Autonomous Support for Microorganism Research in Space

Aerospace Engineering Sciences
University of Colorado
Boulder, Colorado

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ABSTRACT

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A preliminary design for performing on orbit, autonomous research on microorganisms and cultured cells/tissues is presented. An understanding of gravity and its effects on cells is crucial for space exploration as well as for terrestrial applications. The payload is designed to be compatible with the COMercial Experiment Transporter (COMET) launch vehicle, an orbiter middeck locker interface and with Space Station Freedom. Uplink/downlink capabilities and sample return through controlled reentry are available for all carriers. Autonomous testing activities are preprogrammed with in-flight reprogrammability. Sensors for monitoring temperature, pH, light, gravity levels, vibrations, and radiation are provided for environmental regulation and experimental data collection. Additional experimental data acquisition includes optical density measurement, microscopy, video, and film photography. On-board full data storage capabilities are provided. A fluid transfer mechanism is utilized for inoculation, sampling, and nutrient replenishment of experiment cultures. In addition to payload design, representative experiments were developed to ensure scientific objectives remained compatible with hardware capabilities. The project is defined to provide biological data pertinent to extended duration crewed space flight including crew health issues and development of a Controlled Ecological Life Support System (CELSS). In addition, opportunities are opened for investigations leading to commercial applications of space, such as pharmaceutical development, modeling of terrestrial diseases, and material processing.

Class Roster Academic Year 1991 / 1992

Space Habitation ASEN 4055 / 5055

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF FIGURES

Autonomous Support for Microorganism Research in Space
Executive Summary

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INTRODUCTION

Gravity is easily taken for granted, but its constant inertial acceleration affects every aspect of our lives. In fact, gravity affects all Earth's life forms and has done so throughout evolution. The fight against gravity has led to the formation of extremely strong biological support structures such as cellulose, chitin, and bone. Animal movement must first counteract the force of gravity, therefore, muscle and other methods of movement (flagella, cilia, and contractile filaments) must reflect this in their structure and function. Gravity is also responsible for processes such as convection and sedimentation that cells and organisms have evolved to use. Life on Earth today is highly diverse and constantly changing, but no matter what the organism or its habitat, gravity has surely played an important role in its development and life cycle.

Many biological experiments have been performed in the microgravity environment of space to determine what influence gravity has on life. The results: gravity does play an important role in the development and maintenance of life, but the specific mechanisms of gravity perception, adaptation, and use are not well understood. For example, the bodies of astronauts are dramatically altered in microgravity. Bone and muscles degenerate, the immune system is weakened, and cardiovascular and neurovestibular systems that control circulation and balance change. Major adaptations adjust the body to the new reduced gravity environment. But how is the presence or absence of gravity sensed by a bone or muscle cell? Why do cells and organisms respond to gravity the way they do? How can these gravitational responses be inhibited to insure astronaut health or enhanced to produce new plants or microorganisms with special desirable traits? The answers to these and many similar questions are unclear, and they will remain unclear until biology and microbiology can be studied easily and extensively in microgravity.

Space Habitation, a NASA/USRA National Aeronautics and Space Administration/ University Space Research Association sponsored advanced design class at the University of Colorado, is devoted to addressing issues concerning space life sciences and the commercialization of outer space. In an effort to make the microgravity environment of space more easily accessible for biological research and commercial application, the Spring 1992 class has developed a design for a small, versatile, biological research tool called the Cell Module for Autonomous Space Support (C-MASS). C-MASS meets many current needs for biological research in space and is responsive to the changing directives of today's U.S. Space Program which emphasizes reliable, faster, better, and less expensive missions.

BACKGROUND

Since 1958, the U.S. Space Program has brought the mysteries, challenges, and achievements of space exploration home to America. Recently, millions of viewers witnessed three space-walking astronauts from the Space Shuttle Endeavour working together to capture a stranded communications satellite by hand when hardware built for the job failed to work. The excitement and intrigue generated by space activities such as this provide an incentive propelling the nation forward in science and technology. However, even more important gains have come from scientific information and the many spin-off products and technologies derived

throughout the Space Program. Space exploration, transportation, and life support challenge the limits of today's technology. Advancements in automation, computer technology, miniaturization, and remote sensing have followed. Spin-offs from those advancements include insulative and fire retardant materials, recycling technology, computer software, imaging systems, and medical techniques. Spin-offs mean better products, an increased standard of living, and consumer savings. For example, biotelemetry (the remote sensing of blood pressure, heart rate and rhythm, and temperature using very small, durable, light weight sensors) was originally developed as a ground based method to monitor astronauts. Now, biotelemetry packages are used to safely monitor heart attack patients in their own homes. This allows them to return to their normal activities and eliminates the need for prolonged hospitalization and related medical costs (Borer, 1991). Excitement in the space program is generated by human achievements like the satellite capture and the economic/technical importance of the space program arises from spin-offs that touch the lives of millions of people each and every day.

An area that has great potential and provides spin-offs is space life science. Space life sciences address the issues of Controlled Ecological Life Support Systems (CELSS), astronaut health, and basic gravitational biology. The bioregenerative aspects of CELSS will greatly reduce the costs and Earth-dependency of life support systems, providing a means to fulfill long term NASA goals such as a permanent return to the moon. Due to the lack of gravity in orbit, astronauts suffer from accelerated forms of many common ailments found on Earth including osteoporosis (mineral loss in bones), muscle atrophy, space sickness, and cardiovascular alterations. For example, on Earth osteoporosis affects over 24 million elderly Americans today and is the cause of 1.3 million fractured bones each year (at an annual consumer cost of $7-10 billion) (Healy, 1991). Developing treatments for the health problems astronauts face will

lead to cures for diseases people suffer on Earth saving lives, productivity, and money.

Basic gravitational biology focuses on the basic effects of gravity and mechanisms of gravity sensing in cells. With an understanding of the effects and perceptions of gravity at the level of the single cell, scientists may find ways to use the unique microgravity environment of space to perform biological manipulations or processes not possible on Earth. The value of these biological experiments could be well worth the high investment required for development and flight time. For instance, a single cell genetically altered in space to produce a beneficial byproduct could be brought back to Earth to reproduce, creating entire populations of cells or organisms with the same beneficial trait. In addition, the combination of gravitational biology and the unique environment of space may open the door to future commercial development of space.

The goals of space life sciences and the returns it will provide cannot be achieved instantly. A phased mission approach is required which employs many small missions, each contributing new technology, information, protocols, and spin-offs to bring the Space Program closer to its long term goals in a step-by-step process. The phased mission approach is consistent with the Space Exploration Initiative (SEI), the new directive for the U. S. Space Program. SEI has a twofold strategy: "First, to develop and conduct small scale robotic/automated precursor missions designed to fill gaps in the nation's scientific and technological knowledge," and second to establish a "management culture" that can be relied upon to get the job done on time and for less money (David, 1992). This new emphasis on smaller low cost payloads will allow industries and research organizations to get involved transforming the Space Program into a search for commercial applications and developments as well as a mission of science and exploration.

Space life sciences is one of the gaps in scientific and technological knowledge to

which SEI refers. As an empirical science, it depends on multiple tests done in the space environment. Early missions placed little emphasis on life sciences beyond the minimum necessary to sustain humans for a voyage to the moon and back. Today, principle investigators like biologists and physicians who are not directly involved with NASA need greater access to space.

Unfortunately, there is no way to learn how gravity is sensed or what the extent of its effects on life are without performing experiments in the microgravity environment of space. The costs of sending even small packages into orbit is extremely high, and stringent NASA requirements make flight qualified hardware complex and time consuming to develop. Machines on Earth such as the clinostat (which slowly rotates specimens to produce a constantly reorienting gravity vector that averages over time to zero) and the centrifuge can only be used to alter how gravity is perceived by organisms. Short term microgravity environments achieved on KC135 aircraft or sounding rockets are only somewhat helpful because they do not produce long enough periods of microgravity for many biological experiments.

To fill the gap in scientific and technological knowledge for space life sciences, an effective infrastructure for biological experimental hardware must be in place. This will make more frequent and longer duration experiments possible using new generic hardware with variable capabilities to cut through integration costs and NASA paperwork difficulties.

RATIONALE/OVERVIEW
The role of Space Habitation has been to address space life science issues and support the further exploration and commercialization of space through design work. In the past, the class has focused on missions that would generate interest and excitement for the U. S. Space Program. These projects concentrated on developing a CELSS and achieving the NASA long term goal of returning to the moon. However, to accommodate the Space

Exploration Initiative and immediate problems facing space life scientists, Space Habitation has recently turned its focus toward smaller missions emphasizing basic biological science and potential commercial applications. The design response developed by the Spring 1992 semester class is called the Cell Module for Autonomous Space Support (C-MASS).

C-MASS is a small autonomous payload designed to support on-orbit testing for a variety of microorganisms and cultured cells/tissues for periods of up to 30 days. It uses only existing or modified off-the-shelf hardware and currently available technology, thereby minimizing cost and maximizing reliability. C-MASS is designed for many types of experiments. It brings together an extensive variety of data acquisition capabilities not integrated in any existing space hardware of its size. The large commitment to data acquisition provides a means to obtain detailed information in flight instead of having to rely solely on the analysis of returned samples that cannot reveal time-dependent gravitational effects. C-MASS is also designed for compatibility with the Shuttle middeck locker, SpaceHab, Spacelab, COMmercial Experiment Transporter (COMET) and Space Station Freedom (SSF). Carrier versatility enables C-MASS to take advantage of the benefits offered by each: access to frequent Shuttle missions, 30 day missions and very low gravity levels on COMET, and even longer missions and extremely low gravity levels on the initial crew tended stages of SSF. To perform on-board control experiments, a 1-g centrifuge is also incorporated into the design. The combination of autonomy, extensive data acquisition, and design for long duration missions makes C-MASS a unique and valuable research tool. Table 1 compares C-MASS with other current related hardware.

A functional diagram for C-MASS is shown in Figure 1. The diagram shows the six major subsystems and power, data, and fluid interfaces. Biological experiments are housed in the experimental volume and 1-g control centrifuge. The fluid transfer

system is responsible for sample taking, nutrient delivery, waste removal, and organism transfer within the biological experiment vials. Data acquisition occurs through imaging systems and sensors. Imaging systems include photography, microscopy, and video for observing visible cellular changes in the microgravity of space. Sensors include spectroscopy and ELISA for specific analytical techniques and environmental sensors such as vibration, radiation, temperature, pH, and light levels to record environmental conditions within the payload. The C-MASS communications system allows for data and video downlink as well as uplink, including in-flight reprogrammability for adapting experiments while in progress. C-MASS is a small, low cost, reliable payload designed to help fill the gap in space life science knowledge and technology.

C-MASS SUBSYSTEM DESIGNS
An overall view of the C-MASS payload and its various subsystems is shown in Figure 2. C-MASS has outer dimensions of 11" x 14.5" x 15.75" for the limiting case of COMET. The design of the subsystems utilized an iterative process in which system requirements and objectives were identified. Next, design options using current technology and off-the-shelf hardware, modified where necessary, were conceived for each system. Finally, trade studies were performed to determine the

preferred method. The use of current technology and readily available hardware maximizes performance and reliability, while keeping costs and payload development time to a minimum. The subsystem descriptions that follow are reflective of this design philosophy.

Experimental Volume: All microgravity experiments will take place in the experimental volume, therefore, it must be capable of supporting various microorganism and cell culture experiments for up to 30 days. This entails allowing fluid transfers between individual experiment containers; providing lighting for photosynthetic organism growth, spectroscopy and visual imaging; and facilitating data acquisition. The experimental volume is designed to maximize the total volume available for experimentation and data acquisition.

The experimental volume consists of two separate regions: an outer positionable ring that permits visual data acquisition from experiments through the imaging system and an inner non-moving region. As shown in Figure 3, the entire volume is 8.25 cm in radius and 7.0 cm in height. The outer ring contains 40 individual experiment vials, each 1.2 cm in outer diameter and 5.0 cm high, for an internal fluid volume of approximately 3.0 ml per vial. These containers are placed with their centers at a

	Autonomous	Visual Imaging	1g Centrifuge	Variable Fluid Transfer	Carrier
CGBA		✓			Shuttle
Biomodule	✓	✓			Shuttle, ELVs
Biorack		✓	✓		Shuttle
Biosample	✓	✓	✓	✓	Eureca
C-MASS	✓	✓	✓	✓	COMET, Shuttle Freedom

•••••FLUIDS   ▬▬ DATA   ▬ ▬ POWER

Table 1: A comparison of C-MASS to related hardware for supporting microbiological experiments in space. C-MASS incorporates many capabilities from other hardware into one small versatile research tool.
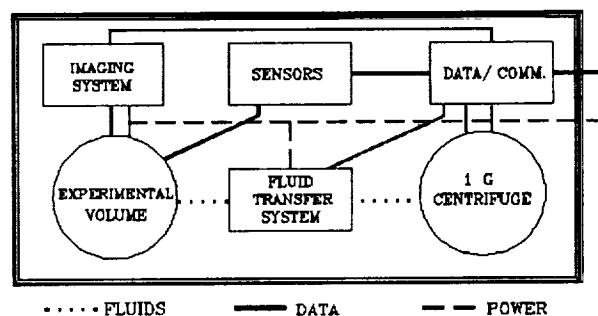
Figure 1: A functional diagram of the C-MASS design showing subsystems and power, data and fluid interfaces.

radius of 7.6 cm from the center of the experimental volume with their long axis parallel to each other. The vial size and arrangement maximizes the number of experiments that may be conducted and exposed to the onboard data acquisition systems, while minimizing volume usage.

The space between the two regions of the experimental volume house the various lighting sources used in C-MASS. An electroluminescent sheet provides ambient lighting for the outer experiment ring. A stationary light source is required for photography and microscopy, and several LEDs of varying wavelengths permit spectrophotometry as well as the use of fluorescent dyes and markers. The actual LED wavelengths can vary depending upon experimental requirements.

In order to maximize the experimental capabilities of C-MASS, a flexible experimental vial design was chosen. Three basic vial designs were conceived: the aerobic microorganism vial, the cell tissue vial, and the anaerobic vial. As shown in Figure 4, the three containers all have the same basic components, simply organized differently. The four base components are a rubber cap containing a resealable membrane; a clear, rigid, optically clear, plastic cylinder; a flexible plastic bag; and a semi-permeable membrane.

The resealable membrane may be pierced by a fluid transfer needle, allowing fluid addition or removal, while maintaining system closure. The rigid cylindrical portion of the vial allows for imaging of the experiments, and the flexible portion permits the internal volume to fluctuate with the introduction and removal of fluids, thereby maintaining a "hard filled" fluid environment. Depending upon the type of experimental vial, a semi-permeable membrane is placed in either the rigid or the collapsible portion, or it may be eliminated entirely. In the aerobic microorganism configuration, the membrane effectively separates the vial into two regions: an upper section that contains organisms in a nutrient solution, and a lower section containing gases. In the cell tissue configuration, the membrane allows nutrient replenishment in the upper compartment while keeping cells isolated in the remaining portion. Membrane porosity is matched to these different requirements. In addition, the elimination of the membrane provides a single environment for the study of anaerobic organisms.

For aerobic bacteria and other microorganism experiments, the organisms are contained within the rigid upper region of a vial. This allows for an aliquot (a small sample) to be taken by the fluid transfer system and used to inoculate a new nutrient-filled vial once the population has reached its saturation point. This process can be repeated many times, allowing the researcher to study changes in behavior and structure over multiple organism
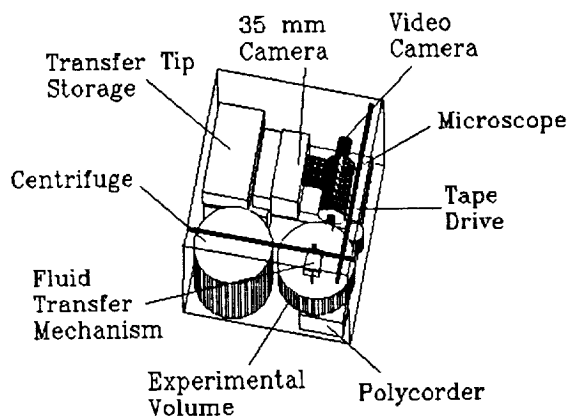

Figure 2: Isometric view of C-MASS showing subsystem and component placement.
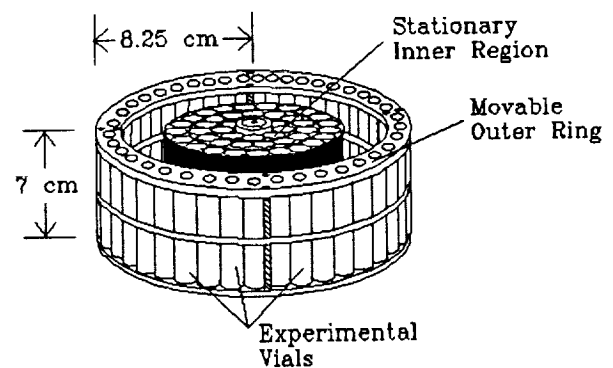

Figure 3: Isometric view of the C-MASS experimental volume.

generations. In contrast, for cell tissue experiments, the cells are placed on the other side of the semi-permeable membrane. This allows for fluid removal and nutrient replenishment without damage to the fragile tissues.

The non-rotating inner portion of the experimental volume can hold up to 42 sample vials. These are similar to the anaerobic experiment vial, but with a shorter rigid section, and may contain nutrients, fixative, other experiment support fluids. This area may also be used for additional experiments not requiring any in-flight assay capability.

The final element of the experimental volume is the DC stepper motor which positions the outer experiments for the various assay techniques. The motor is connected to the experimental volume via sprockets and a nylon chain. The volume will only be moved slowly a few times a day. These short durations and low accelerations were deemed to have a minimal effect upon the microgravity experiments.

1-g Centrifuge: C-MASS's launch, orbital, and landing environments introduce many variables that are difficult to simulate in ground based control experiments. Temperature profiles, vibrational levels, and the extreme launch and reentry loads can all play significant roles in organism development. This problem is compounded by the inherent variability of

living organisms. The best results would be obtained by comparing organisms from the same origin that have been exposed to identical conditions with the exception of gravitational accelerations. Therefore a small 1-g centrifuge is provided on-board C-MASS. The inclusion of the centrifuge ensures that any observed alterations in organism structure, function, or behavior are due solely to spaceflight changes in gravity.

The centrifuge design presents one of the most difficult hardware challenges for C-MASS. All commercial centrifuges are designed for much higher rotational rates than is required for producing accelerations of 1 g. Also, all other centrifuges designed for use in microgravity are either too large or unmodifiable to this particular configuration. Therefore, the C-MASS centrifuge is a unique instrument, but one that utilizes commercially available or readily producible components. In this way, it remains consistent with the drive to use only off-the-shelf hardware.

To maximize the commonality to the experiments in the experimental volume, the centrifuge utilizes an identical circular arrangement using the same types of sample vials. Like the experimental volume, only the outer ring will be capable of motion, while the center portion is fixed to minimize rotating mass. The 7.6 cm radial distance to the center of the outer ring experiments requires that the centrifuge rotate at 108.5 RPM. Motor control is achieved using a small DC gear motor that utilizes a feedback loop to control motor output to within 2 RPM. The gravity gradient across any single experiment is +/- 0.11 g. Therefore, all rotating experiments will see accelerations between 0.89 g and 1.11 g during centrifuge operation.

Several options for fluid transfer within the centrifuge were examined. The simplest, most reliable, and least mass intensive of these is to simply stop the centrifuge for brief periods. Fluid transfer can then be accomplished with the same device and in an identical manner to that used in the

|1.2 cm|

5 cm

Rigid Plastic Tube

Flexible Plastic Bag

Semi-Permeable Membrane

Resealable Membrane

Rigid Plastic Tube

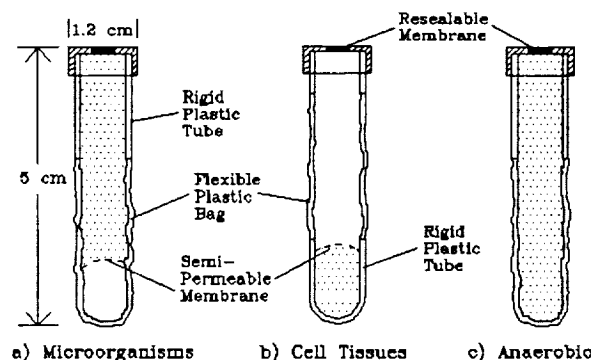a) Microorganisms   b) Cell Tissues   c) Anaerobic

Figure 4: Experimental vial options. a) microorganisms b) cell tissues c) anaerobic bacteria.

experimental volume. Although stoppage of the centrifuge for fluid transfer could affect experiments, it was determined that any changes would remain insignificant if the stoppage were for only a few minutes a day.

The identification of specific vial locations within the centrifuge is accomplished through the use of a small photoelectric sensor and a machined groove of continuously varying depth in the base of the centrifuge platter. By measuring the depth of this groove when the centrifuge comes to rest, the sensor and accompanying software can determine the relative position of any vial in the centrifuge. Based upon this information, the fluid transfer device can move to the appropriate vial. The accuracy of this system is well established in electronic micrometers.

Fluid Transfer System: The fluid transfer system provides C-MASS with the capability of supporting a wide variety of experiments. This versatile system has the ability to remove or add fluids, such as fixative and nutrient media, to each of the experimental vials. Fluid transfer is necessary to sustain the experiments for the entire mission duration. For instance, the system can remove wastes and replenish nutrients or it can inoculate a few cells in a new nutrient solution. These tasks are accomplished without contamination of the individual experimental vials.

In order to successfully transfer fluid, the experimental vials must be accessed without loss of closure. To accomplish this, a transfer tip, which is similar to a syringe, punctures the resealable membrane at the top of the experimental vial. Once the transfer tip has been inserted into the experimental vial, a combination of two valves and a pumping mechanism are used to force a maximum of 1 ml of fluid either into or out of the transfer tip. This fluid transfer scheme, known to be extremely reliable, is derived from an automatic, battery powered pipettor typically found in laboratories.

The transfer tip design not only facilitates fluid transfer, it prevents contamination of the experiments and reduces possible cell damage as well. A flexible, plastic bag has been attached to the transfer tip needle on the inside of the transfer tip. This bag fills with fluid as it is pumped from the experimental vial, blocking the liquid from entering the pumping mechanism, thus inhibiting the contamination of the pump. Also, 110 transfer tips are located inside C-MASS allowing for transfer tip exchange, avoiding cross contamination between experiments. To reduce cell damage, the fluid inlet into the transfer tip is located on the side of the needle tip instead of on the end. The fluid inlet can then be larger, reducing the shear forces experienced by the delicate cells.

The experimental vials in both the centrifuge and experimental volume are accessed using a robotic arm. An end effector on the arm holds the fluid transfer pumping mechanism and a transfer tip. To accomplish the fluid transfer system requirements, the robotic arm is capable of movement in three dimensions. Three stepper motors are used in conjunction with three orthogonal leadscrews. A diagram of the robotic arm can be seen in Figure 5. The robotic control mechanism uses the positioning system, discussed in the 1 g centrifuge section, to locate the different vials.
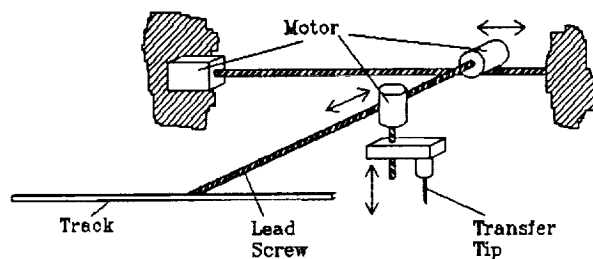

Figure 5: Isometric view of the robotic fluid transfer arm.

Imaging System: Organism growth and development is a dynamic, non-linear process. It is simply not possible to completely understand changes to microgravity and their underlying mechanisms through the analysis of only an end result. Fixing experiments to preserve them for later ground based analysis is often done, but it alters cell structure and prevents their use for beginning new cell lines for terrestrial use. The loads experienced during landing can also alter or even destroy experiments. Therefore, the ongoing visual record provided by the imaging system is essential for establishing a time line of organism development. The imaging system is responsible for producing high quality visual data of the outer ring experiments in the experimental volume. Also, samples saved for return can be compared to those studied *in situ* in the space environment. The centrifuge experiments will not be imaged due to volume limitations. The imaging system is comprised of three major components: a microscope, a video camera, and a photographic camera.

