS
NMOS
Technology
radbase.kgd/
f4*.kgr