Due to the size of the biological organisms under study within C-MASS, a microscope is required for all imaging applications. Basic light microscopy of unstained cells provides very poor resolution of cellular features, and provides only a two dimensional view. This poor resolution may be greatly enhanced using techniques known as differential phase contrast and the Nomarski method (differential interference contrast). The C-MASS imaging system will utilize these techniques to view cellular features and organism surface texture. Total available magnification ranges in power from 10x to 1000x, providing proper magnification for a variety of imaging applications.

A video camera is included in the C-MASS design for its capability of recording organism motion and the ability to provide real time images for downlinking. The output from the microscope can be directed to the small charge coupled device (CCD) camera head. The camera has a resolution of approximately 400,000 pixels with a 12 bit color capability. The video output is stored for later retrieval on Earth. Video images can also be downlinked to a groundstation permitting researchers a small real time glimpse of the activity within an experimental vial.

Photography has a far greater resolution than video imagery due to the much smaller size of light sensitive crystals in film as compared to video pixel elements. Therefore, a photographic camera is also provided within C-MASS to yield high resolution pictures of the experiments within the experimental volume. As with the video camera, imaging is through the microscope. The camera utilized is a commercially available 35 mm electronically controllable, auto focus, auto aperture, auto timing, auto film advance camera with a film back capable of holding a 250 exposure roll of 35 mm film. Several options exist for increasing the number of possible exposures with simple modifications to various camera components. Modifications to the shutter and film advance mechanism would permit the use of multiple rolls of 110 film rather than a single 35 mm roll. The ability to section the film into smaller exposure sizes is also possible. The optimal method for maximizing photographic capabilities may require combination of both modifications.

Sensors: The in-flight sensor measurements taken by C-MASS are extremely important since these will allow researchers to determine the dynamic effects of microgravity on experiments. Sensor selection was difficult because sensors placed in contact with organisms may form biofilms and condensate around them decreasing the accuracy of the sensor readings. Most of the sensors discussed in this section measure the environmental conditions in which the experiments take place. The sensors that fall into this category include temperature, illumination, gravity level, vibration, and radiation. C-MASS also incorporates a spectrophotometer, for obtaining experimental data concerning optical density, and Enzyme-Linked ImmunoSorbent Assay (ELISA) for

detecting the presence of specific biomolecules, such as proteins or peptides.

The wide variety of environmental conditions recorded are measured by the following sensors. The variations of temperature within C-MASS are measured using thermistors, small semiconductors that change their electrical resistance in response to temperature. These thermistors are strategically located throughout the facility and measure both air and surface temperatures between -30 to 100 degrees Celsius. Experiment pH is measured using one of the cameras in conjunction with an indicator chemical added to the solution. The pH indicator used is phenol red, or phenolsufonphthalein, which changes from yellow to red between pH 6.4 and pH 8.2. Either the video camera or 35 mm camera can be used to photograph the vials containing the pH indicator. Video images can be downlinked for immediate quantification, or stored onboard until a later time. The illumination sensors are photoelectric diodes located in several different areas within the centrifuge and experimental volume. Accelerometers are used to measure both the gravity levels and vibrations between 40 micro-g and 10 g. Three orthogonal accelerometers are required to measure accelerations in three dimensions. Cumulative radiation is measured by three orthogonal film dosimeters, which are commonly used to detect radiation levels in laboratories.

The other sensors included in C-MASS provide analytical assay techniques. Spectrophotometry readings are obtained using several light sources and light detectors. The light sources are emitting diodes and the light detectors are photo diodes. There are six different light sources spanning the 200 nm to 1500 nm range, each aligned with a corresponding detector. Since the spectrophotometry sensors remain stationary, only the experiments located in the rotating part of the experimental volume have this assay capability. The other assay method is ELISA: a plastic sheet with specific antigens attached. These antigens are

proteins that can chemically recognize other very specific reagent proteins. When the proteins come in contact with one another, the bound antigen produces a color change in proportion to the amount of reagent protein present. Using this method, very small amounts (as little as 10 picograms) of specific reagents can be detected and their concentrations determined. Currently, several hundred specific assays are possible using this technique.

Data/Commumications: The valuable measurements taken by the sensors and imaging systems require a means of data storage and return. Communications are also necessary between Earth and C-MASS and between its various internal subsystems. The C-MASS design includes both of these data handling means. However, C-MASS is not only capable of downlinking data, but it can also receive uplink commands, allowing for in-flight changes to be made. A standard XMODEM protocol is used for carrier-payload communications.

C-MASS provides the researcher with modular options in data storage. Depending on the amount of specified data to be taken, two different configurations can be used. In the event that large amounts of data are to be taken, an 8 mm magnetic tape drive will be placed on board. Utilizing a modified tape changing mechanism, two 25 gigabyte tapes could be included for up to 50 gigabytes of storage for both sensor and video data. The second option is to store all sensor data in the 448 K data acquisition computer. This method would require that all the sensor data be downlinked periodically instead of permanently recorded aboard C-MASS and that the video images be recorded on video tape. The advantage of the second option is that less volume is used which could allow, for instance, more fluid transfer tips to be available.

The data acquisition computer is the internal and external communications center for the payload. It controls the onboard operations of the subsystems such

as sensors, fluid transfer, and environmental control. It also acts as the communications link with the ground receiving uplinked commands and downlinking requested data.

Cost analysis: The total cost of construction and testing for C-MASS to produce a flight-qualified version of the payload was estimated at $525,000. The actual hardware, modifications, and any raw materials made up only a small portion of that total, $25,000, due to the predominant use of off-the-shelf components and commercially available products. Personnel costs for integration and testing made up the bulk of the estimate at $500,000. This value covers the full-time salaries of a project manager, an electrician, a machinist, and two other technicians for one year, including overhead. It was presumed that this combination working in a small business setting could easily move C-MASS from its current preliminary design phase to ready-to-use flight-qualified hardware well within that time frame. The cost of C-MASS is competitive with other commercially developed space hardware of similar size and function, and it is much less than that of similar NASA sponsored projects which take longer to complete.

C-MASS SCIENCE EXPERIMENTS
Cells are the basic building blocks of life; therefore, an understanding of gravitational effects at the cellular level is absolutely necessary before large CELSS are created, astronaut health issues are treated, or the microgravity environment is used for commercial benefit. The specific physical processes altered in microgravity have both direct and indirect effects on cells which are still not completely understood. C-MASS, with its variety of data acquisition hardware, can be used to document gravitational changes and alterations in ways not currently possible. C-MASS may also be used to take advantage of the quiescent environment offered by microgravity for performing highly sensitive experiments not possible on Earth. In another way, the long term exposure to reduced gravity offered by C-MASS will

allow for experiments designed to reveal adaptations that organisms may undergo over long periods and many generations in a microgravity environment. The experiments C-MASS can support will help answer questions concerning how cells are affected by gravity and they will provide a means to explore future commercial opportunities.

Gravitational cell biology research focuses on the response of a variety of physical phenomena to changes in gravity and the effect those changes have on life. The role of these physical phenomena in extracellular, intercellular, and intracellular processes determines the effect gravity has on cellular functions. Among these physical phenomena are sedimentation and convection. In the absence of gravity these processes do not occur. Other weak physical forces such as hydrostatic pressure and surface tension, normally dwarfed in the presence of gravity, become much more pronounced in the microgravity of space. The absence of sedimentation and convection combined with the enhancement of hydrostatic pressure and surface tension cause both internal (intracellular) and cell-to-cell (intercellular) changes in cell activities.

Gravity causes dense materials to settle or sediment at the bottom of a medium. Plant cells called statocytes use sedimentation to sense the orientation of the gravity vector. Starch granules in the statocyte fall to the cell bottom and react with the cell wall providing a directional reference for plant growth. Cells must also create cytoskeletal structures to inhibit the sedimentation of other organelles such as nuclei. Intercellular sedimentation affects the distribution of cells and materials. In the presence of gravity, prolonged contact between cells of different densities, or between cells and dense materials is impossible. For these reasons, in microgravity, cell differentiation unlike any observed in a terrestrial environment should occur.

Convection currents are caused when gravity acts on thermal and/or density

gradients within a fluid. Intracellular convection is responsible for cytoplasmic streaming, which transports signals and materials within a cell. Intercellular convection creates shear forces that disturb cells and affect the way they develop and communicate with one another. These effects require better characterization to understand the mechanisms by which they act; a job impossible to do in nominal gravity.

Hydrostatic pressure is responsible for the rise of fluid in a capillary tube and surface tension is a measure of fluid adhesion forces. Hydrostatic pressure is important in examining the work done by a system (W = P dV + V dP). In the absence of gravity, the influence of these processes is much more pronounced, altering the fluidic environment both inside and outside cells. Therefore, as the pressure approaches zero, cellular events which involve a volume change, such as secretion or fission, are expected to be affected. There exists surface tension between a cell and its environment and between cells. Research in microgravity, where fluid can be easily manipulated, has provided insight into this behavior and should reveal the importance of fluid interactions in cellular functions.

The capabilities of C-MASS make it a valuable tool for supporting research that will identify and exploit the gravitational effects acting at the cellular level. The versatile fluid transfer system and variable experimental vials give C-MASS the ability to support many types of organisms with different physical needs. The autonomous nature of C-MASS allows payloads on flights without the perturbations caused by crew presence that can ruin the quiescent microgravity environment. The imaging systems and in-flight reprogrammability of C-MASS give investigators control over experiments from Earth to effect adjustments as needed during the flight. On board data acquisition from the sensors and spectroscopy will also provide a dynamic profile of experiments for postflight analysis which may help pinpoint key steps in cellular developmental processes. The environmental sensors will provide a time-dependent record of experimental conditions. This is crucial since cells and microbes are sensitive to variations in their surroundings. The data intensive experiments made possible by C-MASS can be used to reveal how convection, sedimentation, hydrostatic pressure, and surface tension affect cellular processes.

Quiescent Environment Experiments: The absence of disturbing processes such as convection and sedimentation in microgravity make it an ideal environment for performing delicate experiments on cells and biomolecules. The modification of cell lines, the growth of synthetic tissue cultures, and the polymerization of macromolecules may all benefit from experiments that take advantage of the quiescent environment of space. Genetically engineered cell lines have numerous commercial benefits which range from methods of drug delivery to the production of pharmaceuticals. Liposomes (lipid shells or vesicles) are presently used in the analysis of membrane proteins, therapeutic drug delivery, and generating immunogenicity. Liposomes are extremely delicate structures. At 1 g, gravity induced convection currents cause excessive fracturing of the bilayer resulting in small liposomes (Claassen, 1990). A similar problem is encountered in cultured lymphocytes modified to destroy tumor cells in its host organism. Several billion cultured cells are needed per treatment and repeated treatments are necessary. However, only a few million viable cells are usually generated using processes on Earth. Lymphocyte cells grown *in vitro* suffer from fluid shear forces and poor nutrient and waste exchange causing low proliferation and misshapen cells (Ingram, 1991). Both the liposome and lymphocyte experiments have shown increased growth size and an increase in lymphocyte production when performed in a microgravity or simulated microgravity environment. Therefore further study is warranted, in these areas as well as a variety of other cellular studies which have only been carried out in 1 g.

Other experiments that may benefit from the quiescence of space are DNA recombination and molecular cloning. These processes are widely used by the pharmaceutical industry. The final product is material which can be used for the replacement or increased reproduction of any protein in the human body (Swetly, 1989). It is possible that a microgravity environment would allow greater control over the production of human proteins in a host cell since it is known to affect both bacteria and liposome production. As in the two previous examples, a quiescent environment would minimize shear flow patterns caused by convection, guiding the cellular growth in a manner contrary to that found *in vivo*. It would also be possible to impose a small controlled force upon the cells as they grow. This may be especially useful in experiments such as the assembly of collagen, which has a well organized structure *in vivo*, but lacks this structure when growth is stimulated *in vitro* (Bergren 1990). Artificial development of well organized collagen has potential uses for surgical implants to replace damaged tissue.

Communication between cells is necessary for processes like differentiation where a cell uses the genetic material common to all cells to express its genes in a particular manner. For instance, one cell forms skin while another forms an eye, although both cells began with the same information. Complex intercellular communication and specific cytoplasmic elements appear to be the key factors governing differentiation. Data suggests that mammalian cells undergoing differentiation are more sensitive to gravitational effects than nondifferentiating cells and that changes in gene expression can be induced (Cogoli, 1991). One hypothesis presented by D. K. Kondepudi states that in microgravity a system evolving irreversibly toward an end status may proceed with equal probability to another end status, but a system that has evolved for generations at 1 g will give a single and well known end (Cogoli, 1991). Cells communicate through chemical signals carried in a fluid intercellular space. A gravitational change in the fluid due to a

reduction in particle streaming or convection will alter the cell's ability to transmit or receive signals from its surroundings. An understanding of these mechanisms could allow the control over the differentiation of one cell into a desired tissue type enabling transplantable organs to be grown when needed. The quiescent environment of space offers a laboratory where intercellular communication is altered and may be controlled more carefully than on Earth.

Electrofusion of plant cells to form hybrids is also enhanced in a microgravity environment due to the lack of sedimentation and convection (Mehrle 1988). Plants are of interest for terrestrial uses such as pharmaceuticals and as food and oxygen sources for life supporting systems in space. The ability to hybridize a variety of plant cells permits scientists to breed plants with superior qualities such as greater biomass production with an increased resistance to disease. Ultimately, plants may be produced to support microgravity uses, lunar uses, and even Martian uses.

Multigenerational Experiments: In addition to a quiescent environment, COMET provides the opportunity to conduct experiments over a 30 day period which allows for the production of multiple generations of rapidly reproducing organisms such as bacteria. Bacteria are extremely well studied and provide excellent building blocks for gravitational biology research. They are of interest not only for comparison to Earth based studies, but in anticipation for future space habitation. Microgravity experiments on the resistance of the bacteria E. coli to antibiotics (Gmunder, 1988) and their metabolic adaptation (Klaus, 1991) were performed previously on short duration flights. For reasons not yet known, some bacteria grow faster in microgravity and show an increased resistance to antibiotics. Other microorganisms such as the motile *Paramecium* are strongly affected by the gravity vector on Earth since they must expend energy swimming against it. In microgravity the proliferation rate of

Paramecium increases, possibly because the energy previously used to move can be transferred to reproductive activities (Gmunder, 1988). However, to date no observed changes were maintained in subsequent generations on return to Earth. Multigenerational exposure to a reduced gravity environment may result in organisms genetically adapted to microgravity. Organisms which are unable to adapt will expire and only those best suited for survival in microgravity will reproduce. Genetically adapted organisms returned to Earth may have specific traits that could be used in pharmaceutical production or for other scientific benefit.

The gravity sensing properties of plants are currently under investigation, but a 30 day mission will allow observations of the development of some plants and photosynthetic cell colonies to maturity. One-celled algae, for instance, normally grows into an entire kelp plant on Earth. With its variable lighting capabilities, fluid transfer, and the ability to contain a variety of sample vial sizes, C-MASS could be used to observe the growth of a kelp colony under microgravity conditions. The results could provide valuable insights into gravity responses and cellular differentiation in space.

The multigenerational aspect of gravitational research is currently of interest as flights such as COMET become available and in anticipation for future long term microgravity exposure on structures such as Space Station Freedom.

EXPERIMENTAL PROTOCOL
Although the protocol for each experiment may differ, they all have similarities and can be adapted to the capabilities and constraints of C-MASS. The following is an example of a bacteria experimental protocol that is compatible with C-MASS:

One of a number of sample vials containing growth medium will be inoculated with organisms prior to launch. After microgravity is achieved, the next sample vial will be inoculated by the transfer of an aliquot from the first. Every subsequent 48 to 72 hours, when these samples have saturated the medium, an aliquot will be extracted and transferred to another vial containing fresh nutrients. The initial sample will then be fixed with gluteraldehyde for post flight analysis. The process will be repeated until the end of the mission providing multiple generations of bacteria grown in space. Temperature, pH, radiation, and optical density will be measured and visual imaging will be performed on each active sample during the flight. Specific products and metabolic markers will be visualized with ELISA strips throughout the mission. The experiment will provide a dynamic profile of long term gravitational adaptations and changes in the bacteria studied.

Since C-MASS was already designed, built and tested, it is imagined that a team of NIH (National Institute of Health) scientists and industrial scientists simply delivered their respective samples to the launch site a few days prior to launch. These personnel then monitored their experiments daily with data transmitted from the ground stations. And finally, they received postflight samples for more thorough analysis.

CONCLUSION
A preliminary design for C-MASS, a small payload capable of supporting a variety of microbiological experiments in space, has been presented. The important design characteristics have been described and examples of its capabilities and applications have been discussed. C-MASS adds a unique combination of autonomy, mission duration, and experimental capabilities not available with current space hardware. Furthermore, this design supports the low budget, high quality, and commercial application emphasis of SEI. It will provide researchers with generic hardware adding a needed component to the space infrastructure for biological research. Operationally, researchers will use the C-MASS capabilities almost like another piece of laboratory equipment.

C-MASS may be used to satisfy scientific curiosity by offering a means to answer

many of the basic questions concerning the effects of gravity on life. It may also be used to study cultured cells/tissues which are important in addressing astronaut health issues and the treatment of related diseases on Earth. In the future, C-MASS may be used to pave the way toward space commercialization by providing a facility that can utilize the space environment to produce novel biological products such as genetically altered species or specially modified cells. The important needs fulfilled by C-MASS and its commitment to SEI mandates makes it the next logical step in space life sciences development.

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2.0 INTRODUCTION

Life on earth may have appeared as long as 3.8 billion years ago, emerging from a primordial soup of organic compounds including, among other things, DNA. Those first life forms were very simple, probably resembling the common bacteria and blue-green algae we know today. From that original conception billions of years ago to the present, earth's life forms have struggled, evolved, diversified and spread to every corner of the globe. Where there were once only bacteria and algae, now millions of species exist ranging in complexity, behavior, and habitat. One constant all earth's organisms have had to contend with is gravity. Its inertial acceleration of 9.81 m/s^2 has influenced every aspect of life from its emergence through evolution to the present. The constant fight against gravity has likely led to the formation of support structures such as cellulose, chitin, and bone. Animal movement must first counteract the force of gravity, therefore the ways in which cells and organisms move (flagella, cilia, contractile filaments, or muscle) must reflect this in their structure and function. Gravity is also responsible for processes such as convection and sedimentation. Cells and organisms must have evolved to take advantage of these processes guaranteed in the presence of gravity. Plant roots, for example, contain cells called statocytes which appear to sense gravity through the sedimentation of starch granules inside the cell (Sievers, 1991). Life on earth today is highly diverse and constantly changing, but no matter what the organism or its habitat, gravity has surely played an important role in its development and life cycle.

Until the advent of space travel, there existed no means to test hypotheses of life's dependency on gravity. Machines on Earth such as the clinostat (slowly rotates specimens to produce a constantly reorienting gravity vector that averages to zero over time) and the centrifuge can only be used to alter how gravity is perceived by organisms. Short term microgravity environments achieved on KC135 aircraft or sounding rockets are only somewhat helpful because they do not produce long enough periods of microgravity for many biological experiments. The only way to study life in the absence of gravity for more than a few minutes is to perform experiments in outer space.

Since Laika, a Siberian Husky aboard Sputnik II, became the first life from Earth to venture into outer space, many experiments using plants, animals, microorganisms, and people as subjects have been performed to assess the role of gravity in shaping life. The results: gravity does influence the development and maintenance of life but the specific mechanisms of perception and adaptation are not well understood. Does the statocyte really sense gravity through the sedimentation of starch granules? Altered plants without starch granules still manage to direct their roots downward and their shoots upward (Sievers, 1991). The bodies of astronauts are dramatically altered in microgravity. Bone and muscles degenerate, the immune system is weakened, and cardiovascular and neurovestibular systems that control circulation and balance change. Major adaptations adjust the body to the newly reduced gravity environment. But how is the presence or absence of gravity sensed by a bone or muscle cell? Why do cells and organisms respond to gravity the way they do? How can these gravitational responses be inhibited to produce healthier astronauts or enhanced to produce new plants or microorganisms with special desirable traits? One example might be a bacterium that devotes more energy to producing a specific pharmaceutical product (like insulin). The answers to these questions and many like them are unclear, and they will remain unclear until biology and microbiology can be studied easily and extensively in the microgravity of outer space.

Space Habitation, a NASA/USRA (National Aeronautics and Space Administration/University Space Research Association) sponsored advanced design class at the University of Colorado, is

1

devoted to addressing issues concerning space life sciences and the commercialization of outer space. In an effort to make the microgravity of space more accessible for biological research and commercial application, the Spring 1992 class has developed a design for a small, versatile, biological research tool called the Cell Module for Autonomous Space Support (C-MASS). C-MASS meets many current needs for biological research in space and is responsive to the changing directives of today's U.S. Space Program which emphasizes reliable, faster, better, and less expensive missions.

The Cell Module for Autonomous Space Support is a small payload designed to autonomously support microbiological experiments in a microgravity environment for long periods. It uses only existing or modified off-the-shelf hardware and currently available technology. C-MASS is versatile, designed for many types of data acquisition including photography, spectroscopy, microscopy, and video imaging; it is also compatible with the Shuttle middeck locker, Spacelab, COMmercial Experiment Transporter (COMET), and Space Station Freedom. C-MASS will provide researchers with generic hardware for performing a diverse range of biological experiments quickly and more easily than by using current hardware and methods. In the future, C-MASS may be used to pave the way toward commercialization of space by offering a means to answer many of the basic questions concerning the affects of gravity on life.

The goal of this report is to present C-MASS and the rationale behind its necessity. First a background section summarizes some of the drivers and benefits of the U.S. Space Program, emphasizing the needs and returns of life science studies in space. A rationale follows, describing how C-MASS satisfies the goals of the Space Habitation class and meets the requirements of the Space Program and the Space Exploration Initiative (SEI). A payload overview is next which summarizes the design process and

general capabilities of C-MASS. Each of the C-MASS subsystems are described in detail and a variety of representative science experiments are reviewed to provide an illustration of function and capabilities. Finally, commercial applications are presented which enumerate the specific benefits and returns that will be provided by an operational C-MASS facility.

2.1 Background

The U.S. Space Program has always been a source of excitement, intrigue, and national pride for America. Nearly 2/3 of the world's population watched live or on delayed telecast Neil Armstrong's "Giant leap for mankind" as he stepped onto the lunar surface in July 1969 (Haggerty, 1983). The excitement and interest from that event spurred an incredible 27% increase in college math and science enrollment (Dittmer et. al., 1991). Recently, millions of viewers witnessed three space-walking astronauts from the Shuttle Endeavour working together to capture a stranded communications satellite by hand when hardware built for the job did not work. When asked whether or not the daring rescue was worth the costs and dangers, Endeavour commander Dan Brandenstein replied, "It was well worth doing. Already we've gotten tons of letters from young kids in school that are just really fired up. They want to be engineers or they want to be astronauts, and anytime you can fire up kids to be enthused about setting goals and continuing their education, that's probably worth the price right there" (Sawyer, 1992). The excitement and intrigue generated by space activities such as this provide an incentive propelling the nation forward in science and technology.

The space program is not just exciting, useful scientific information has been obtained and many spin-off products and technologies have come into use on Earth in areas from auto manufacturing to medical instrumentation. Geophysical information from the moon and planets has helped scientists better understand the age

of the Earth and solar system and how they may have formed. The technological challenges of space exploration, transportation, and life support have led to spin-offs in areas such as computer technology, miniaturization, and remote sensing. Spin-offs mean better products, an increased standard of living, and consumer savings. An offshoot of the computer program NASTRAN developed by NASA for computer testing of aircraft/spacecraft is now used by Honda for computerized structural analysis of auto parts (Haggerty, 1988). In the area of biomedical technology, one spin-off example is biotelemetry: the remote sensing of blood pressure, heart rate and rhythm, and temperature using very small, durable, light weight sensors. It was originally developed as a ground based method to monitor astronauts. Now, biotelemetry packages are used to safely monitor heart attack patients in their homes. This allows them to return to their normal activities and eliminates the need for prolonged hospitalization and related medical costs (Borer, 1991). Excitement about the space program is generated by human achievements like the satellite capture, and the economic/technical importance of the space program arises from spin-offs that touch the lives of millions of people each and every day.

One area which has great potential to stimulate interest and provide spin-offs is space life sciences. Space life sciences addresses the issues of Controlled Ecological Life Support Systems (CELSS), astronaut health, and basic gravitational biology. CELSS will use plants and animals to recycle wastes and produce food for astronauts. The development of CELSS will reduce the cost, mass, and Earth-dependency of life support and make possible longer missions further from Earth. This will lead to the fulfillment of long term NASA goals such as a return to the moon and eventually a manned mission to Mars. The interest stimulated by these missions will be enormous.

The most immediate spin-offs from space life sciences may come from studying astronaut health issues. Due to the lack of gravity in orbit, astronauts suffer from accelerated forms of many ailments found on Earth. These problems include such things as osteoporosis (mineral loss in bones), muscle atrophy, space sickness, and cardiovascular adaptation. Today, osteoporosis affects over 24 million elderly Americans and is the cause of 1.3 million fractured bones annually (at an annual consumer cost of $7-10 billion) (Healy, 1991). Muscle atrophy affects immobilized individuals who can not exercise properly, and motion sickness disrupts the lives of countless individuals. Cardiovascular disease which is the number one cause of death in America was responsible for 44% of all deaths in 1989 (Healy, 1991). Clearly, understanding the health problems astronauts face will not only produce healthier astronauts, but it will lead to better treatments for important diseases on earth, thereby saving lives, productivity, and money. Basic gravitational biology focuses on the basic effects of gravity and mechanisms of gravity sensing in cells. With an understanding of the effects and perceptions of gravity at the level of the single cell, scientists may find ways to use the unique microgravity environment of space to perform biological manipulations or processes not possible on Earth. The enhancement of crystal growth in space is currently under study as a method to produce finer quality protein crystals for determining the 3-D conformation of those proteins by X-Ray crystallography. The value of these biological experiments could be well worth the high investment required for development and flight time. For instance, a single cell genetically altered in space to produce a beneficial byproduct could be brought back to Earth to reproduce, creating entire populations of cells or organisms with the same beneficial trait. In addition, the combination of gravitational biology and the unique environment of space may open the door to the future commercial development of space.

The study of life sciences in space provides many opportunities to stimulate interest in the space program and provide spin-offs

3

and potential commercial applications, however, the goals of space life sciences and the returns it will provide cannot be achieved instantly. A phased mission approach is required which employs many small missions, each contributing new technology, information, protocols, and even spin-offs to bring the Space Program closer to its long term goals in a step-by-step process. The lunar landing was a step-by-step process that began with the Mercury missions, proceeded through Gemini, and finally on to the Apollo missions. Space life sciences must also use this phased mission approach to achieve long term goals and produce spin-offs.

The phased mission approach is consistent with the Space Exploration Initiative (SEI), the new directive for the U.S. Space Program. SEI has a twofold strategy: "First, to develop and conduct small scale robotic/automated precursor missions designed to fill gaps in the nation's scientific and technological knowledge," and second to establish a "management culture" that can be relied upon to get the job done on time and for less money (David, 1992). This new emphasis on smaller low cost payloads will allow industries and research organizations to get involved, transforming the Space Program into a search for commercial applications and developments as well as a mission of science and exploration.

Space life sciences is one of the gaps in scientific and technological knowledge to which SEI refers. As an empirical science, it depends on multiple tests done in the space environment. Early missions placed little emphasis on life sciences beyond the minimum necessary to sustain humans for a voyage to the moon and back. Today, principle investigators like biologists and physicians who are not directly involved with NASA need greater access to space.

Unfortunately, there is no way to learn how gravity is sensed or what the extent of its effects on life are without performing experiments in the microgravity environment of space. The costs of sending even small packages into orbit is extremely

high, and stringent NASA requirements make flight qualified hardware complex and time consuming to develop.

To fill the gap in scientific and technological knowledge for space life sciences, an effective infrastructure for biological experimental hardware must be in place. This will make more frequent and longer duration experiments possible using new generic hardware with variable capabilities to cut through integration costs and NASA paperwork difficulties.

2.2 Rationale

The role of Space Habitation class has been to address space life science issues and to support the further exploration and commercialization of space through design work. In the past, the class focused on missions that would generate interest and The role of Space Habitation class has been to address space life science issues and support the further exploration and commercialization of space through design work. In the past, the class focused on projects that would generate interest and excitement for the U. S. Space Program. These projects concentrated on CELSS and achieving the NASA long term goal of returning to the moon. However, to accommodate the Space Exploration Initiative and immediate problems facing space life sciences, Space Habitation has recently turned its focus toward smaller missions emphasizing basic biological science and potential commercial applications. The spring 1992 semester class proceeded through an iterative design process with the goal to develop a design that was both responsive to the needs of life scientists and fitting with the requirements of the Space Program. The result is a preliminary for a payload called the Cell Module for Autonomous Space Support (C-MASS).

2.3 Payload Description

C-MASS is a small autonomous payload designed to support on orbit testing for a

4

variety of microorganisms and cultured cells/tissues for periods of up to 30 days. It uses only existing or modified off-the-shelf hardware and currently available technology. C-MASS is versatile, designed for many types of experiments and data acquisition; it is also compatible with the Shuttle middeck locker, Spacelab, COMmercial Experiment Transport (COMET), and Space Station Freedom. To perform on-board control experiments, a 1-g centrifuge is incorporated into the design.

A functional diagram for C-MASS is shown in figure 1. This design shows the six major subsystems and their power, data, and fluid interfaces. Biological experiments are housed in the experimental volume and 1-g control centrifuge. The fluid transfer system is responsible for sample taking, nutrient delivery, waste removal, and transfer of fluids within the biological experiments. Data acquisition occurs through imaging systems and sensors. Imaging systems include photography, microscopy, and video; sensors include spectroscopy and environmental parameters such as vibration, radiation, temperature, pH, and light levels.

C-MASS is a small autonomous payload designed to support on-orbit testing for a variety of microorganisms and cultured cells/tissues for periods of up to 30 days. It uses only existing or modified off-the-shelf hardware and currently available technology, thereby minimizing cost and maximizing reliability. C-MASS is designed for many types of experiments. It brings together an extensive variety of data acquisitions capabilities not integrated in any existing space hardware of its size. The large commitment to data acquisition provides a means to obtain detailed information in flight instead of relying solely on the analysis of returned samples that cannot reveal time-dependent gravitational effects. C-MASS is also designed for compatibility with the Shuttle middeck locker, SpaceHab, Spacelab. COMmercial Experiment Transporter (COMET) and Space Station Freedom (SSF). Carrier versatility enables C-MASS

to take advantage of the benefits offered by each: access to frequent Shuttle missions, 30 day missions and very low gravity levels on COMET, and even longer missions as well as extremely low gravity levels on the initial crew tended stages of SSF. To perform on-board control experiments, a 1-g centrifuge is also incorporated into the design. The combination of autonomy, extensive data acquisition, and design for long duration missions makes C-MASS a unique and valuable research tool. Table 2-1 compares C-MASS with other current related hardware.

A functional diagram for C-MASS is shown in Figure 2-1. The diagram shows the six major subsystems and power, data, and fluid interfaces. Biological experiments are housed in the experimental volume and 1-g control centrifuge. The fluid transfer system is responsible for sample taking, nutrient delivery, waste removal, and organism transfer within the biological experiment vials. Data acquisition occurs through imaging systems and sensors. Imaging systems include photography, microscopy, and video for observing visible cellular changes in the microgravity of space. Sensors include spectroscopy and ELISA for specific analytical techniques, and environmental sensors such as vibration, radiation, temperature, pH, and light levels to record environmental conditions within the payload. The C-MASS communications system allows for data and video downlink as well as uplink, including in-flight reprogrammability for adjusting experiments while in progress. C-MASS is a small, low cost, reliable payload designed to help fill the gap in space life science knowledge and technology.

	Autonomous	Visual Imaging	1g Centrifuge	Variable Fluid Transfer	Carrier
CGBA		√			Shuttle
Biomodule	√	√			Shuttle, ELVs
Biorack		√	√		Shuttle
Biosample	√	√	√	√	Eureca
C–MASS	√	√	√	√	COMET, Shuttle Freedom

TABLE 2-1: MICROORGANISM FLIGHT HARDWARE COMPARISON
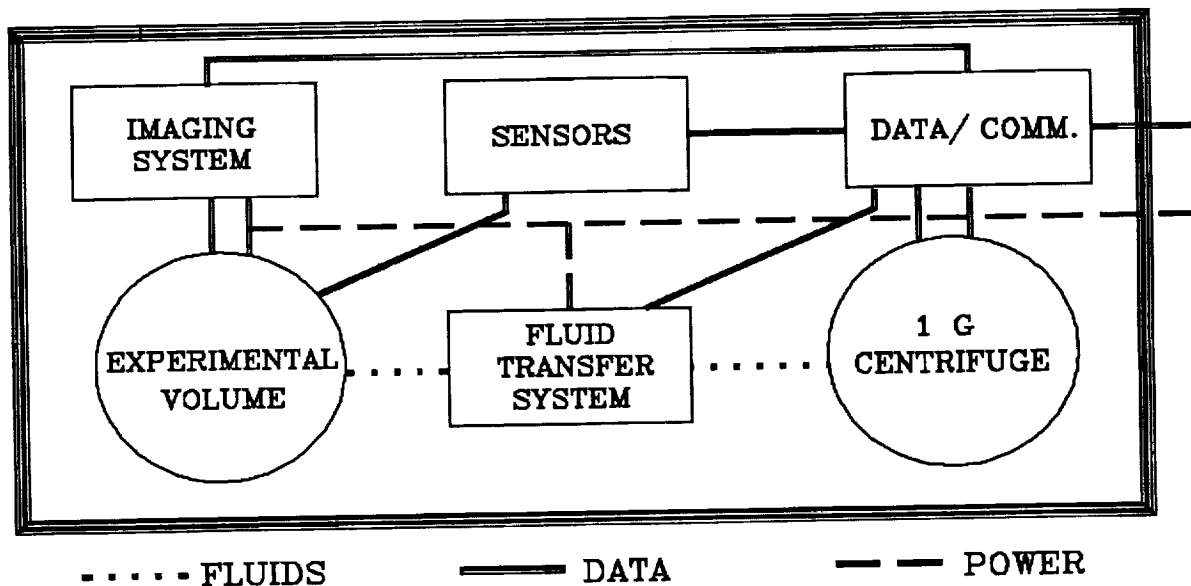

FIGURE 2-1: C-MASS FUNCTIONAL DIAGRAM

3.0 PAYLOAD OVERVIEW

3.1 Payload Objectives

The mission of Space Habitation Spring 1992 was to design a small, autonomous payload that will permit on orbit testing for microorganisms and cultured cells/tissues. The payload will utilizes considerable uplink and downlink capabilities, and autonomy uses telepresence and robotics. Commercial utilization has been stressed throughout the design process.

The payload design obtained is a unique approach to the problem of providing on-orbit testing for microorganisms and cultured cells/tissues. The payload uniqueness is due to its ability to support a variety of different experiments while maintaining its ability to be launched easily and readily. Presently, if a researcher wishes to do on orbit testing, he or she would have to design a system capable of supporting their experiment and find a means of launching this system. This process could take several years from beginning to end and might have lost its potential usefulness in this time. However, using the C-MASS payload the researcher could have obtained useful data in a significantly reduced time. This is due to the modularity of the C-MASS system and its ability to readily support a variety of experiments with only minor modifications.

The variety of experiments that can be launched aboard C-MASS is due to its capability of supporting organisms needing nutrient addition or inoculation. Nutrient addition refers to the ability of the payload to remove wastes and replace nutrients. For example, a tissue experiment would need this capability to remain alive for the duration of the mission. Inoculation is the ability of the payload to remove an amount of a sample and place it in a new nutrient solution. This capability is necessary so that bacteria can be grown for numerous generations in the space available for the entire mission duration. The ability of the payload to support both these types of experiments significantly enhances its usefulness. The payload, besides being able

to support a variety of experiments, has a mission duration long enough to supply useful data regarding organism adaptation to microgravity. The payload will also be returned to Earth so that the organisms can be thoroughly analyzed. The mission length of C-MASS differs depending upon which launch vehicle used.

3.2 Payload Capabilities

An isometric view of C-MASS is shown in Figure 3-1. C-MASS has outer dimensions of 11" x 14.5" x 15.75". These dimensions allow it to be compatible with a number of different carriers. C-MASS is capable of launching aboard the COMmercial Experiment Transporter (COMET) or inside of a middeck locker aboard the U.S. Space Shuttle. COMET's mission length is 30 days, while currently the Space Shuttle's is approximately two weeks, but is soon to be extended to 30 days with modifications. Using these two vehicles, the nominal g-level for the organisms will be less than 10-4 g. C-MASS is also designed for compatibility with Space Station Freedom where its experiments can benefit from the extremely quiescent environment during the crew tended phase. The multitude of carriers C-MASS is compatible with simply increases the launch opportunities for the payload, allowing scientists to run more frequent experiments.

The payload is capable of sampling and fixing the experiments so that different stages of development can be observed once C-MASS has returned to Earth. To ensure suitable experimental control, the payload also includes a 1-g centrifuge. C-MASS has a controlled temperature range along with variable lighting for different experiment needs. The payload also provides a sterile environment so that activities such as sampling will not interfere with organism development.

C-MASS has a vast array of data acquisition equipment. An arsenal of measuring devices are available to the researcher. For instance, a spectrophotometer, used to measure optical

7

density, is included on-board. C-MASS uses a microscope in conjunction with either a video camera or a 35-mm camera to provide visual images. The sensors on board will be able to monitor pH, temperature, light intensity, gravity levels, vibration levels, and cumulative radiation levels.

The payload includes data storage and communication capabilities so that data can be analyzed not only when C-MASS is returned to Earth, but also while in orbit. The data storage is capable of storing video images and all the measurements taken by the C-MASS system. Researchers may uplink commands to control the video camera, 35-mm camera, microscope, to change any environmental or experimental parameters, or alter the experiment protocol. The payload is also able to downlink camera images and any environmental or experimental parameters.

3.3 Design Methodology

The design of the subsystems utilized an iterative process in which system requirements and objectives were identified. Next, design options using current technology and off-the-shelf hardware, modified where necessary, were conceived for each system. Finally, trade studies were performed to determine the preferred method. The use of current technology and readily available hardware maximizes performance and reliability, while keeping costs and payload development time to a minimum. The subsystem descriptions that follow are reflective of this design philosophy.
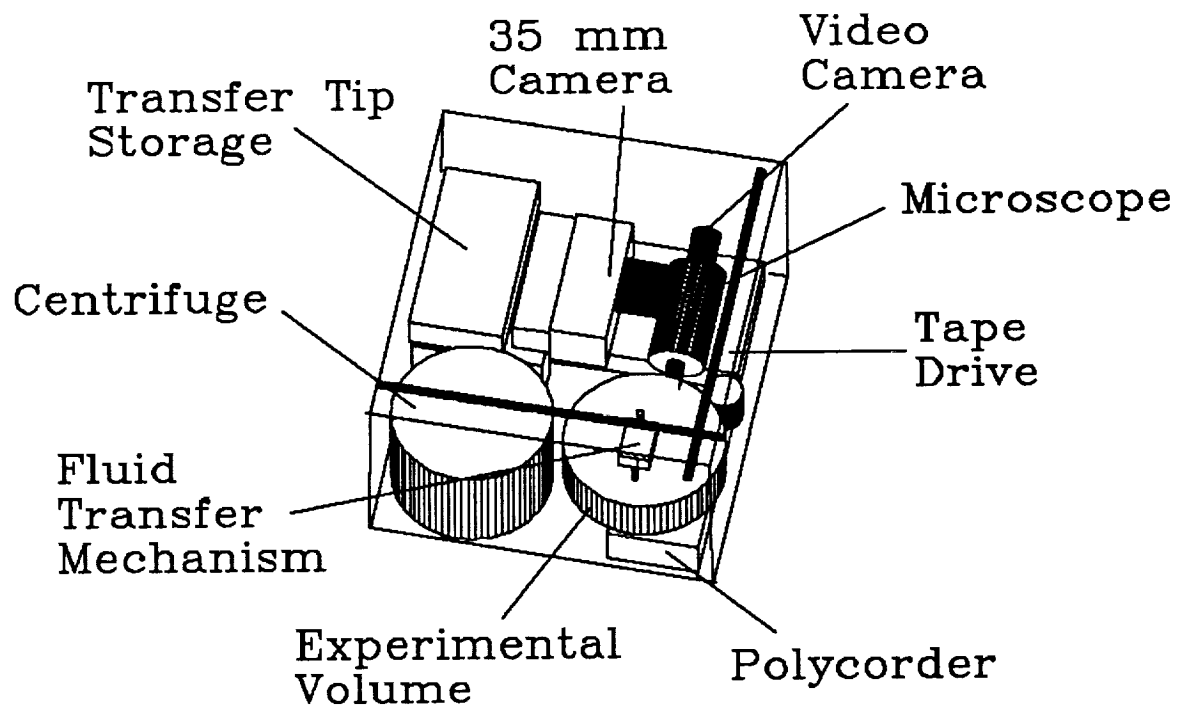
Transfer Tip
Storage

35 mm
Camera

Video
Camera

Microscope

Centrifuge

Tape
Drive

Fluid
Transfer
Mechanism

Experimental
Volume

Polycorder

FIGURE 3-1 C-MASS ISOMETRIC VIEW

4.0 SUBSYSTEMS

4.1 Experimental Volume

4.1.1 Rationale/Requirements
The experimental volume is the location within C-MASS that houses all microgravity experiments. Therefore, it must provide adequate space to support several types of microorganisms and various other cell cultures autonomously for 30 days in a microgravity environment. The main requirement driving the experimental volume design is the need to maximize the total volume for experiments and the number that may be exposed to the various onboard assays and sensors. The experimental volume must also store all nutrients, fixatives, and other support fluids in addition to experimental vials.

The experimental volume allows for multiple generations of experimental cultures to be grown and samples and assays of individual experiments to take place. Experiments can be fixed to allow for further ground based analysis. The assays will provide insight into the effects of microgravity on microorganisms, tissues, and other organisms grown in space. The onboard assays include spectrophotometry, photography, and microscopy. Selected data will be stored onboard or downlinked to a control station. Uplink capabilities also exist if experimental protocol needs to change.

A mechanical arm with a transfer tip, which will be used for the fluid transfer, is discussed elsewhere. The overall experimental volume uses a basic, modular design which requires simple changes to support a diverse range of organisms. The overall design uses readily available or producible parts and current technology.

4.1.2 Design Options
Three different arrangements were studied for the experimental volume: a completely stationary model, a snake belt model, and a rotating disk. The simplest of these is the stationary model which would have no moving parts. The location of specific experiments for fluid transfer would also be easy. Unfortunately, assaying a large number of experiments with this arrangement is difficult. The snake belt model involves moving the experimental vials along a belt to position them for assay. A considerable advantage of this method is the ability to assay all experiments, while a disadvantage is system complexity. The final design option involves using a rotating disk to house the experimental vials. This method represents a compromise between the other two. It is capable of positioning a portion of the vials for assay while using a relatively simple system.

Several options also exist for the design of the individual experimental vials. Two basic concepts were studied: the bioreactor and the test tube models. Also, a number of different configurations for the test tube model were studied as well.

4.1.3 Trade Studies
The stationary model was not chosen as the experimental volume design because it presents problems in assaying a significant number of the experiments. It would entail moving the assaying equipment to the vials, a complex and mass intensive process. Both the snake belt and rotating disk methods use the opposite principle, move the experiments to the assays. The snake belt model is better for data acquisition because it provides the capability to assay every experimental container. However, it is very volume intensive and complex, with a large number of moving parts. These disadvantages completely outweigh the benefits of the increased data acquisition capabilities. Therefore, although the rotating disk method does not allow assays of every container, it was the chosen method. Depending upon the size and configuration of the experimental vials, a large significant number may still be assayed.

After choosing the rotatable disk model, experimental vials needed to be chosen. The bioreactor and the test tube model were both looked at. The bioreactor was not chosen because, if it had to rotate with

the disk, fluid transfer became very complicated. Tubes would need to be set up so that tangles would not occur as the volume moved. For this reason, a simple test tube model was chosen. This model uses a semipermeable membrane like that of the bioreactor. The test tube model also allows for size changes that allow for larger experiments to take place.

4.1.4 Subsystem Description

As shown in Figure 4.1-1, the experimental volume consists of a maximum of 82 vials each with an internal fluid capacity of 3 ml. 40 of these vials are situated on a moveable outer ring of 16.5 cm diameter. These 40 vials hold the experimental cultures that will undergo the various assays provided with the experiment. A sprocket, nylon chain and motor system turns the ring to expose the experiments to the various assays. A potentiometer and lever switch measure ring and vial position. The remaining 42 vials are situated on a stationary center disk of 9.5 cm diameter. These 42 vials contain fixative, nutrients, and experiments not requiring assays. A mechanical arm with a transfer tip will be used for all fluid transfers.

Each vial has a 1.2 cm outer diameter and a 5.0 cm height and stands parallel to all other vials. The vial volumes were chosen to optimize use of space. The vials provide adequate volume for most experiments, yet still allow numerous experiments to be run simultaneously in our limited space. This means that more experiments can be exposed to the various onboard assays.

Bioreactors were not chosen for the experimental vials because they required complicated valve systems and were harder to assay. Also, if larger experimental vials are necessary, the shown vials can be replaced by larger vials which occupy the same space. Setting up bioreactors in this manner utilized space inefficiently. Therefore, the test tube model was chosen for the experimental vials.

A flexible experimental vial design was chosen to maximize the experimental

capabilities of C-MASS. Three basic vial designs were conceived: the aerobic microorganism vial, the cell tissue vial, and the anaerobic vial. As shown in Figure 4.1-2, the three containers all have the same basic components, simply organized differently. The four base components are a rubber cap containing a resealable membrane; a rigid, optically clear, plastic cylinder, a flexible plastic bag; and a semi-permeable membrane.

The resealable membrane may be pierced by a fluid transfer needle, allowing fluid addition or removal while maintaining system closure. The rigid cylindrical portion permits imaging of the experiments, and the flexible portion allows the internal volume to fluctuate with fluid introduction and removal, thereby maintaining a "hard filled" fluid environment. Depending upon the type of experimental vial, a semi-permeable membrane is placed in either the rigid or the flexible portion, or it may be eliminated entirely. In the aerobic microorganism configuration, the membrane effectively separates the vial into two regions: an upper section that contains organisms in a nutrient solution and a lower section containing gases. In the cell tissue configuration the membrane allows nutrient replenishment in the upper compartment while keeping cells isolated in the remaining portion. Membrane porosity is matched to these different requirements. In addition, the elimination of the membrane provides a single environment for the study of anaerobic microorganisms.

During aerobic bacteria and other microorganism experiments, the organisms are contained within the rigid upper region of a vial. This allows for an aliquot (a small sample) to be taken by the fluid transfer system and used to inoculate a new nutrient-filled vial once the population has reached saturation. The process can be repeated many times, allowing the researcher to study changes in behavior and structure over multiple organism generations. In contrast, for cell tissue experiments, the cells are placed on the other side of the semi-permeable membrane. This allows for fluid removal

11

and nutrient replenishment without damage to the fragile tissues.

The vials on the outer ring are held in place by a bottom ring and an upper ring. The upper ring has holes in it to allow for fluid transfer (see Figure 4.1-1). A sprocket is attached to the bottom ring, and a chain to a DC motor is used to move the experiments. A potentiometer interacting with the motor will measure gross movements of the experiments. Dimples on the surface of the upper ring will be measured by a lever switch to determine exact positioning of the experiments. Numerous supports are attached to the bottom and top rings. An inner and outer metal band is attached to these supports. These metal bands prevent lateral movement of the vials, yet allow light to pass through the experiments so that assays may occur. An electroluminescent light sheet provides lighting if required by the particular experiment.

The stationary inner experiments are attached to a center support shaft. The inner experiments are not moved because they do not undergo analysis. Moving the inner experiments would have increased the power requirements of the motor and would have influenced the ability to accurately move the experiments undergoing analysis. The stationary center experiments also provide a structure to which the lighting may be attached. The vials in the inner volume are held in place by a bottom plate, a top plate (not shown) with holes for fluid transfer, and shimstock supports or bands encircling each concentric layer of vials. An electroluminescent light source encircling these vials provides lighting for experiments requiring light.

The empty space between the outer ring and inner disk will house a stationary electroluminescent light source, a light source for microscopy and photography, a light source for chromatography, and several LEDs of varying wavelengths for spectrophotometry. The measurement devices for these various assays are located outside the rotating ring and are stationary.

The lights for spectrophotometry are stacked 3 high. This use of space allows for a large number of wavelengths to be tested. The electroluminescent light source was chosen for its variable shape and volume requirements. This light source presents light to experiments which require a light source for survival.

An external DC stepper motor will rotate the outer ring, and hence present the specimens on the outer ring to the various assays and the fluid transfer tip. The outer ring will only move small increments, depending on the experimental situation. A potentiometer will be used to determine gross outer ring position. Dimples placed on the upper ring will be measured by a lever switch. The switch will determine exact positioning of the experimental volume. A DC motor, potentiometer and switching mechanism were chosen over a step motor because of volume constraints and ease of control. The outer ring will only have to be moved a few times every day. The motor will turn the volume slowly. Even though these are microgravity experiments, short duration and low acceleration movements were deemed to have a minimal effect on the experiments.

The experimental volume chosen allows vastly different experiments to occur within universal vials. These vials are simple and can be expanded to house larger experiments. The vials can be easily removed, filled and loaded before launch, but are held firmly in place by the experimental volume frame. The experimental volume itself can be easily manufactured, and simple devices used to move and measure movement of the outer volume. The volume provides space for experiments as well as additional nutrients and fixatives. Space for housing lights and assaying equipment is also available in the experimental volume.
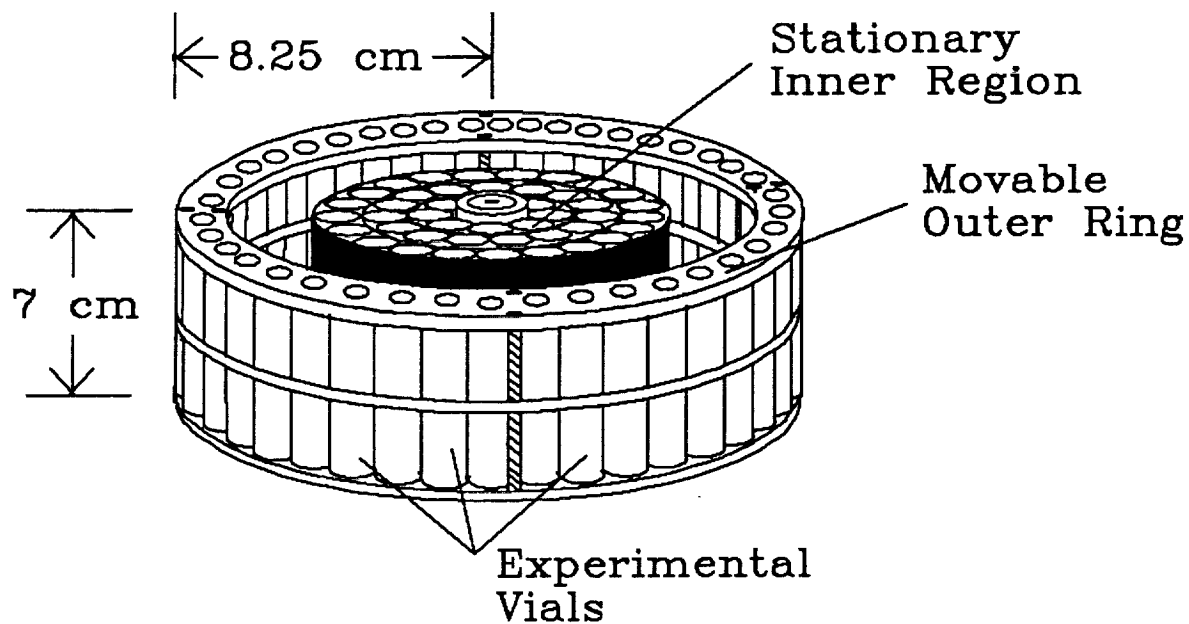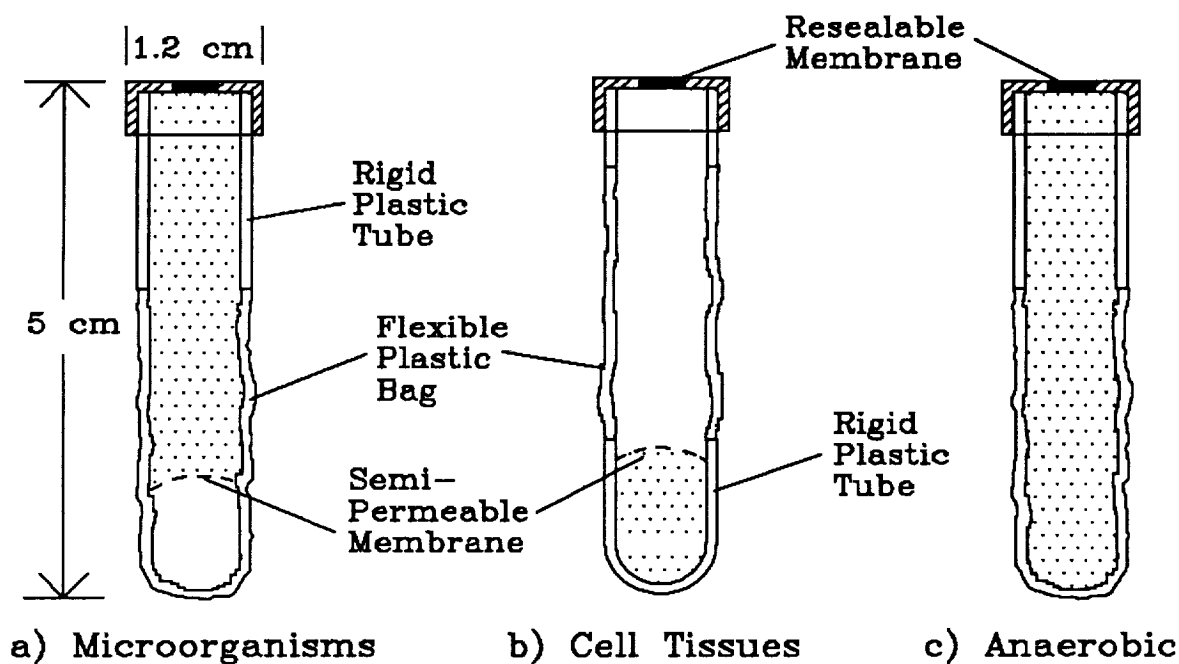
FIGURE 4.1-1: EXPERIMENTAL VOLUME SCHEMATIC

FIGURE 4.1-2: EXPERIMENTAL VIALS

4.2 1-g Centrifuge

4.2.1 Rationale/Requirements

The 1-g centrifuge is a critical component of the C-MASS payload. It allows experiments to be performed under gravitational accelerations equivalent to those experienced on the Earth's surface. This provides a basis of comparison for the microgravity experiments housed in the experimental volume. In the past the majority of these control experiments have simply been performed on Earth. However, the launch, orbital, and landing environments experienced by C-MASS introduce many variables that are difficult to simulate in ground based experiments. The extreme launch and landing loads, temperature profiles, and vibrational levels can all have a profound effect on organism development. This problem is compounded by the inherent variability of living organisms. As any microbiologist will attest, it is extremely difficult to exactly duplicate an experiment using organisms from two different origins. The best experimental results would be obtained using organisms from the same origin that have been exposed to identical conditions, with the exception of the acceleration due to gravity. Therefore, the 1-g centrifuge onboard C-MASS ensures that any changes in structure, function, or behavior that are observed in the living experimental systems are due solely to microgravity and not to any of these other factors.

There are many requirements imposed upon the design and operational characteristics of the centrifuge. The most important of these are listed below:

1) Provide accelerations of 1 +/- 0.125 g to the experiments. This ensures that no part of a functional experiment will experience accelerations of less than 0.875 g nor greater than 1.125 g.

2) Support at least ten experiments.

3) Allow fluid and mass transfer between experiments within the centrifuge and the rest of the payload. This should be a generic capability for the transfer of samples, nutrients, fixative and any other fluid required by the experiments.

4) Minimize the required power, mass, and volume.

5) Maintain a payload microgravity level of $<= 10\text{-}4$ g. This is the point that is commonly used to define microgravity

6) Maximize the commonality between the experiments in the experimental volume and those in the centrifuge. This is important for maintaining the similarity between the control group and the microgravity experiments.

4.2.2 Design Options

There are many design options that would meet the stated requirements. To determine the best design configuration and operational characteristics, a number of trade factors were considered. The first of these is whether or not to stop the centrifuge for the transfer of fluids. The next is the size of the centrifuge moment arm and the size of the experimental containers. These are important in determining the total number of experiments that the centrifuge is capable of supporting and the g gradient that they will experience. Likewise, the orientation of the experimental containers within the centrifuge also has a bearing on these factors. Finally, the perturbation of the payload microgravity environment by the centrifuge is also important.

4.2.3 Trade Studies

The design option with the largest effect upon the design and operation of the centrifuge was the manner in which fluid transfer would occur. Two methods of fluid transfer were considered that would allow the centrifuge to operate continuously. Stopping the centrifuge was also considered as a design option. The first method of fluid transfer during continuous operation is to use a fluid transfer arm capable of spinning independently from the centrifuge. The arm would be capable of spinning up from rest to match the rotational velocity of

14

the centrifuge. By slightly changing its rotational rate it could reposition itself to anywhere in the centrifuge, thereby allowing it to transfer fluids to and from any container. The drawbacks of this method are its tremendous complexity and the fact that it is very mass intensive. The second method allowing continuous operation is to use centrifugal force to move fluids between containers. Stored nutrients, fixatives, and other fluids in the center portion of the centrifuge could be transferred to other containers further to the periphery by opening the appropriate valves, allowing centrifugal force to move the fluid outwards. The main problem with this system is the complicated system of tubing and valves that would be required and its limited sampling capability. The final option is to simply stop the centrifuge. This simplifies the fluid transfer process significantly by allowing the fluid transfer mechanism used by the experimental volume to also service the centrifuge.

Positioning of the centrifuge for fluid transfer to and from individual containers could be accomplished in two ways, either passively or actively. If the position of a reference point was known at any given moment, the position of any particular experiment could then be calculated. The centrifuge could then be spun slightly to exactly position the desired container in the appropriate location, or the fluid transfer arm could be programmed to move to the desired position. Despite the simplicity of this system, stopping and starting the centrifuge could potentially have some effect upon the experiments contained within.

Position determination can be accomplished in a couple of ways. The first is to use a potentiometer attached to the centrifuge. A potentiometer is basically a variable resistor that changes depending upon its position. This is a simple mechanism that is used worldwide but also not extremely accurate. The second method uses a photoelectric sensor to measure the depth of a machined groove, a color change, or recognize various marks on the centrifuge. Based upon this data,

the angular position of any point can be calculated. This is an extremely accurate method for position measurement.

The next important trade study involved the size of the centrifuge and its experimental containers. The important considerations here are the centrifuge size, rotational rate, and experiment g gradient. The relationship between these parameters is illustrated in Figures 1 and 2. As you can see, the rotational rate required to maintain 1-g decreases as the centrifuge radius increases. Lower rotational rates are desired to minimize the power required and to lessen vibrational perturbations to the payload. This must be balanced by the requirement to minimize the volume required for the centrifuge by using a small centrifuge radius. The length of the centrifuge moment arm also has an effect upon the maximum sample size capable of maintaining the +/- .125 g gradient as specified in the requirements. As the second graph shows, the maximum sample size increases linearly with an increase in centrifuge radius.

The orientation of the sample containers within the centrifuge also has an impact upon the centrifuge volume and the experiment g gradient. Two possible orientations are the horizontal and vertical configurations. The horizontal configuration involves orienting the long axis of the experimental containers perpendicular to the centrifuge axis of rotation. This decreases the height of the centrifuge but also decreases the amount of containers that the centrifuge may support. It also makes it very difficult to achieve the desired g gradient. The second option, the vertical configuration, places the long axis of the experimental container parallel to the axis of rotation. Although this results in a taller centrifuge, it allows for more experiments to be supported and eases the obtainment of the required g gradient.

The final trade study to be performed involves the minimization of the perturbation to the payload microgravity environment by the centrifuge. It is an extremely complicated process to assess the

contributions of individual components to the payload accelerations. However, methods do exist, and this analysis is planned for the future.

4.2.4 Subsystem Description
The design of the centrifuge represents one of the most severe tests to our philosophy of using only off the shelf hardware. All commercial centrifuges are designed for operation at much higher rotational rates than is required in C-MASS. There have been a few 1-g centrifuges designed for use in microgravity, but they are either too large or unmodifiable to our particular configuration. Therefore, the centrifuge is a unique instrument but one that utilizes commercially available or readily producible components, thereby remaining consistent with our design philosophy.

Although the stoppage of the centrifuge to allow fluid transfers could possibly affect the experiments, it was determined that this would be minimal if the stoppage were for only a few minutes a day. The simplicity of this system outweighs any potential effects that would occur. It was also determined that the center portion of the centrifuge would not rotate and would contain storage containers for nutrients, samples, and fixatives. This minimizes the mass that the centrifuge is required to accelerate. The fact that this storage section will not rotate means that the fluid transfer arm must be capable of accessing almost the entire centrifuge. Since the arm must already be capable of transferring fluids between many different points, the passive method of centrifuge positioning was deemed the best option. Therefore, precise motor control is not required for the centrifuge, and the fluid transfer arm must be able to move to any given point based upon measured positional data.

Due to its high accuracy, a photoelectric sensor was chosen for calculating the angular position of the centrifuge. This sensor will measure the depth of a groove of continuously varying depth that is machined into the base of the centrifuge platter. Based upon this depth, the

accompanying software can calculate the angular position of the centrifuge as it comes to rest. The fluid transfer system can then move to any desired vial within the centrifuge.

The desire to maximize the commonality between the microgravity experiments and those in the centrifuge was the deciding factor in the rest of the trade studies. In effect the 1-g centrifuge is designed to be identical to the experimental volume with the exception that it rotates at approximately 108.5 RPM. The configuration is shown in Figure 3. The centrifuge is 8.5 cm in radius, 15 cm in height, and uses the same experimental containers as the experimental volume. These are place in a vertical orientation with their centers at a radial distance of 7.6 cm from the centrifuge center, identical to the experimental volume. Motor output is controlled to within 2 RPM through the use of a negative feedback loop. This fact coupled with the .6 cm radius of the experimental vials means that the maximum g gradient for any experiment is +/- 0.11 g during centrifuge operation. Lighting is accomplished in a manner identical to the experimental volume and storage containers are located in the non-rotating center of the centrifuge in the same configuration.
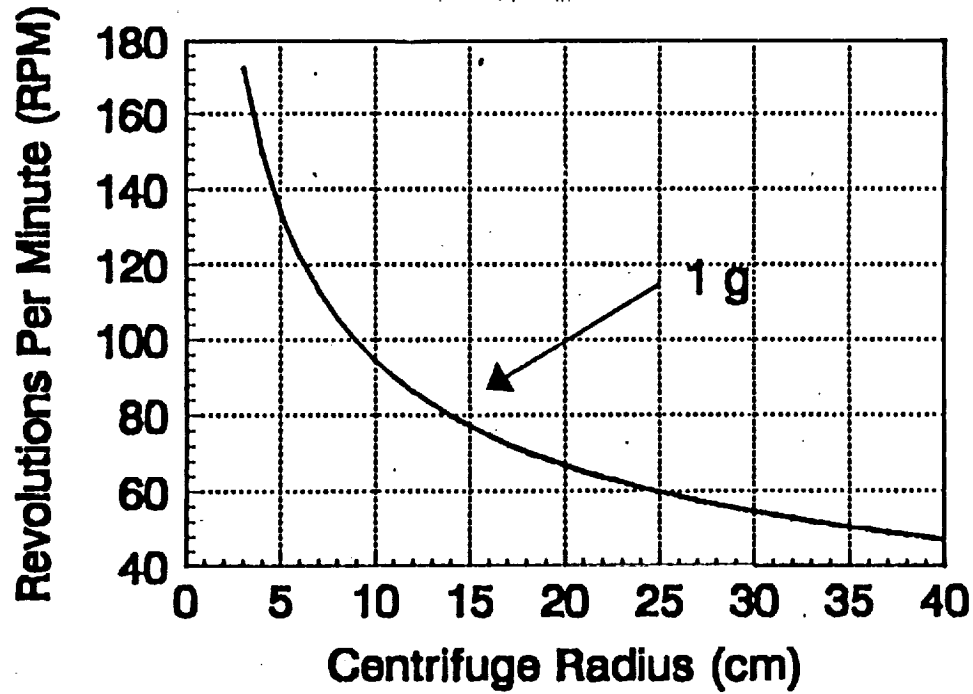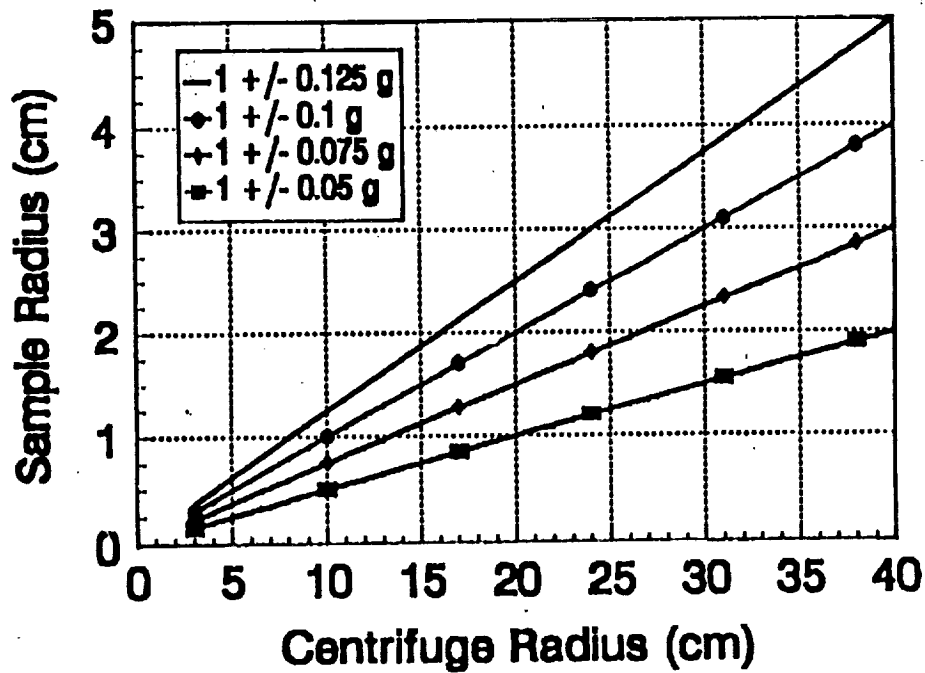
FIGURE 4.2-1: RADIUS VS ROTATIONAL RATE
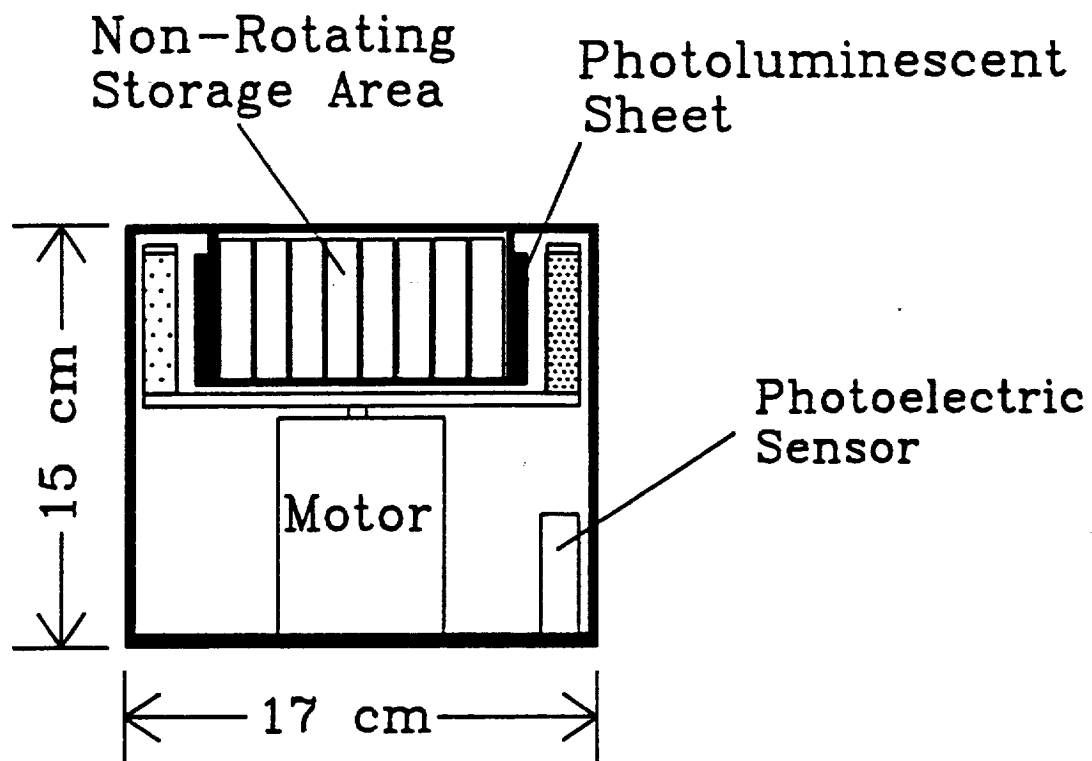

FIGURE 4.2-2: RADIUS VS G GRADIENT

Non−Rotating
Storage Area

Photoluminescent
Sheet

Photoelectric
Sensor

15 cm

Motor

17 cm

FIGURE 4.2-3: 1-G CENTRIFUGE SCHEMATIC

4.3 Fluid Transfer System

4.3.1 Rationale/Requirements
The design of the experimental volume and centrifuge require the capability of fluid transfer throughout the entire mission duration. In addition, the fluid transfer system should provide C-MASS with the ability of supporting a wide variety of experiments. Nutrients, fixative, and individual experiments are stored separately in individual experimental vials. The transfer of a specific amount of fluid from one experimental vial to another will be required at varying times. For instance, the system needs to be able to remove wastes and replenish nutrients or inoculate a few cells in a new nutrient solution. Therefore, a versatile fluid transfer system is needed.

One of the most important factors in the fluid transfer system is to maintain sterility. Each individual transfer of cells, nutrients, or fixative should be as sterile as possible since experiments could be ruined if sterility is not maintained. The system must also be able to transfer different volume amounts of fluid. The transfer of volumes between two or three drops and up to one or two milliliters will be necessary. The fluid transfer system will also be required to reach all the experimental vials within the experimental volume and the centrifuge. This procedure must be accomplished while avoiding the blockage of any camera lenses or various other components inside C-MASS.

4.3.2 Design Options
There are basically two different methods that would allow for each experimental vial to be accessed. The first option is a series of pumps and valves that would run between each of the vials. The second option is to use some type of robotic arm. However, there are two types of robotic arms that could be implemented. Either a retractable arm device or a system based on X-Y plotters could be used.

In order to successfully transfer fluid, the experimental vials must be accessed without loss of closure. If the combination of pumps and valves is used, access to the experimental vials will be accomplished through valves. However, if one of the robotic systems is used, the experimental volumes would be accessed using a syringe-like device.

The next step in the fluid transfer process is to remove or insert fluids into a experimental vial. A pumping mechanism will be used in whichever motion system is decided upon. However, depending on which motion system is chosen, different pumping systems are applicable.

4.3.3 Trade Studies
As stated previously, there are several options available for fulfilling the requirements of the fluid transfer system. The first, the series of pumps and valves, is not only complicated, but would be extremely volume intensive. Due to the wide number of pumps and valves necessary to reach all of the experimental vials, failure would be an serious problem, but redundancy would increase the volumetric requirements even more. Also due to the number of pumps and valves, maintaining of sterility would be a complicated and almost impossible task with the C-MASS constraints. The second option, or robotics, appears to be more feasible. However, robotics are also somewhat volume intensive, but less so than the combination of pumps and valves. The two types of mechanical arms available, a retractable arm and an X-Y plotter based system, each have advantages and disadvantages. Both systems are currently used in laboratory settings and have proven to be reliable and durable. However, a retractable arm is more complicated to control than the X-Y plotter based system thus requiring a larger volume for robotic programming.

Independent of which fluid transfer mechanism is implemented, the chosen system must be able to transfer fluids while maintaining sterility. The series of pump and valves would have to pump a sterilizing fluid through the system whenever necessary. This process would not only be inefficient, but hard to implement. This

form of sterilization would also require significant amounts of sterilizing fluid, which would occupy much needed volume. The robotic arm has two means of sterilization. A fluid transfer tip, a syringe-like device, was determined to be the method for accessing the experimental vials. The fluid transfer tip is discussed in the next section. However, to sterilize the transfer tip, the transfer tip can either be inserted into a sterilizing solution or the transfer tips could be exchanged. The difficulty with inserting the transfer tip into the sterilizing fluid is the removal of the sterilizing fluid before the transfer tip is placed inside the experimental vial. If sterilizing fluid were to be placed inside the experimental vials, the organisms would be adversely affected. This problem could be avoided by exchanging transfer tips when necessary, but this method will require extra volume.

There is a wide range of pumping mechanisms that could be used for fluid transfer. The trade-offs in determining a pumping mechanism include size, pumping power, durability, and reliability.

4.3.4 Subsystem Description

The fluid transfer system will use a robotic arm based upon technology derived from X-Y plotters. The system will consist of three stepper motors which turn three lead screws. The three lead screws are orthogonal to one another so as to provide the necessary three dimensional motion. A diagram of the robotic arm can be seen in Figure 4.3-1. The primary motor, or the stationary one attached to the wall of C-MASS, is 36 mm by 42 mm by 42 mm (Compumotor, 1991). The two secondary motors are 22.7 mm in diameter and 36.5 mm in length (Emerson Electric Company, 1990). The tracks that one of the lead screw rides upon is a LM guide (THK Company, 1990). The exact LM guide can be determined once the exact weight of the robotic arm is determined.

The fluid transfer tip, a diagram of which is shown in Figure 4.3-2, is a syringe-like device, which is capable of transferring a maximum of 1 ml of fluid. The needle tip

punctures the resealable membrane at the top of the experimental vial. Once the needle has been inserted, the pumping mechanism can be engaged. The transfer tip design not only prevents contamination of the experiments, but reduces possible cell damage. A flexible, plastic bag has been attached to the transfer tip needle on the inside of the transfer tip. This bag fills with fluid as it is pumped from the experimental vial, blocking the liquid from entering the pumping mechanism, thus inhibiting the contamination of the pumping device. The transfer tips are also interchangeable, so as to prevent contamination. There are 110 transfer tips located inside C-MASS which allow for transfer tip exchange. The transfer tip reduces cell damage by placing the fluid inlet on the side of the needle instead of on the end. Thus, the fluid inlet can be larger, which in turn reduces the shear forces experienced by the delicate cells.

The pumping mechanism employed by the fluid transfer system is based upon an automatic, battery powered pipettor typically found in laboratories. The pipettor examined was a MOPET pipettor (VWR, 1989). The pumping mechanism works as is shown in Figure 4.3-3. The pumping mechanism has two openings, one of which always creates an increase in pressure and the other which always creates a decrease in pressure. Thus, by simply closing the tube on the right hand side, using a solenoid, the pumping mechanism forces fluid into the transfer fluid tip. In order to reverse the process, the solenoid on the right is retracted and the solenoid on the left is extended. This pumping mechanism is known to be extremely reliable and durable since it is derived from pipettors which are tested in a variety of laboratories. The pumping mechanism is located on the robotic arm's end effector, directly above the fluid transfer tip. The robotic control mechanism uses the positioning system, discussed in the 1 g centrifuge section, to locate the different vials. For further information on the components of the fluid transfer subsystem, see Appendix C.
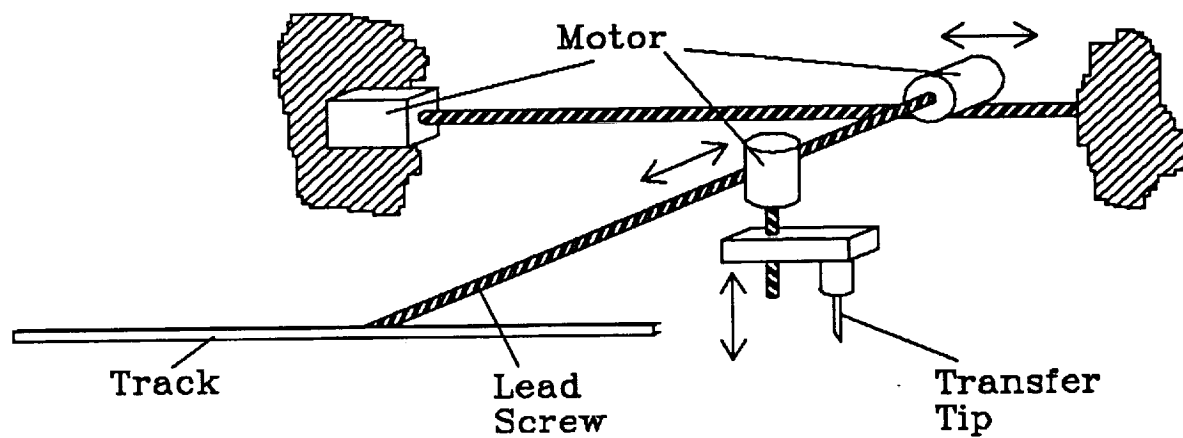
20

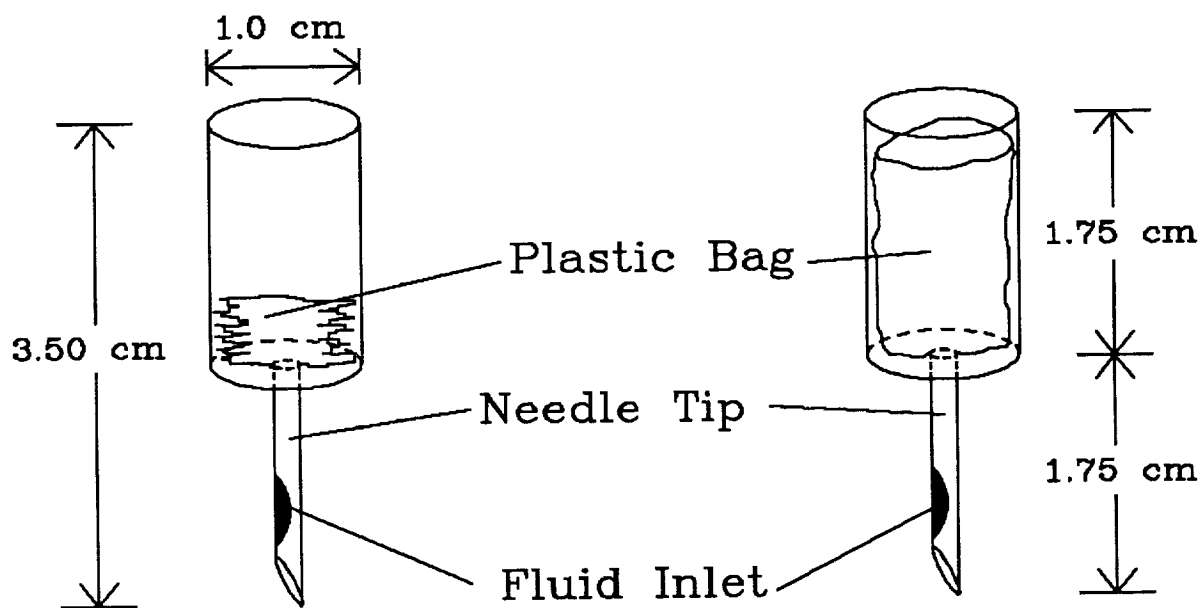**FIGURE 4.3-1: ISOMETRIC VIEW OF THE ROBOTIC FLUID TRANSFER ARM**

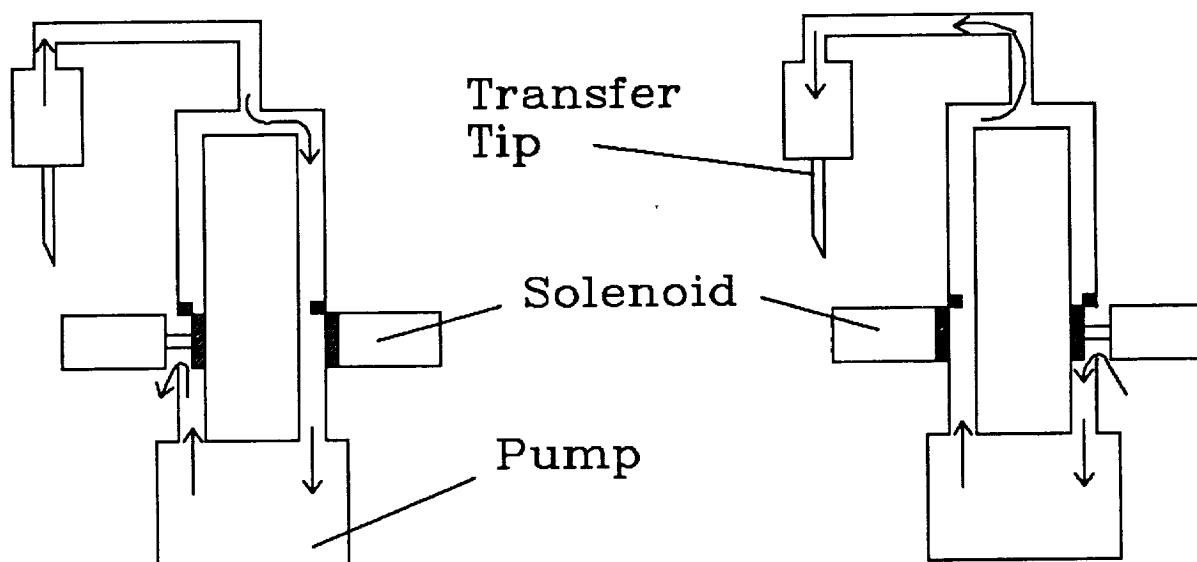**FIGURE 4.3-2: DIAGRAM OF THE FLUID TRANSFER TIPS**

FIGURE 4.3-3: SCHEMATIC OF THE PUMPING MECHANISM

4.4 Imaging System

4.4.1 Rationale/Requirements

Organism growth and development is a dynamic, nonlinear process. It is simply not possible to understand changes in organism structure and behavior due to the presence of microgravity through the analysis of the end effect alone. Periodically fixing samples is a common method of preserving samples for later ground based analysis. While this gives some indication of a time history, it also alters the cell structure and prevents them from being used to begin new terrestrial cell lines. In doing so, much of the potential for commercial spin-offs from the experiments is lost. Also, the extreme loads experienced during landing can alter or even destroy the experiments. Therefore, the ongoing visual record provided by the imaging system is essential for establishing a time line of organism development.

Since the experiments within C-MASS deal with microorganisms, a microscope is required for all imaging applications. High resolution of cellular features was a necessity, along with the ability to downlink real time visual images to ground based researchers.

4.4.2 Design Options

Four distinct microscopy methods were evaluated during the design process: basic transmitted light microscopy, confocal microscopy, phase contrast microscopy, and differential interference contrast (DIC) microscopy. Basic light microscopy is the simplest, least expensive, and most widely used microscopic technique. Indeed, transmitted light microscopes can be found in labs all the way down to the elementary school level. However, they provide very poor resolution of cellular features.

Confocal microscopy was the second method evaluated. A confocal microscope is based on the concepts of selective aperture and selective illumination. The selective aperture, shown in Figure 4.4-1, allows light from only one specific plane within the specimen to be viewed at a time.

It eliminates the scattered, reflected, or fluorescent light from all other planes, resulting in an image of only one plane within the object (Duke and Michette, 1990). In contrast, a standard microscope accepts light from planes other than the one in focus, i.e. out of focus planes above and below the focal point, which clouds the image and reduces clarity of the details of interest.

The second advantage of confocal microscopy is selective illumination. It uses a monochromatic light source, typically a laser, and selectively illuminates points within the plane of interest. This method also eliminates the "pink fog" normally associated with live biological tissue viewed using reflected light microscopy.

Two types of confocal microscopes exist. The first is the multiple-aperture array Tandem Scanning Microscope (TSM). A large number of apertures and light sources are used to simultaneously illuminate all points of the object in the focal plane, typically utilizing 1000 light sources or more. This is accomplished using a spinning disk with holes placed near the edge. The second type is the Confocal Scanning Laser Microscope (CSLM). This concept utilizes a single fixed laser and a mirror mechanism used to target the laser beam and illuminate the focal plane point-by-point (see Figure 4.4-1).

The third type of microscopic technique is phase contrast microscopy. This technique exploits the fact that light rays undergo phase changes when they pass through transparent objects with different refractive indices. These phase changes do not show up in the visible image as the amplitude changes are. Instead they form a "ghost image" that consist of interference patterns of maxima and minima at different phases. This phase object can be made to look like an amplitude object by attenuating the zeroth order maxima and delaying it in phase by 90 degrees (James and Tanke, 1991). This can be accomplished through the use of special objective lenses with a standard microscope. The result is an image with much sharper contrast than an

23

image from a normal light microscope. This sharper view yields a far better picture of cellular features. The image is not as good as from a confocal microscope and it is not a true three dimensional view, but phase contrast is smaller, less power intensive, and far less expensive than confocal microscopy.

Differential interference contrast (DIC) microscopy is similar to phase contrast microscopy in that they render transparent objects visible by converting the phase changes in the light that passes through them into changes in wave amplitude (Ross, 1967). However, a measuring beam and a comparison beam interfere after passing through the object at a short distance form one another. The mutual interaction between the two coherent wavetrains convert gradients of optical path length differences into intensity variations, forming visible contrasts. This method is preferable to phase contrast microscopy when dealing with objects having large differences in optical thickness.

A video camera is needed to meet the requirement of downlinking real time data. Current technology for 8 mm video cameras use charged-couple devices for imaging purposes. Because CCDs are made from silicon, it is useful to understand the properties of silicon and the way light reacts with it. The silicon used to make imaging devices is in its crystal form. In a silicon crystal lattice each atom is covalently bonded to its neighbor. When these bonds are broken electrons flow through the crystal lattice. The bonds can be broken in the following manners: by incident photons, x-rays, high energy particles, and thermal agitation. Figure 4.4-2 presents a two-dimensional picture of a silicon crystal lattice showing these various forms of excitation. When used as an imaging device, the incident photons are the primary concern of the CCD, and means should be taken to eliminate all other forms of excitation.

A CCD imager acquires its image by measuring the amount of electronic charge produced by the incident photons.

Independent potential wells within the CCD device are used to store the electrons excited by the incident photons over a given period of time. This two-dimensional array is known as a parallel register. The parallel register will accumulate a pattern of charge from an image focused upon it that is proportional to the amount of incident photons. The parallel register is then emptied by a serial register , after the exposure time has passed. The serial register then moves the charge packets to the output amplifier.

Video can not meet the requirement for high quality visual data. Photography has a far greater resolution than video imagery due to the much smaller size of the light sensitive silver halide crystals in film as compared to video pixel elements. Cameras using two basic film sizes, 35 mm and 110 (11 mm), are currently commercially available. 35 mm film provides a larger image size and 35 mm cameras are used by far greater numbers of people. On the other hand, 110 has the advantage of being about a third the size of 35 mm film. More 110 film can be stored in a given volume than for 35 mm, thereby greatly increasing the total number of available exposures. In either case the chosen camera must be electronically controllable, auto timing, auto film advance, auto aperture, and auto shutter.

4.4.3 Trade Studies
The science requirements dictated a microscope system capable of extended depth focusing and 3-D imaging. In addition, the resolution needed to be at least 256 by 256 pixels and image reconstruction time of no more than 2.5 to 3.0 seconds. Although neither phase contrast nor differential interference contrast microscopy yield results as good as a confocal microscope, both are far better than basic light microscopy. The imaging benefits of confocal microscopy is offset by its high cost, volume, and power. In addition, since DIC depends upon the lighting conditions and phase contrast uses different objectives, the capability to do both can be incorporated into the design.

24

Therefore, both will be used in C-MASS.

A study of the video cameras that are commercially available was conducted. This study showed that Hitachi, Sony, and Canon all had commercial products which meet C-MASS's requirements. The power consumption of the cameras ranged between 4.9 to 7.8 Watts during recording. The weight ranged from 770 to 950 grams without tape or battery. The lighting requirements were as low as 2 lux for imaging. Each brand used an 8 mm (metal particle) tape, which gives 90 minutes of storage at best resolution, and 120 minutes at a slower speed. All of the cameras use 12 bit resolution for color and have pixel resolutions in the hundred thousands. All of the brands considered in the trade studied meet the requirements. While there are slight differences in the weight, power consumption, and lighting requirements for each of the brands considered there was no significant differences

Commercial trade studies have shown that the Nikon N 8008 S is the only camera which meets C-MASS specifications and is capable of very high shutter speeds. There is no commercially available 110 camera that is electronically controllable with all of the required automatic features. The Nikon N 8008 S is completely electronically controllable and has all of the auto functions specified. The camera is powered by 4 AA batteries, so there would be no power draw from the carrier. The camera body has dimensions of 15.4 cm by 10.3 cm by 6.7 cm and weighs 695 grams.

4.4.4 Subsystem Description
The inclusion of the capability to perform both phase contrast microscopy and DIC allows for a very flexible imaging system. Depending upon the organism to be monitored, a different imaging technique may be employed. For instance, phase contrast is much better at imaging thin cells, while DIC performs better with thicker cells. Also, total magnification ranges from 10x to 1000x to provide the proper magnification level for a wide variety of imaging applications.

The output from the microscope can be directed to the CCD video camera. The camera has a resolution of approximately 400,000 pixels with 12 bit color resolution. Normally, the video data is stored onboard by the data/communication subsystem. However, video images may also be downloaded to researchers on the ground. This small glimpse into the activity within an experiment that they receive will allow them to change the experiment protocol in-flight should the need arise.

As with the video camera, imaging with the 35 mm camera is through the microscope. The camera uses a film back capable of holding a 250 exposure role of standard 35 mm film. However, several options exist for increasing the number of possible exposures with simple modifications to various camera components.

For instance, the film advance mechanism can be modified to hold three roles of 110 film side by side. By exposing one film strip at a time, the number of exposures can be tripled. Also, by modifying the shutter and film advance mechanism, it is possible to section the film into much smaller partitions than is standard. It is possible that the optimal method for maximizing photographic capabilities requires a combination of the two methods.
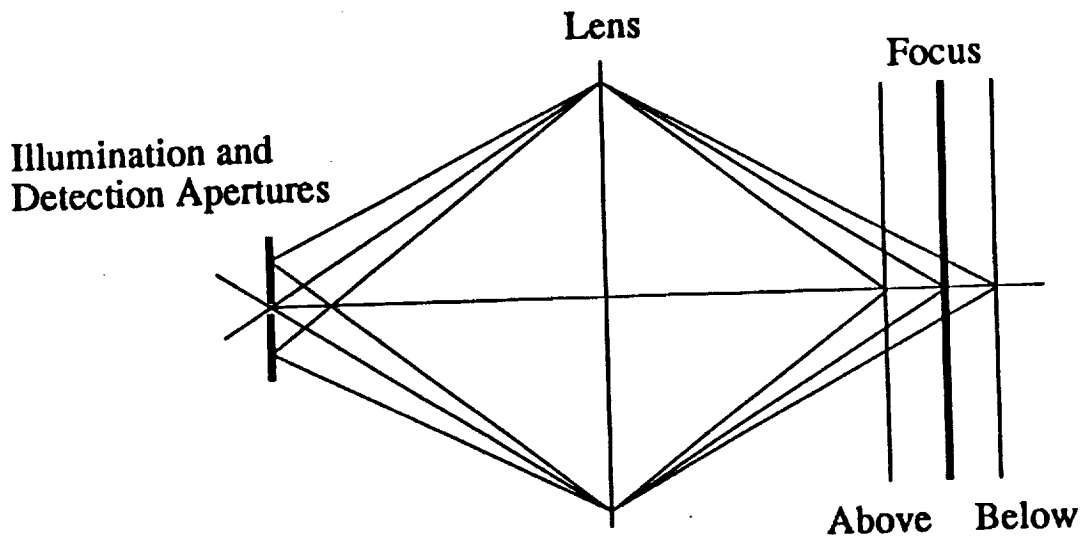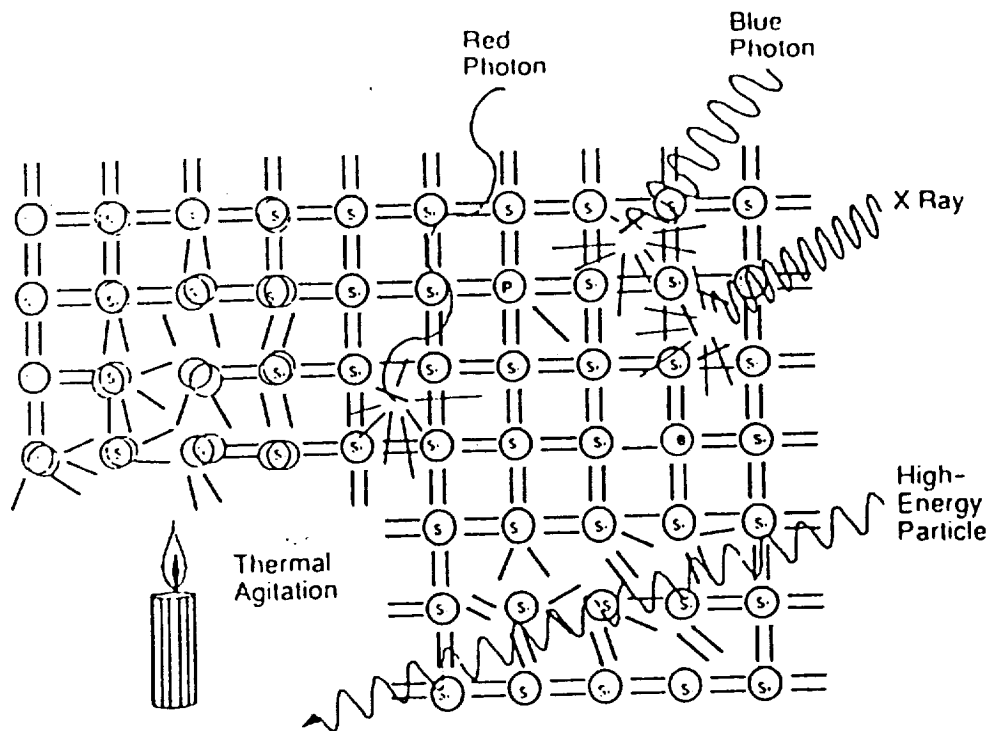
FIGURE 4.4-1 CONFOCAL IMAGING CONCEPT

FIGURE 4.4-2 CCD SILICON LATTICE EXCITATION

4.5 Sensors

4.5.1 Rationale/Requirements

The variety of measurements taken aboard C-MASS will allow researchers to determine the dynamic effects of microgravity. A significant number of the sensors discussed in this section measure environmental conditions. The environmental sensors are capable of monitoring temperature, illumination, gravity level, vibration, and radiation. However, C-MASS also incorporates several assay methods. The assays methods available include spectrophotometry, for obtaining optical density measurements, and Enzyme-Linked ImmunoSorbent Assay (ELISA) for detecting the presence of specific biomolecules, such as proteins or peptides. The selection of the sensors was difficult for several different reasons. The sensors must not only be capable of operating in a microgravity environment for the entire mission duration, but must be able to obtain data without adversely affecting the experiments. Also, when sensors are placed in contact with organisms, biofilms and condensate may form around them which will decrease the accuracy of the sensor readings. The sensors must avoid these problems while still maintaining minimal power, mass, and volume.

C-MASS is capable of providing the researcher with a multitude of measurements and the reasons for choosing these measurements are as follows. All living organisms respond to temperature changes and cannot survive outside a given range. In addition, C-MASS experiments are dependent on the reproduction rates of microorganisms, which are known to vary with the surrounding temperature. It is thus important to monitor the ambient temperatures within the payload volume. The pH value is an essential parameter in cellular and subcellular biology and is defined as the negative logarithm of the hydrogen ion (H+) concentration. Only slight changes in hydrogen ion concentration can cause marked alterations in the rates of chemical reactions in the cells, some being accelerated and others

depressed. Normally, the allowable range for pH values is very narrow, usually between 6.8 and 8.0. All these factors make pH measurement an important capability. Some of the organisms to be flown aboard C-MASS are dependent upon the incident light as part of their environment. Thus, illumination sensors are available. The inherent difference between Earth-based experiments and C-MASS experiments is the gravity levels experienced. The gravity levels can be influenced by perturbations due to onboard machinery, orbital maneuvers, and launch/re-entry loads. It is therefore desirable to monitor gravity levels over the entire mission duration. Radiation is monitored since it could have an adverse affect upon the experiments. As stated earlier, C-MASS has several different assay methods. These methods were chosen so as to significantly increase the data taking capability of the payload without the addition of major complications. Spectrophotometry readings provide invaluable information on population density, which is especially important in multiple generation experiments, while ELISA allows for the detection of specific proteins.

4.5.2 Design Options

Several different sensors are available to measure each of the desired variables. The solutions presented are not the only choices that satisfy the requirements, but are believed to be the best choices. Thermal conditions could be monitored using either a thermocouple or a thermistor. Sensors suited for pH measurements include electrodes, optrodes, and non-interactive chemicals. To provide illumination information, photoconductive detectors or photovoltaic detectors could be used. The gravity sensors are basically limited to different accelerometers. Radiation measurement devices studied are Thermal Luminescent Dosimeters (TLD) and tissue equivalent proportional counters. Sensors used for spectrophotometry include light detection and light source devices. The light detection devices are either photovoltaic or photoconductive detectors, same as for illumination measurements.

The different light sources could be either be Light Emitting Diodes (LED) or gas-filled bulbs. ELISA can only be accomplished using specific devices which will be discussed in the following section.

4.5.3 Trade Studies
Thermal sensors utilize the fact that the resistance of metal varies with temperature due to thermally induced strains. As a result, a current can be applied and the voltage will react according to the law $V = IR$, where V is voltage, I is current, and R is the resistance. Temperature is then correlated with the measured voltage such that temperature can be monitored. This is accomplished in two ways. The first way is to use a thermocouple. A thermocouple is a probe that consists of two wires of dissimilar metals joined together at their ends, forming two junctions. When the two junctions are at different temperatures, a voltage is produced that is proportional to the temperature difference. The choice of metals depends on the desired temperature range. The second possibility is using a thermistor. A thermistor is a small semiconductor that changes its electrical resistance in response to temperature. Besides measuring temperature electronically, it also serves to compensate for excessive power consumption by an electronic circuit that senses the accompanying temperature increase and applying negative feedback, which returns the circuit to a safe operating level. The trade-off considerations include reaction time, size, sensitivity, and repeatability. Both sensor types are available in all sizes, shapes, sensitivity, and repeatability, although thermistors generally have faster response time and are more resistant to mechanical shock.

As previously discussed, pH can be measured in three different ways. The first is through the use of electrodes. This type of pH sensing system has two electrode components: a sensing and a reference electrode. These components are often combined to form a combination electrode. This sensor depends on a change in the voltage caused by the interaction of the medium and the electrodes, which is directly dependent on the ion concentration. The second approach to pH measurement is to use optrodes or optical electrodes. Optrodes use fiber optics to transmit light to and from the sample and then measures the pH of the sample by observing changes in the output light intensity. The optrode is a special termination of the distal end of a fiber optic cable, which aids in the increase, decrease, or initiation of fluorescence when the exciting light interacts with the sample to be measured. Laser light of specific wavelength is used for this purpose. The third method is based on the use of a non-interactive pH sensing chemical that changes color according to the pH level. The color can then be determined through using one of the two cameras. Trade-offs for pH sensors include considerations such as re-calibration, sample contact, size, accuracy, range, and power. Electrode sensors are very small, usually no bigger than 2 square millimeters, meaning they can be used with small amounts of sample medium with low power consumption. However, they require constant re-calibration, cannot be left in the sample, and their selectivity and repeatability is rather poor and is highly dependent on the re-calibration procedure. Optrodes do not require re-calibration after use and do not require contact with the sample. In addition, since the optrodes depend on changes in optical signal rather than an electrical one, they are not affected by outside electrical interference. On the negative side, the support equipment must include a laser, optical coupler, and spectral sorter as well as the optrodes. Also, optrodes only work well for a narrow concentration range of the test material, which is dependent on the end termination of the fiber optics cable. Finally, they are not commercially available and still have a few problems that need to be corrected. The pH sensitive chemicals are a proven technology and do not require re-calibration nor do they use power. A pH chemical could be used in conjunction with one of the cameras, thus using support equipment already available on C-MASS. The camera would simply take a picture of

the sample of the experimental vial for later quantification. However, immediate quantification could be accomplished if the video camera was used and the image was immediately downlinked.

Two illumination sensors are available. Photoconductive detectors produce a current in response to incident light, whereas photovoltaic detectors generate a voltage in response to illumination. Single element, planar diffused silicon photodiodes are designed for general purpose, medium to high speed applications and consist of a silicon photodiode element mounted in a small, sealed metal case. These are capable of operating over a wide spectral range from low level visible spectrum to the near infra-red. Specific wavelength sensors are available if further breakdown of the incident light is required, i.e. red light intensity, blue light intensity, etc.. Trade-offs for light sensors are size, sensitivity, and power requirements. All types of light sensors are small, and since few are required, this is not an issue. Similarly, photodiodes require very little power and sensitivity over 30 days will not vary appreciably. As a result, the only real trade-offs are related to how many sensors are required and whether specific color intensities need to be measured independently.

The only gravity level sensor that meets the requirements of C-MASS is an accelerometer. This occurs mainly due to size and power constraints. The exact accelerometer chosen to be used within the payload will be discussed in the next section. The only drawback to this system is that three different accelerometers, each orthogonal to the other, must be used to obtain the three dimensional measurement requirement.

Basically, two different radiation detectors were compared. The first, the tissue equivalent proportional counter, is a volume intensive instrument, but has the capability of supplying a complete time history of the radiation within C-MASS. The second, the TLD, is a passive device

which requires no power and is not volume intensive. TLDs are commonly used in laboratories to measure amounts of radiation. However, a TLD simply provides information on the maximum radiation levels and is thus not capable of providing a radiation time history.

Spectrophotometry is an optical method that measures density based on light absorption. Population counts are then possible based on the correlation between light absorption and population density. This requires a monochromatic light source and an associated photoreceptor. Different wavelengths are used to measure various density characteristics of the medium and are dictated by the specific needs of the experiment. One of the science requirements is to have wavelengths from 200 nm to 1500 nm. Trade considerations focus on the required wavelengths, power requirements, and size of the light source and photoreceptor. The size of the light bulb and the power required are dictated by how quickly the measurement needs to be taken. For example, monochromatic LED light sources use very little power and are small, but require higher sampling time so that the photoreceptor can pick up enough residual light to make the measurement. Another consideration is the type of light source, such as LED vs. gas-filled bulb. However, gas-filled bulbs are larger and produce more heat than LEDs.

Enzyme-Linked ImmunoSorbant Assay (ELISA) does not have any specific trade-offs, it was chosen as an assay method due to the amount of data that can be obtained using this method. ELISA is a plastic sheet with antigens attached. These antigens are proteins that can chemically recognize other very specific reagent proteins. When the proteins come in contact with one another, the bound antigen produces a color change in proportion to the amount of reagent protein present. Using this method, very small amounts (as little as 10 picograms) of specific reagents can be detected and their concentrations determined. Currently, several hundred specific assays are possible using this technique.

4.5.4 Subsystem Description

The trade-offs made determine the components to be placed within the sensor subsystem. To measure temperature, thermistors will be used. The thermistors chosen are capable of measuring both air and surface temperatures from -40 to 150 and -30 to 100 degrees Celsius respectively (Cole-Parmer Instrument Company, 1990). These temperature measuring devices are placed strategically throughout the facility. The pH measurements will be done using pH sensitive chemicals in conjunction with one of the cameras. One such indicator is phenol red, or phenolsufonphthalein, which changes from yellow to red between pH 6.4 and 8.2 (Sigma Chemical Company, 1992). The illumination sensors are simply standard photodetectors that are capable of measuring light in the visible range (Siemens, 1990). The accelerometers have the ability to measure gravity levels and vibrations between 40 micro-g and 10 g (Vibra Metrics, 1992). Measurement of radiation will be accomplished using a TLD since a time history is not necessary (Lab Safety Supply, 1990). Spectrophotometry will be provided using LEDs and photodetectors. When inside the visible range, standard LEDs and photodetectors will be used (Siemens, 1990). However, the system is required to span the range from 200 nm to 1500 nm. Thus, when outside of this range, special devices such as UV and blue-enhanced silicon photodetectors and InGaAs detectors and emitters will be used (UDT Sensors, 1992). The other assay method, ELISA, will be accomplished as described earlier. For more information on the components of this subsystem, see Appendix C.

4.6 Data/Communications

4.6.1 Rationale/Requirements

The valuable measurements taken by the sensors and imaging systems require a means of data storage and return. Communications are also necessary between Earth and the payload and between its various internal subsystems. The C-MASS design includes both of these data handling means. However C-MASS is not only capable of downlinking data, but it can also receive uplink commands allowing for in-flight capabilities. These capabilities allow C-MASS to be an extremely versatile research tool. Downlinking is required in order to monitor experiments during the mission while uplink is used to alter the systems programming. For instance, if an unexpected change in an experiment is noticed, using the downlinking capabilities, commands could be uplinked to change the experiment protocol. One of the difficulties in designing this system is the limited communication windows. These windows are very limited due to carrier restrictions, approximately five minutes distributed over eight passes are available.

4.6.2 Design Options

A storage device is needed in order to store the vast amount of data for in-flight and post-flight retrieval. The media used can either be optical magnetic or simply magnetic. Also, a system must be chosen that can uplink, downlink, and control the payload. In order to accomplish this, several different hand held acquisition computers were evaluated.

4.6.3 Trade Studies

In order to be beneficial to the system, the storage device must minimize power, mass, and volume while maximizing storage capacity and reliability. There must be enough space to store at least several minutes of real time video as well as all the sensor data. It must also operate intermittently for the entire thirty day duration of the mission with no maintenance. It must be able to operate within the specified environment without

significantly affecting it. The drive must operate in a temperature range of 0-40 degrees Celsius, must be able to withstand the 12 g reentry shock as well as the micro-g environment of space, and it must operate effectively in the reduced pressure of 10 psi. Also the rotation, heat and electromagnetic radiation of the drive cannot affect the experimental environment.

A tape drive is used as opposed to other storage devices because of its cartridge removability, magnetic media, and the fact that it is a tape system. A removable cartridge is easier to retrieve upon return of the cargo than an entire unit. The tape or tapes can simply be removed from the payload and read on another drive. Cartridge removability also provides the possibility of in-flight cartridge exchange for greater capacity. Certain missions may require more data acquisition than others and the number of tapes can be increased rather than changing storage units. The tapes can be changed either by the robotic arm in the payload or by an independent mechanical tape switching system. The advantage to the robotic switching is the ability to choose which tape is inserted for data retrieval and downlink.

Magnetic media is advantageous due to its reliability and capacity although it is vulnerable to damage from strong electromagnetic radiation. Magnetic media have been used for a long time and the technology has grown to be very reliable compared to systems designed specifically for this project. Also, power fluctuations will not affect the already stored data as it would with active electronic storage. The disadvantage to magnetic storage is the vulnerability to electromagnetic interference from other subsystems. A solution to this is to use optical storage, however, the probability of strong enough interference to damage a tape drive's information is not high enough to justify the added bulk and expense of an optical drive.

The use of a tape for storage has many advantages over other technologies such as hard disks or electronic storage. A tape is very insensitive to shock due to the fact that

31

it moves slowly compared to a disk and the head is already on the media so there is no danger of a crash. A tape has high capacity of its size compared to disks or optical drives. A single 3.7 x 2.5 x 0.6 inch tape can store five gigabytes. Due to the slow movement during normal operation and lack of a large rotating mass, the power consumption and heat output are low compared to a hard disk or optical drive and the environment is not greatly affected. A large rotating mass may ruin the microgravity environmentally and high heat output would obviously affect the temperature.

The tape drive being considered is Exabyte's EXB 8205 8 mm Cartridge Tape System (Exabyte, 1991a). The drive is 1.625 x 5.750 x 8.000 inches and weighs 2.57 lbs. It requires fifteen watts of power and has an operating range of -10 to 40 degrees Celsius. The drive has a Mean Time Between Failure (MTBF) of 40,000 hours. The drive accepts a standard Exatape 8 mm Data Cartridge which has dimensions of 3.7 x 2.5 x 0.6 inches and, in the case of the 112 meter tape, a capacity of 5.0 gigabytes (Exabyte, 1991b). The drive comes with the Improved Data Recording Capability (IDRC) compression algorithm which can expand the storage capacity of each tape to a maximum of 25 gigabytes.

The data acquisition computer, like all the subsystems, must have low mass, volume and power consumption. It must operate reliably in the payload's environment and control all the systems efficiently while processing the data. The data acquisition computer must be able to act as the communications link and accept new programming during the mission.

The data acquisition computer that best fulfils the requirements is built by Omnidata and is called the Polycorder. The Polycorder weighs 2.4 pounds and has dimensions of 8.0 x 4.0 x 2.1 inches which gives it a volume of 67.2 cubic inches. It operates in a temperature range of -20 to 50 degrees Celsius and has 448 Kbytes of static RAM for storage of programs and data. Ten single ended analog input

channels are available with two needed for any differential measurements. It is capable of sampling at 76,800 samples per second if a single channel is used and 2,500 samples per second if channels are switched between readings. The unit comes equipped with fifteen digital input and outputs, eight dedicated as input and three dedicated as outputs with 4 programmable as either. It communicates at a baud rate 9600 bps using the XMODEM protocol thorough a RS-232-C serial port. The software used is POLYCODE and it is programmable from a PC, the unit's keypad or from a remote site.

The communication specifications are restricted by the carriers but COMET is the most limiting so these are the specifications considered in design. COMET provides a total of forty minutes per day for all the payloads, it is estimated that this particular payload is allowed 5 minutes per day distributed over eight passes. The uplink rate is 9600 bps using an XMODEM protocol. These are conveniently the same specs as the Polycorder so no translation is required for the uplink of program updates or commands to the Polycorder. The downlink rate is 250 kbps which allows for about 1 second of real time video if no compression is used. This can be increased with the use of various compression methods. COMET may provide compression within its communication system but the U.S. Space Shuttle has no such capability.

One compression technique which can be utilized in communications to provide about 5 seconds of real time video transmission is Differential Pulse Code Modulation (DPCM). This method compresses data on a line by line basis and is based on the concept that values of adjacent pixels are highly correlated. DPCM records the value of one pixel and then predicts the value of the next pixel. The difference between the predicted value and the actual value is usually much smaller than the original value and so it is stored instead. Adaptive techniques of DPCM yield reduction factors of 3 to 5.

The three components discussed are all necessary but can be used in slightly different capacities and relationships with each other and the various subsystems depending on the needs of the particular mission and the capabilities of the equipment. Options to be considered are how the video data is stored and transmitted and where the sensor data is stored.

The video images can either be stored digitally or analogically, either way they are stored on magnetic tape and can be stored directly on the tape without going through the Polycorder. If they are stored digitally, the signal comes directly from the CCD camera without going through an A to D converter. If they are stored analogically the signal is converted and stored on a much simpler system compatible with the video camera only. This eliminates the bulk of the tape drive but also limits transmission options.

Video images must be digital in order to be transmitted through the communication system. The data can come from the tape drive or directly from the camera. In order to retrieve data from the drive the Polycorder must search for the correct data and transmit it from the tape, this prevents any data from being recorded during this time. It becomes even more complicated and lengthy if there is more than one tape. The other option is to transmit directly from the digital output of the CCD camera, however, due to the limitations of the communication rate it would probably be impossible to transmit any real time data this way with acceptable resolution.

Sensor readings must go through the Polycorder and can either be stored there or on the tape drive. The issue here is the amount of information; it is certainly simpler to store the data in the Polycorder but it is impractical if the amount of data exceeds the remaining storage capacity of the Polycorder. Some of the Polycorder's 448 K is taken up by programming, how much depends on the complexity of the program which varies with every mission. One option is to transmit all the sensor

data at each pass to make room for more data.

4.6.4 Subsystem Description

The components described in the previous section will be used aboard C-MASS, however, they will be used in different manners depending upon the mission. Depending upon the amount of data to be taken, two different configurations can be used. In the event that large amounts of data are to be taken, the 8 mm magnetic tape drive will be used. Utilizing a modified tape drive mechanism, two 25 Gbyte tapes can be included, for a total of 50 Gbytes of storage. The other option is to store all sensor data in the 448 Kbyte Polycorder. This method would require that all the sensor data be downlinked periodically instead of permanently recorded aboard C-MASS and that the video images be recorded on video tape. The advantage to the second option is that less volume is used which allows, for instance, more fluid transfer tips to be available. For more information on the subsystem components, see Appendix C.

5.0 VOLUMETRIC MOCK UP

C-MASS was designed to conform to the volume and mass requirements needed to fly on either a shuttle mid deck locker or on the Commercial Experiment Transporter (COMET). A mid deck locker is 10" x 17.3" x 20.3" and experiment space aboard COMET is 11.0" x 14.5" x 16.0", so C-MASS was designed to fly on the more restrictive COMET. Both options allow for an experiment of approximately 70 lbs. The interior volume available (assuming an outer support structure with sides 1/8" thick and attachment to a 1/4" thick plate) was 35.3 L of which less than 15 L was needed to contain the C-MASS subsystems (Table 1). Therefore, the arrangement of the subsystems was not dictated by tight volume constraints, but by the proximity requirements of each subsystem.

5.1 Constraints/Requirements

The following constraints and requirements were used as a guide for positioning each subsystem within the allotted volume:
- Experimental volume and centrifuge must be free to spin
- Fluid transfer mechanism must be within reach of the experimental volume, centrifuge, and syringe storage. It must also be able maneuver about them unobstructed
- 35 mm camera and video camera must access microscope lens and have viewing access to experimental volume
- Sensors need access to experimental volume
- Tape drive requires space to insert and remove tapes
- Subsystems oriented to facilitate support during launch and reentry
- The entire volume is attached to a 0.25" thick plate perpendicular along a 14" x 16" wall leaving a final height of 10.75". The 12 g during launch is perpendicular to this plate.
- Heat producing systems (i.e. electronics, polycorder) grouped together and away from experiments to facilitate thermal control.

These requirements were satisfied by the volumetric mock up and the final configuration was determined after the following trade studies.

5.2 Trade Studies

The above constraints were met by several different arrangements of the subsystems, but the final version was determined by comparing the various options. The most restrictive constraint presented was to allow the fluid transfer mechanism sufficient room to manipulate syringes and reach the specified subsystems. When the experimental volume and centrifuge were placed with their axes parallel to the 10.75" or 14.5" walls, the mechanism had a maximum lateral movement capability. When their axes were parallel to the 16.00" wall there was maximum vertical movement. These subsystems were placed parallel to the 10.75" wall to maximize the room available for the imaging systems and to facilitate support since the 12 g loading during launch and reentry occur parallel to the 10.75" wall. In order to maintain the balance of the centrifuge and ease support of the other subsystems, the axes of the centrifuge and experimental volume were oriented parallel to the direction of the maximum g levels. Orientation of the experimental volume and centrifuge also affected the placement of the cameras and the microscope. The option listed above provided room to place the visual hardware around the experimental volume so the experiments could be viewed directly without the aid of mirrors. Originally, both the centrifuge and experimental volume were to have data acquisition capabilities, however, acquiring measurements from the experiments in the centrifuge posed a problem due to its constant movement. The centrifuge was to be stopped periodically to allow for imaging and sensory data using a system of mirrors to switch the camera between the two volumes. However, alignment problems associated with the mirrors and a need to minimize stoppage led to the decision to only stop the centrifuge for fluid transfers and to only image the experimental volume.

5.3 Subsystem Location and Rationale

34

The trade studies dictated the approximate location of the experimental volume, centrifuge, cameras, sensors and microscope. The remaining task was to fine tune their placement and locate the remaining subsystems in the space available, but out of the way of the fluid transfer mechanism. The experimental volume and centrifuge were placed as far apart as possible to reduce vibrations from centrifuge affecting experimental volume and to allow them to spin freely. A two inch high bar was placed around the experimental volume to support the spectroscopy and pH detectors and any other sensors which do not require direct contact with the experimental fluid (Figures 5-1, 5-2). Inside the volume a ring was placed to hold LEDs for spectroscopy and pH measurements and general lighting. This ring does not spin with the experimental volume, but is attached to the outside or top walls. The experimental volume (7 cm high) was placed on an 8 cm shelf in order to place the top of this volume on the same level as the top of the centrifuge (15 cm high). This was done to make the experimental volume and centrifuge symmetrical about an axis to facilitate programming of the fluid transfer mechanism. The support shelf is wide enough to support the experimental volume, the microscope and the 35 mm camera without interfering with the centrifuge. The polycorder, tape drive and accelerometers fit underneath this shelf (Figures 5-3, 5-4). The microscope was placed on the shelf along with the lenses to place it at the same level as the experiments. The charge-coupling device from the video camera and the lense of the 35 mm camera were placed on the same level and aligned with the microscope (Figures 5-5, 5-6). The tape drive was placed underneath the shelf with sufficient room to transfer disks. The electronics were placed in the back corner to remove them from the fluid transfer arm's path and away from the experiments for thermal reasons. The video camera controls were placed between the electronics and centrifuge. The transfer tip storage was placed in the same corner with no

obstructions above and as near to the centrifuge as possible so that the tips can be accessed by the fluid transfer mechanism. The fluid transfer mechanism was attached to the side walls and move along a track directly above the experimental volume and centrifuge.

5.4 Conclusion

The final volumetric mock up satisfies the main constraints of the subsystems of C-MASS: support, fluid transfer mobility and proximity for imaging systems. This configuration meets the volume and mass requirements for both COMET and a mid-deck locker while supporting all of the hardware required for the C-MASS experiments.

5.5 COST ANALYSIS

In order to determine if C-MASS would be competitive with other similar payloads, a cost analysis was performed. First of all, an estimate of the actual hardware, hardware modifications, and any raw materials necessary to make the modifications was determined. Due to the fact that C-MASS is devoted to the use of off-the-shelf components which are commercially available, obtaining an estimate was fairly simple. The price of the components from each of the subsystems was added together to yield a total hardware price estimate. After this step was completed, the components that required modification were determined. The necessary raw materials were thus obtained and the cost of the modifications estimated. The estimated cost for the actual hardware, including raw materials and modification costs, equals $25,000.

The next step in this process is to determine the personnel required to build the payload. It was assumed that C-MASS will be built in a small business setting. This estimate covers personnel cost for integration and testing. In order to assemble C-MASS and properly test the facility, an electrician, shop technician,

35

project manager, and two other technicians will be required to work full-time for one year. These full-time salaries, including overhead, were estimated at $500,000. Thus, the total cost of construction and testing for C-MASS to produce a flight-qualified version of the payload is estimated at $525,000.

Using this estimate, C-MASS is competitive with other commercially developed space hardware of similar size and function. In addition, C-MASS costs significantly less than similar NASA sponsored projects which take longer to complete.

FIGURE 5-1

Front View of Experimental Volumes and Fluid Transfer
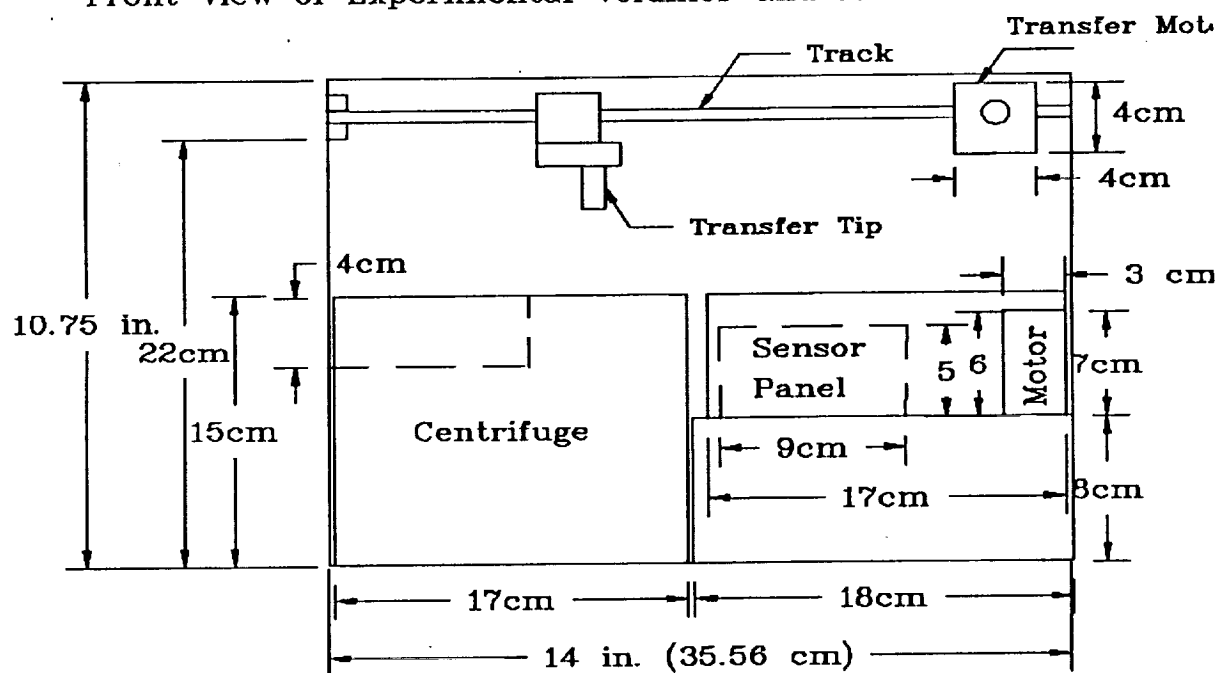
FIGURE 5-1 FRONT VIEW OF EXPERIMENTAL VOLUME
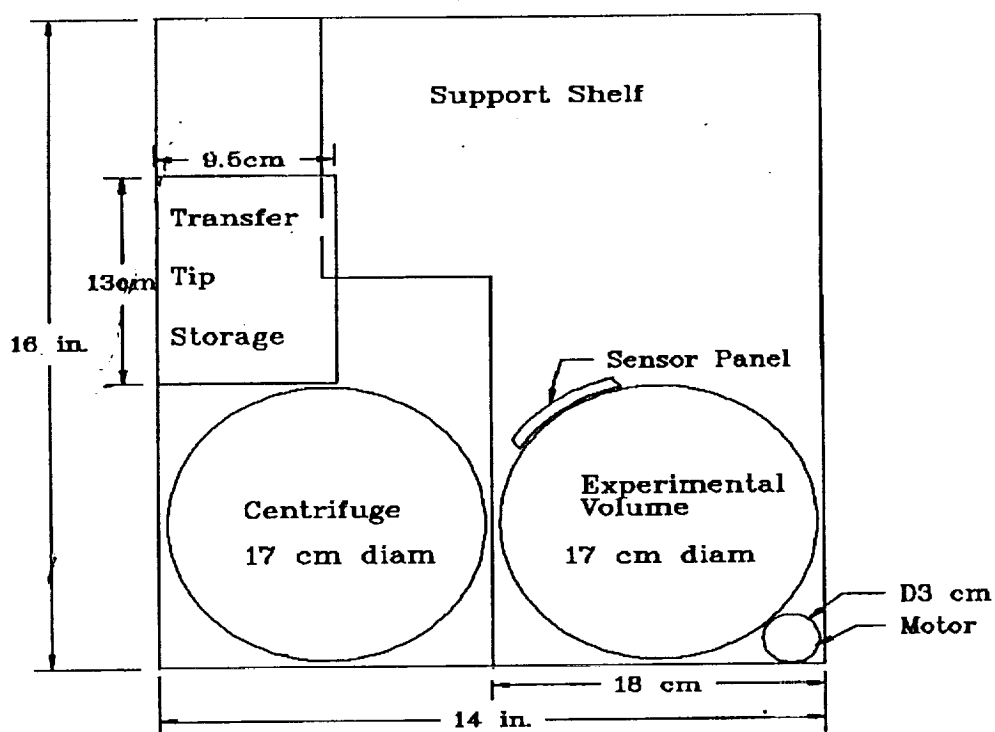
FIGURE 5-2 TOP VIEW OF EXPERIMENTAL VOLUME

Front View (Electronics, equipment under shelf)

10.75 in.

15.5cm

Electronics

9.5cm

18cm

Support
Shelf

8cm

7.5cm
4.5cm

3.5cm

5.5cm

10cm

3cm

14.5cm
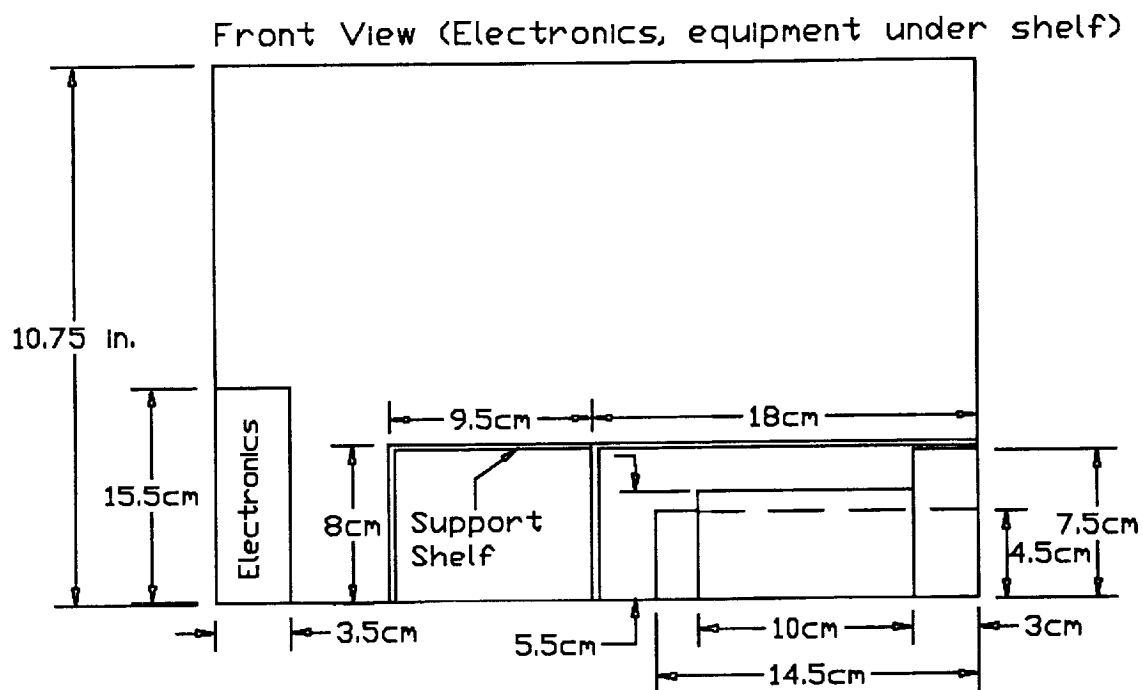
FIGURE 5-3 FRONT VIEW OF ELECTRONICS

FIGURE 5-4
Top View (Beneath shelf - dotted line)

11cm

16 in.

Electronics

Extra
Tapes

10cm

Tape
Drive

14.5cm

24.5cm

20.5cm

Polycorder

Accelerometers
(2 not shown in front view)

14 in.
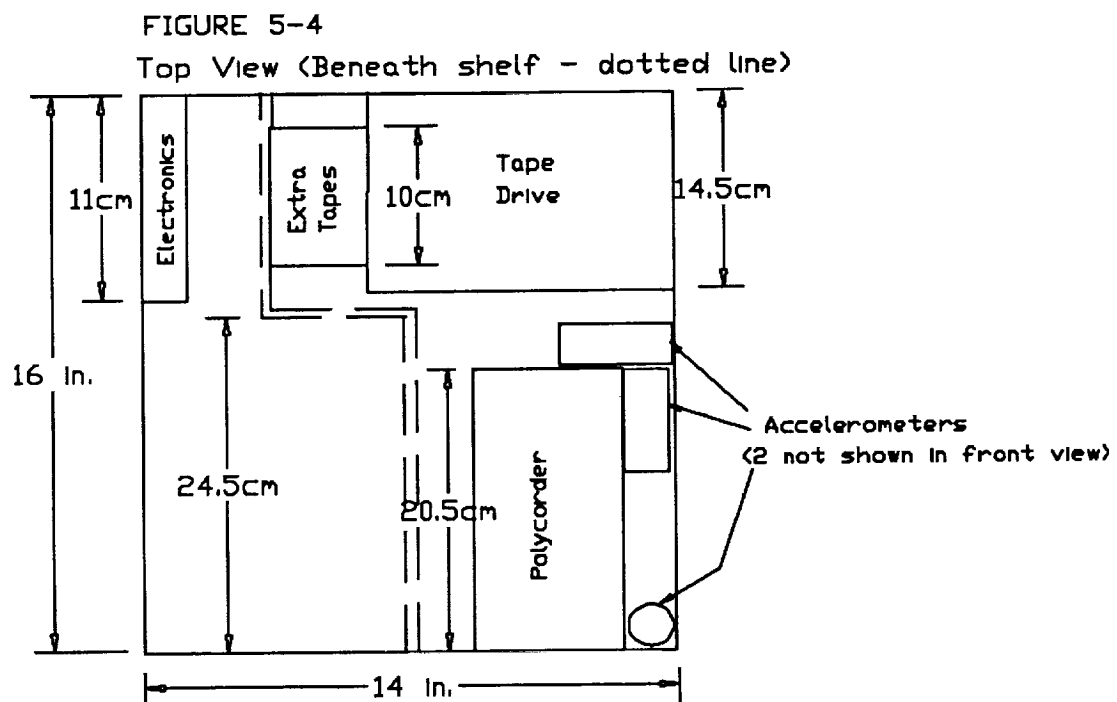
FIGURE 5-4 TOP VIEW OF ELECTRONICS

Top View (Imaging Systems)
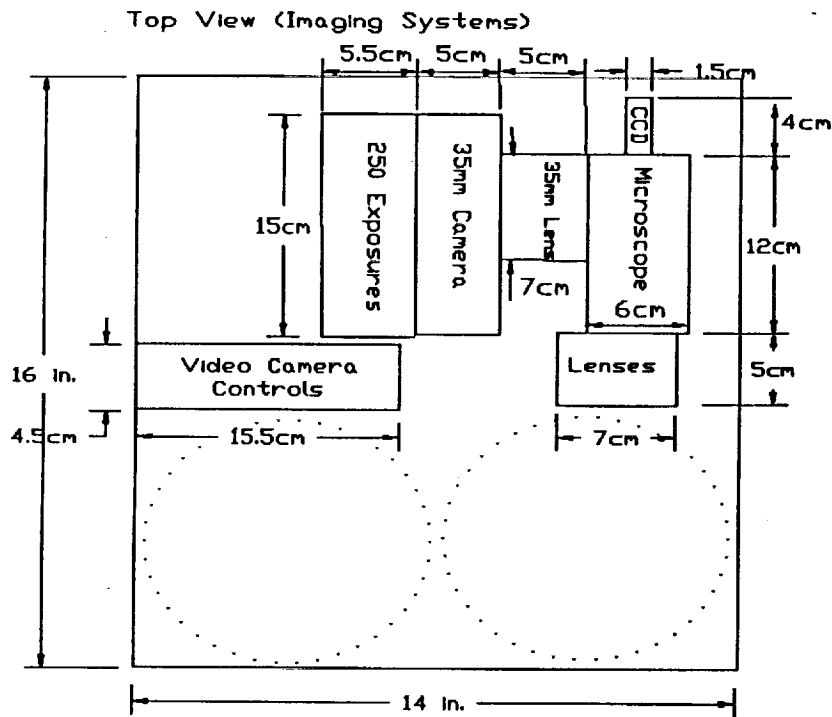
FIGURE 5-5 TOP VIEW OF IMAGING SYSTEM

Front View of Imaging Systems
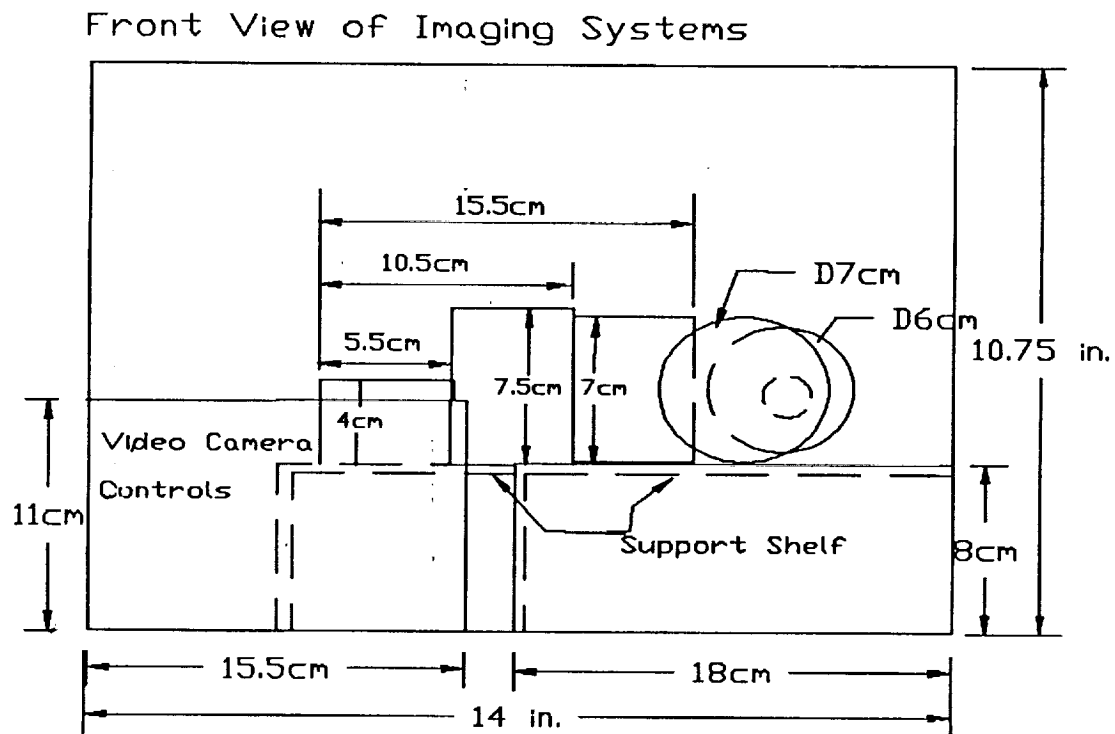
FIGURE 5-6 FRONT VIEW OF IMAGING SYSTEM

6.0   REPRESENTATIVE   SCIENCE EXPERIMENTS

6.1 Introduction

Protocols for several types of experiments were studied during the design of the hardware. The hardware was designed to have the capability to perform experiments on microorganisms and cell or tissue cultures.

The experiments are grouped into two different classes: 1) experiments in which the organisms are transferred to the nutrient and 2) experiments in which the nutrients are transferred to the organisms.

This first type of experiment is for the photosynthetic microorganisms *Chlorella* and *Euglena*, and the two well-studied bacteria *Bacillus Subtilis* and *E. Coli*. The second type is for a mammalian tissue experiment in which ground based studies have been done to prepare for a microgravity mission of the length anticipated.

6.2   Transfer of Organism to Nutrient (Inoculation)

6.2.1 Photosynthetic Microorganisms

Both *Euglena* and *Chlorella* are small, relatively simple and easy to grow. Euglena manufacture chloroplasts and all photosynthetic pigments found in higher plants. When grown in the dark the *Euglena* will lack chloroplasts, but will produce chloroplasts when stimulated with light. Light adaptation requires 12 days for completion, but most changes occur within the first 72 hours. *Chlorella* manufacture chloroplasts and are used as a model for understanding chloroplast development. Both have been studied in microgravity previously, but a longer mission such as one in C-MASS could provide insight into the possible photosynthetic performance of higher plants grown in a microgravity environment in preparation for extended space habitation or for medical uses.

6.2.2 Experimental Procedure

Between 30 and 40 nutrient filled vials will be placed in the hardware prior to launch with approximately 25% of the samples located in the 1 g centrifuge. Growth will be initiated once microgravity has been achieved by introducing a sample of the organisms into one or two experimental vials and one 1 g control vial. They will then be exposed to light. The samples will be exposed to light in a cycle of 12 hours light, 12 hours dark.

An additional experiment for Euglena would place the organisms in a dark environment until they become dark adapted and lack chloroplasts. They would then be exposed to light and their ability to adapt in microgravity recorded.

When the medium is saturated, the fluid transfer mechanism will remove an aliquot of organisms and into another vial containing fresh medium. The first vials will be fixed for post flight analysis. This will produce a time history of the organism growth and show possible adaptations to microgravity.

Data acquisition will consist of 35 mm photography, spectrophotometry of white light absorption for each sample twice during each light period, pH measurements, and temperature.

For the Euglena "light adaptation" experiment, data acquisition will concentrate on the period following light exposure since most changes will occur in the next 72 hours.

6.2.3 Bacteria

A similar type of experiment will be done using *Bacillus Subtilis* and *E. Coli*. The reason for choosing them is that they are small, well-studied, and are expected to be present in space in the future. Both are chemeheterotrophs which require organic molecules both for energy and as a source of carbon skeletons. Both reproduce by binary fission and will double their population every 30 to 60 minutes. This rapid reproduction rate would allow for

multiple generations during a 30 day mission. Researchers could study them for possible adaptation effects to microgravity.

6.2.4 Experimental Procedure

Of the 20 to 30 samples placed in the hardware prior to launch, only one or two would be inoculated initially. After microgravity is achieved, these samples would be initiated and transferred to a fresh medium every 48 to 72 hours. The original samples would then be fixed. This process will be repeated until the end of the mission.

6.3 Transfer of Nutrients to Organisms (Replenishment)

6.3.1 Mammalian Cell

The last experiment contains mammalian cell and tissue cultures. The larger size of the experimental subjects does not allow them to be removed from a vial in which the nutrient has been depleted and inserted into a vial of fresh nutrient.

These experiments are important for learning the effects of long term microgravity exposure on humans. Many possible experiments exist, but the one presented here will study the mineralization rate, cell proliferation and collagen synthesis of bone marrow tissue cultures.

6.3.2 Experimental Procedure

The bone marrow tissue is obtained from the shafts of femurs of 3 month old mice. This tissue culture is affixed to a collagen matrix and placed in the samples filled with Tissue Culture Medium. Ground based experiments showed that a gas phase above the tissue culture and medium was not required, so the vial will be hard filled with medium. These prepared samples will placed in the hardware as close to launch as possible and held at a constant temperature of 37°C.

Once in microgravity, the tissue culture medium must be completely replaced every 72 to 96 hours. At different times, labeling substances will be placed in the medium. A different label is used to study each characteristic of interest.

Mineralization rate of the collagen will be monitored by Strontium-85 which is radioactive and will be incorporated into the compound and mineralize the matrix.

Cell proliferation will be measured by titiaterd thymide (^{3}H-Tdr) which will be incorporated into the DNA of newly forming cells.

Collagen synthesis will be monitored by ^{3}H-proline. This radioactive compound will be incorporated into the collagen formed during the presence of proline in the sample.

Any one sample will receive only one of these labels and will receive it at different times during the mission. The last important point is that all labeling compounds must be removed from the sample after the initial medium is removed. This must be done to provide a reliable time history of the tissue s performance. Only cell performance during the time the label was present should be recorded. the parallel study of the three cell performance rates along with a control experiment will require 30 samples.

Data acquisition will include temperature, radiation and gravity levels, along with measurements of waste products produced in the sample. All samples will be fixed prior to re-entry and detailed analysis of the tissue cultures will occur post-flight.

41

7.0 CONCLUSION

7.1 Payload Growth Potential

C-MASS may be used to perform specific experiments on both one-celled organisms and cultured tissue cells, however, the modularity of this the design allows for simple modifications that can considerably increase its payload variability and experimental capabilities. By changing the sizes and internal configuration of experimental volume containers and the commitments of varied scientific hardware, C-MASS can support experiments that will address issues including embryonic development, invertebrate physiology and microecology.

The embryonic stages of development are particularly sensitive to gravitational effects due to the intense cell proliferation and distribution of genetic information that occur during these periods. Some embryos may also require gravity for alignment or orientation in order to properly develop. C-MASS may already be used to study the development of microorganisms. For larger animals, the small ~3 ml experimental volumes may be removed and replaced with larger ones. Fertilization and embryogenesis in organisms as large as frogs could be studied for periods of up to 30 days with only this change in the size of experimental volume containers.

The same type of modification could allow small invertebrates such as brine shrimp, plankton, or planarian to be studied. These types of organisms occupy important niches in most natural ecosystems. For this reason the life cycles of these organisms are important for future application in controlled ecological life support systems. Some invertebrates have also become highly adapted to particular environments through special behaviors or functional systems also found in higher organisms. This makes them ideal for studying these adaptations and functions without requiring large facilities or complex life support systems. Due to the macroscopic size of many small invertebrates, the commitment to video and camera data may be increased by simply increasing film and tape banks.

With or without larger experimental volumes, entire communities of different species may be introduced into one volume allowing researchers to study microecology under gravity unloading conditions. Microorganisms form the base of most natural ecosystems. Understanding the behavior and competition for resources in a microecosystem in space will benefit CELSS technology in two ways. First, this knowledge can be directly applied to the design of larger systems which use microorganisms to produce or degrade wastes. Secondly, the knowledge can be extrapolated to larger ecosystems which may play important roles in future bioregenerative life support systems.

The modular design of C-MASS facilitates simple modifications that can considerably enhance its research value. The two small modifications discussed here allow for larger organisms to be studied without requiring significant payload alterations. All these experiments can be performed without any modification to other C-MASS subsystems.

7.2 Conclusions

The objective of the Cell Module for Autonomous Space Support (C-MASS) is to provide a means for scientists to easily study microorganisms and tissue cultures under gravity unloading conditions. A preliminary design for C-MASS has been presented which maximizes research value and versatility while minimizing complexity and cost. This design was arrived at through an iterative processes which incorporated the needs of scientists, the requirements of engineers, and the current U. S. Space Exploration Initiative.

C-MASS uses a modular design with subsystems devoted to experimental containment, fluid transfer, sensing, data acquisition, and communications. It may be flown on either a Shuttle middeck locker or on board COMET allowing for varied experiment durations of up to 30 days.

Experiments are performed in 3 ml vials on two carousels. One remains essentially stationary while the other spins to provide a 1-g control environment. Sampling and fluid transfer are accomplished by an automated inoculation mechanism capable of multiple transfers to and from each experimental vial. Sensing systems are capable of monitoring important parameters including temperature, pH, light, gas partial pressures, radiation, gravity level, and vibration. Other data acquisition subsystems allow for optical density measurements, 35 mm photography, and real-time video. Both uplink and downlink capabilities are possible as well as mechanisms for on-board data storage and autonomous operation. Each subsystem is designed with off-the-shelf hardware and proven technology in order to produce a low cost and highly reliable experimental payload. Modularity also allows for payload growth and the incorporation of new technologies as they are made available.

The Space Exploration Initiative (SEI) emphasizes a return to basic research in the areas of space biology and life support systems that will lead to advancements in manned space exploration. It also calls for smaller, cost effective missions with commercial benefits and applications. C-MASS has been designed to conform to both these aspects of SEI. The facility is capable of cheaply and reliably supporting many parallel experiments on one-celled organisms and cultured cells with a 1-g control. The results of these experiments will provide information about the performance of life in outer space on its most fundamental level- the cell. This information can be used to address crew health issues such as bone decalcification, muscle atrophy, immune system response, and proliferation of infectious bacteria on future missions. Information on the performance of microorganisms and small invertebrates may also be used in the creation of future controlled ecological life support systems. C-MASS also has Earth-bound commercial applications. Initial experiments will provide scientists with an understanding of how gravitational

unloading can be used as a tool for biological research and development. The simplicity, low cost, and proven capabilities of this facility will then make it ideal for commercial experiments designed to produce new biological products, such as specially constructed pharmaceuticals or altered organisms. In this way scientists and industry may bypass the costs, time, and experience required in developing space rated experimental payloads by simply using C-MASS directly.

The Cell Module for Autonomous Space Support (C-MASS) is a small, autonomous payload capable of supporting biological experiments on microorganisms. It supports the current Space Exploration Initiative by providing a tool for addressing basic space biology and life support systems issues regarding future manned missions of increased duration. It will also provide access to space for scientists and industries interested in using the advantages of that environment for biological and pharmaceutical purposes. C-MASS represents one small step in a much larger plan to explore and commercialize space; but just as importantly, it is a project, sponsored by the University Student Research Association, that has provided students with a real-world, open-ended, engineering problem requiring a synthesis of engineering experience in an educational environment.

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9.0 APPENDIX

9.1 Appendix A: Launch Vehicle Constraints

Spacehab (using Shuttle Middeck Locker)

Duration:	depends on Shuttle flight length (up to 2 weeks)
Power (payload):	1.4 to 3.15 kW
Ascent/Descent:	625 W
Volume (payload):	Interior = 2.0 cubic feet
Interior dimensions:	9.969 in H, 17.337 in W, 20.320 in D
Mass:(payload)	54 lbs
(payload and locker)	70 lbs
Cooling (payload):	4.0 kW Liquid 2.0 kW Air
Communications (payload):	2 kbps Command 16 kbps Telemetry Available for 1-2 min/day

Random Vibration: Composite = 6.5 g(rms)
    20 - 150 Hz   +6.00 dB/Octave
    150 - 1000 Hz   0.03 g2/Hz
    1000 - 2000 Hz   -6.00 dB/Octave

COMET (COMercial Experiment Transporter)

Duration:	Recovery System: 30 days Service Module: 130 days
Power:	200 W continuous 400 W peak for 200 hrs Ascent/Descent: 100 W for 1 hr (L-10 sec to L+1 hr) AMASS uses: 35 W Ascent/Descent: 25 W PMASS uses: 120 W 140 W peak for ? min
Volume:	Recovery System (pressurized) < 10 ft3 Service Module (unpressurized) < 15 ft3
Mass:	Recovery System: 300 lbs minimum Service Module: 150 lbs minimum
Cooling:	Cold plate removes 1 W/in2 of surface area contact Cold plate removes 400 W total
Communications:	(uplink) 9.6 kbps (interleaved telemetry and video) 250 kbps 40 min data acquisition per day (5 passes/day) PMASS uses (each pass): 6 video images 250 kbps

Random Vibration: Composite = 11.5 g(rms)

10 - 150 Hz	+42 dB/Octave	
150 - 1000 Hz	0.08 g2/Hz	
1000 - 2000 Hz	-32 dB/Octave	

9.2 Appendix B: Additional Science Experiments

Multicellular Experiment: Effects of Microgravity on Fertilization and Embryonic Development of Amphibians and Aquatic Animals.

I. Previous Work
A. Goals
1. To determine if gravity plays a role in an embryo establishing it's Dorso/Ventral axis (5-10 min. duration sounding rocket flights).
2. To see how gravity affects sperm and therefore fertilization rate.
3. Find effects of micro-g fertilization on future embryonic development.
4. Find effects of microgravity on ground-fertilized, maturing embryos.

B. Results
1. Xenopus laevis (South African Clawed Toad)
a. Fertilization shown to occur normally in microgravity
b. Eggs fertilized in microgravity show abnormal embryonic development. It is not clear if this is due to re-entry, microgravity conditions, or other causes.
c. Embryos at stages 12/15 and 47 were subjected to microgravity for 154 hours, where they matured to stages 47 and 48 and showed no ill-effects of microgravity.

2. Sea Urchin eggs - similar to Xenopus, fertilization rate appears to be unaffected in microgravity. Abnormalities also discovered in maturing embryos once returned to earth.

II. Possibilities for Further Research on C-MASS
A. Further Xenopus studies
1. Rationale
a. With longer mission, could allow for fertilization followed by any degree of embryonic development to occur in microgravity.
b. To confirm or deny the fact that fertilization in microgravity results in abnormalities in developing embryo.

2. Science Requirements
a. Life support of eggs/embryos
i. O2 requirements will vary with size and number (approx 1ml/hr total)
ii. Nutrients supply - carbohydrates, proteins, and fats (at T = 18 C)
b. Automated fertilization/fixation in space
i. Egg sizes of .5mm - 5mm
ii. Fertilization in MMR solution

51

Glutaraldehyde as fixative.
iii. Need means of removing sperm from frog
testes and introducing to egg.

B. Pick A New Species To Study
1. Rationale
a. Since these types of experiments done in
liquid medium, they are the obvious next step from
cellular-level experiments.
b. To confirm prior results done with other
species.
2. Requirements of new choice
a. eggs and sperm easily obtainable and species
durable to survive flight.
b. Eggs/embryos of a small but manipulatable
size
c. Extensive literature exists on early
development of species.
3. Candidates include axolotl, squid, starfish, and
mollusks

Effects of Microgravity on Fertilization and Long-Term Effects on Development of Xenopus Embryos.

I. Experiment Description
A. Goals
1.   To confirm previous results that microgravity has
no appreciable effects on fertilization rates in
Xenopus eggs.
2.   Determine effects of an embryo being both
fertilized and matured in a microgravity environment.
3.   If microgravity does affect embryonic development,
determine the stage at which abnormalities begin to
occur.

B. Rationale
1.   Previous Xenopus experiments showed that embryos
fertilized in microgravity incurred abnormal
development upon return to earth. However, it is still
unclear as to whether this was due to re-entry
perturbations, microgravity, or some other factor.
2.   Experiments flown containing ground-fertilized
embryos showed that Xenopus embryos show no ill-effects
of subjection to microgravity during later stages.
However, these stages were post-first cleavage stages
and it still remains to be seen if normal development
can occur through the early stages of embryonic
development.

3. Xenopus frogs easy to obtain and to induce to spawn
(in order to obtain egg and sperm).

C. Procedure
1.   Will fly experiment on long-duration flight

of 10-30 days.

2.   Will utilize the Automated Experiment Container (AEC) as used in earlier experiments as a means for fertilization. (See Refs. 1 and 3)

3.   Larger experimental containers will be used to mature the embryos outside of the AEC's.

4.   Nutrients will be provided and environmental parameters necessary for life will be sustained throughout flight or until fixed.

5. Fixations will take place at multiple stages of development to keep accurate record of developmental progress and developing abnormalities.

6.   1-g centrifuge to be utilized as microgravity control.

II. Pre-Launch Configuration
A. Experimental Setup

1.   Experiment will consist of approx. 20 AECs (as described in Refs. 1 and 3).

2.   Each AEC will have corresponding embryo development containers (approx 20 ml) holding a culture medium conducive to development.

3.   Storage containers for fixative(glutaraldehyde), nutrients, and O2 all isolated.

4. Devices for sampling, fixing, transporting and inserting nutrients, sensors, etc.

B. Requirements on experiment at launch
- If flown aboard Shuttle, AECs must be stored at 9.5 deg. C to slow metabolism of eggs and sperm during long period of time(up to 24 hrs.) between loading and launch.

III. In-Flight Configuration/Procedure
A. Environmental Chambers

1. Upon reaching microgravity with all parameters stable, each of the AECs will be activated to begin fertilization which should be completed within about 10 minutes.

2. Before first cleavage (which occurs about 1 hr. 30 min. after fertilization), the eggs should be transported to their given embryo development chamber.

3. Throughout flight, different experiments will be fixed at different times.

B. Life Support System

1. Nutrient requirements

a. each embryo will require up to 2 microliters of O2/hour

b. other sustaining nutrients - proteins, carbohydrates, fats , etc.

C. Experimental Transport System
>1. Safe transportation of eggs of approx .5 mm dia. from AECs to embryo development containers.
>2. Sterile delivery of nutrients
>3. introduction of fixative to experiments

IV. In-Flight Data Acquisition
>A. Continual
>>1. Temperature - affects rate of embryonic development and if varies too rapidly may be fatal
>>2. Gravity/acceleration - to assure experiment was done completely in microgravity acceleration needs to be measured in three directions to deduce vibrations incurred - esp. during launch and re-entry.
>>3. ph of experimental chambers

>B. Periodic
>>Video monitoring to study swimming habits and to see if they are still alive. Used in conjunction with microscopy.

V. Ground Control/Monitoring
   A. Downlink Requirements
      5 min video daily
   B. Uplink Requirements - tbd

Protocol Chlorella
A. Title
   Long term effects of microgravity on photosynthesis and
   chloroplast development in Chlorella

B. Experimental Description
   1. Goals
      a. understand if and how photosynthesis and
      chloroplast composition are affected by development in
      microgravity over many generations
      b. establish a performance record for *chlorella* in
      microgravity

   2. Rationale
      a. *Chlorella* is small, relatively simple, and easy to
      grow
      b. *Chlorella* manufacture chloroplasts and have been
      used as a model for understanding chloroplast
      development
      c. Viability, cell growth, population growth, and
      biomass production of *Chlorella* have been studied in
      microgravity.

   3. Procedure
      a. grow *Chlorella* to a maximum density in a 2 ml
      environmental chamber for one day
      b. activate plunger to squeeze a small sample of
      organisms into an adjacent 2 ml chamber
      c. move chambers along a conveyor refrigerating the
      mature culture and exposing the new culture to light
      stimulating its growth
      d. repeat procedure for each day or when each culture
      reaches maturity.

C. Prelaunch Configuration
   1. Immobilize 20, 2 ml samples of Chlorella in
   nutrient solution by cold storage 5-10 C
   2. Five samples are located on a 1-g centrifuge
   3. Temperature must be monitored and controlled to
   within 2 degrees C
   4. No other data acquisition, lighting, or fluid
   transfer are required during this phase.

D. In Flight Configuration
   1. Environmental chamber
      a. size allows for 2 ml fluid volume
      b. shape may vary but cylindrical is preferable
      c. no substrate required

d. one area of chamber must be able to accommodate changes in internal fluid volume (e.g.   movable wall)
e. chamber must be made of transparent and biologically nonreactive material
f. an area of at least 1 square cm of the chamber must be devoted to a gas permeable interface

  2. Life support system
     a. Nutrients- each chamber begins with the required nutrients for its culture
     b. Water- each chamber begins with the required water for its culture
  3. Experimental transport system
     a. a transport tube with a one-way valve is used to transfer .1 ml samples of mature culture into an adjacent chamber without organisms each day
     b. a conveyor is used to move mature cultures into a refrigeration unit and new cultures into the light.

E. In Flight Data Acquisition
  1. Continual
     a. Oxygen evolution and carbon dioxide uptake to measure photosynthesis
     b. Light intensity (nominally 100-300 fc continuous)
     c. Temperature to 2 degrees Celsius
     d. Gravity level.

  2. Periodic
     a. Spectrophotometer measurement of white light absorption for each sample four times per day

F. Ground Control/Monitoring
  1. Downlink
     a. some amount of all acquired data each must be downlinked each day to determine the experiment condition and success
  2. Uplink
     a. control of conveyor and fluid transfer must be able to override from earth

G. Post Experimental Configuration
  1. All mature cultures are preserved in cold storage at 5-10 degrees C
  2. Only temperature must be monitored and controlled at this stage

Protocol Euglena

A. Title
  Long term gravitational effects on photosynthesis and chloroplast development in Euglena.

B. Experiment Description

1. Goals
    a. Understand how 1-g affects Euglena's adaptation to light and dark growth
    b. Understand how 1-g affects Euglena s chloroplast development and composition over successive generations
    c. Understand how 1-g affects phototaxy in Euglena.

2. Rationale
    a. Euglena is small, comparatively simple, and easy to grow
    b. Euglena have a short life cycle
    c. Euglena manufacture chloroplasts and all photosynthetic pigments found in higher plants
    d. Dark grown Euglena, absent of chloroplasts, will produce chloroplasts when stimulated with light
    e. Photosynthetic and phototaxic activity of Euglena in microgravity is documented
    f. Light adaptation of Euglena requires 12 days for completion (most change in first 72 hrs).

3. Procedure
    Convert Euglena from dark adaptation to light adaptation many times in 1-g by the addition or deprivation of light.
        a. Observe time required for adaptation by recording photosynthetic activity with spectroscopy
        b. Observe chloroplast development and composition over time
            1. In flight with microscopy, photography and spectroscopy
            2. Post flight with separation techniques for chloroplasts and their constituents.
        c. Observe movement over time using computer scanning with spectroscopy.

C. Prelaunch Configuration
    1. Forty, 1 ml vials (wet volume) of Euglena are immobilized by cold storage at 5-10 C
    2. Half of the vials contain light adapted Euglena and half contain dark adapted Euglena
    3. Ten vials (10 light, 10 dark) are located on a 1-g centrifuge
    4. Temperature must be monitored and controlled to within 2 degrees C
    5. No other data acquisition, lighting, or fluid transfer are required during this phase.

D. In Flight Configuration
    1. Environmental chamber
        a. size allows for 5 ml fluid volume
        b. shape is deep in two dimensions
        c. no substrate required

      d. chamber must be made of transparent and biologically nonreactive material

      e. an area of at least 1 square cm of the chamber must be devoted to a gas permeable interface

  2. Life support system

      a. Nutrient delivery

          1. Water

          2. Nutrient Concentrate

      b. Waste removal

  3. Experimental transport system

      a. Inputs

          1. original transport into chamber and activation

          2. Final fixation of chamber contents

      b. Outputs

          1. six samples taken from each chamber of about 2 ml and fixed

E. In flight data acquisition

  1. Continual

      a. Oxygen evolution and carbon dioxide uptake to measure photosynthesis

      b. Light intensity nominally 100-300 fc at periodicity 12:12. Taken at different depths within sample

      c. Temperature to 2 degrees Celsius

      d. Gravity level

  2. In Flight

      a. Take three samples from each chamber within 72 hrs after light is added to chamber

      b. Photography of a Euglena from 10 viable chambers with 35 mm film at 400x often during first 2 hours after adding light to chamber but infrequently at other times

      c. Spectroscopy of each chamber at least once per hour for each sample

F. Ground Control/Monitoring

  1. Downlink

      a. Microscopic video images twice per day

      b. Spectroscopic data at least twice per day

      c. periodic access to other continual data should be possible

  2. Uplink

      a. All data acquisition and fluid transfer should be able to override if necessary from earth

G. Post experimental configuration

  1. method of preservation

Outline of a Mammalian Cell Space Experiment

A.   AN ASSAY FOR BONE CELL DIFFERENTIATION IN VITRO AS A TOOL FOR MICROGRAVITY STUDIES IN SPACE

B.   EXPERIMENT DESCRIPTION
    1.) Goals:
To develop an in vitro assay for differentiation of osteogenic (bone producing) cells which can be performed in an automated experiment container in space and evaluated after return to earth. The effects studied will be: mineralization rate, Cell proliferation, and collagen synthesis of bone marrow tissue cultures.

    2.) Rationale:
        a. New bone is produced over the entire lifespan but the exact nature and localization of osteo-progenitor cells (those which produce the bone producing cells) in adult tissue is unknown.
        b. This information would be essential for understanding and preventing defects related to bone formation such as may be introduced under microgravity circumstances.

    3.)   Procedure:
        a. Osteogenic cultures in vitro were obtained using bone marrow from 3 month-old mice. Femurs are dissected from anesthetized animals.
        b. The femurs are cleaned and the ends were separated from the midshaft.
        c. The marrow is flushed from the shaft with a needle connected to a syringe and collected on a collagen matrix as a marrow plug without disrupting its three dimensional structure.
        d. The collagen matrix, with the marrow fragment on top, is then placed on a substrate to be inserted into the experimental equipment and enough tissue culture medium (TCM) is placed in the experimental environment to completely submerge the culture.
        e. The TCM consists of BGj-G medium, 10% fetal calf serum, 1% L-glutamine, and 1% gentamycin, and $10-2$ M beta-glycerophosphate.
        f. The cultures are incubated at 37 deg. C.
        g. The TCM is completely changed every 72 to 96 hours.
        h. Mineralization Rate:
            i. Parallel experiments have Strontium-85 introduced at different time periods with the regular exchange of TCM.

ii. It is thought all experiments will be initiated upon entry to microgravity and different cultures will be preserved with fixative after all unincorporated Sr-85 has been removed from the issue culture environment.
iii. The fixed cultures will then be analyzed upon return to earth to determine mineralization rate by measuring the amount of Sr-85 uptake by the tissue cultures at different lengths of time in *in vitro* culture.

i. Cell Proliferation
i. Parallel experiments have titrated thymide (3h-Tdr) introduced at different time periods with the regular exchange of the TCM.
ii. The cells dividing the time the 3H-Tdr is present will die as the radioactive isotope is incorporated into the cells' DNA.
iii. The tissue culture will be fixed after excess 3H-Tdr has been removed from the tissue culture environment. The tissue cultures will be analyzed upon return to earth.

C. PRELAUNCH CONFIGURATION
1. Experiment Set-up and Requirements
This experiment will not require access before launch as the tissue cultures can survive in TCM for 72 to 96 hours before needing to be exchanged, but the cultures should be put into the microgravity environment as soon as possible after being prepared. It is not known if these cultures can be held in suspended animation effectively until microgravity is achieved.

D. INFLIGHT CONFIGURATION
1. Environmental Chamber
a. The envisioned experimental equipment is the sample vial to be used in the experimental volume and centrifuge. The vial will be completely filled with TCM.
b. The tissue culture and collage matrix are affixed to the lower side of the membrane.

2. Life Support System
a. Nutrients are delivery through the membrane which is impermeable to the tissue culture but allows the nutrients, which is introduced above this membrane, to enter the tissue culture environment.
b. Waste removal is accomplished through the membrane as the TCM is exchanged through this

membrane at regular intervals.

   3. Experiment Transport System
        a. Input
                  i. The labelling materials will be introduced
                  through the membrane with the exchange of the
                  TCM.
                  ii. Removal of excess labelling material at
                  the end of the exposure period will be
                  accomplished through the membrane the TCM may
                  have to be exchanged several times to ensure
                  complete removal of labels.
                  iii.   Fixative may also be introduced through
                  the membrane.
        b. Output
        Old TCM, excess labelling materials, and fluid
        used to wash the tissue cultures prior to fixing
        will be extracted through top of the vial by the
        sampling arm.

E. In Flight data Acquisition
   1. Continual
        a. Temperature: the experiments should be held at 37
        deg C.
        b. The standard environmental data: gravity,
        radiation, etc.
   2. Periodic
        a. Photography will not be required
        b. Microscopy will be required only to check tissue
        culture viability.

F. GROUND CONTROL/MONITORING
   1. Downlink requirements, to ensure experimental procedures
   have been completed
        a. Will be required during TCM exchange and labelling
        material introduction and removal
        b. Will be required at fixing for individual tissue
        cultures.

   2. Uplink requirements
        a. Will be required during TCM exchange and labelling
        material introduction and removal
        b. Will be required at time of fixing of individual
        cultures.
        c. Will also be required to initiate experiments if
        they are not all started previous to launch

G. POST EXPERIMENTAL CONFIGURATION
   1. Most or all tissue cultures will be preserved in
   fixative.
   2. No special requirements are seen to be required during
   re-entry for continuing experiments aside from ensure the
   TCM in the experiment is sufficient to support the tissue
   cultures.
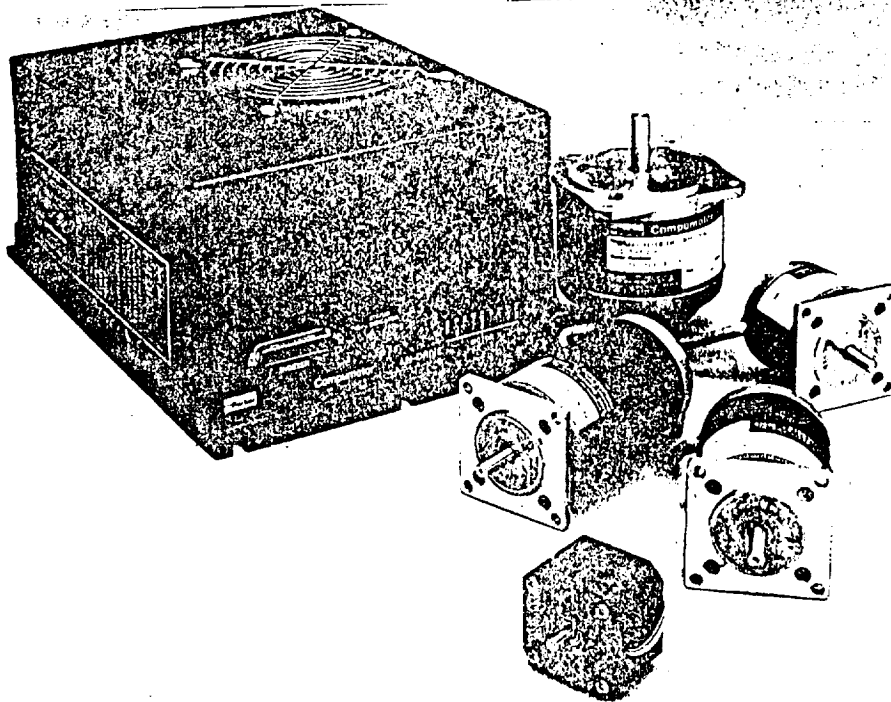
LN Series
Low EMI Microstepping Systems

The LN Series represents the latest advancement in electrically quiet microstepping motor/drive technology. A linear amplifier design is coupled with excellent protection circuitry to produce a highly reliable motion control system that meets FCC Class A EMI criteria.

Its low EMI design allows the LN to significantly outclass PWM drives when in the presence of sensitive instrumentation. The LN is ideally suited to applications requiring high accuracies and smoothness in medical or laboratory environments; such as instrument calibration, semiconductor material measurement, magnetic media certification, servo track writing, and wire bonding.

Dip switch selectable motor/drive resolutions up to 101,600 steps per revolution are combined with high speeds (up to 40 rps), to power five different stepping motor sizes (NEMA 17, 23, 34) with up to 150 oz-in of torque. Long, reliable service life is promoted by short circuit protection, phase to phase and phase to ground, undervoltage and overtemperature protection and full optical isolation on all inputs. The packaged LN is shipped with a fan kit for maximum torque draw at elevated temperatures. A switchable power supply allows input voltages from 90 to 135 VAC or 184 to 275 VAC.

Features
- FCC approved linear amplifier, Class A Digital Device pursuant to Part 15
- Torques from 15 to 150 oz-in
- Full short circuit protection for phase-to-phase and phase-to-ground short circuits.
- Overtemperature and undervoltage protection
- Optically isolated step, direction and shutdown inputs.
- 90-135 VAC/185-275 VAC, 50/60 Hz power input, switch selectable
- 2 MHz maximum step input frequency
- Dedicated optically isolated fault output
- 16 DIP switch selectable motor/drive resolutions (200 to 101600 steps/rev)
- DIP switch selectable motor currents from 0.07 to 2.20 Amps
- Autostandby automatically reduces current by 50%
- LED status indicator: power, undervoltage, overtemperature, motor fault
- Self test DIP switch
- Low power dissipation results in less motor heating
- Replaces the Compumotor LE Series

Options
-E Encoder Option
- 1000 line two phase optical incremental encoder
- Z channel home reference
- Not available on LN43-34

-S Single Shaft Motors
- Not available on LN43-34

Referenced from (Compumotor, 1991)

62

LN Series

Low EMI
Microstepping
Systems

Specifications

Parameter	Value
Performance	
Accuracy	±5 arc min (.0833°) typical
	Unloaded-bidirectional with Compumotor supplied motors. Other motors may exhibit different absolute accuracy.
	±1 arc min (.0167°)
	Loaded-in addition to unloaded accuracy, per each frictional load equal to 1% rated torque
Relative accuracy	±20 arc sec (.0056°), step to step, unidirectional
Repeatability	±5 arc sec (.0014°) typical
	Unloaded-one revolution returning to start point from same direction
Hysteresis	Less than 3 arc min (.0501°) unloaded-bidirectional
Resolution	16 DIP switch selectable choices: 200, 2000, 5000, 10000, 12800, 18000, 20000, 21600, 25000, 25400, 25600, 36000, 50000, 50800, 100000, 101600
Waveform	Switch selectable. Allows shaping, microstepping waveform for optimum smoothness or relative accuracy. Pure sine, -1%, -2%, -3%, -4%, -6%, +1% or +2% 3rd harmonics.
EMI Emmissions	FCC Class A
Motors	
Type	2 phase hybrid permanent magnet. Normally 1.8 degree hybrid type.
Breakdown voltage (HIPOT)	750 VAC minimum
Number of leads	4, 6 or 8
Accuracy grade	3%
Inductance	0.5 mH minimum; 5.0 to 50.0 mH recommended range; 80.0 mH max
Amplifier	
Type	Linear amplifier
Weight	16.4 lbs (7.34 kg)
Number of phases	2
Protection*	
Short circuit*	Phase to phase, phase to ground
Brownout	If AC supply drops below 90/180 VAC, depnding on supply
Overtemperature*	Internal air temperature exceeds 158°F (70°C)
Autostandby	Switch selectable. If selected, motor current ramps to 50% of preset value if no step pulses are received for 1 second. Rated current levels are resumed upon receipt of next step pulse.
Self test	Switch selectable. This feature (used primarily for testing and verification of correct wiring) rotates the motor at approximately 1 revolution/second for 6 revolutions in the CCW direction and 6 revolutions in the CW direction.
Drive shuts down in conditions listed. Power must be cycled to resume operations.	
Power Input	
Volts	90-135/184-275 VAC, switch selectable
Frequency	50/60 Hz
Current	1.5 Amps
Environmental	
Operating	32° to 104°F (0° to 40°C)
Drive	Maximum allowable ambient temperature is 104°F (40°C). Fan cooling is standard.
Motor	212°F (100°C) maximum motor case temperature. Actual temperature rise duty cycle dependent.
Storage	-40° to 185°F (-40 to 85°C)
Humidity	0-95%, non-condensing
Inputs	Optically isolated, 6.5 mA minimum, 15 mA maximum
Step input	High going pulse, 300 μsec min width. Max pulse rate is 2 MHz.
Direction	Logic High = CW rotation (300 μsec delay required after last step pulse and before next pulse for each direction change)
Shutdown	Logic High = amplifier disable (100 ms setup time)
	Logic Low = normal operation (100 ms before first step)
Output	Optically isolated
Fault	Open collector, open emitter, 15 mA min, Vce = 30 VDC, 300 mA max

Referenced from (Compumotor, 1991)

Motor Data

Motor Data		Size 17 LN43-34	Size 23 LN57-51	LN57-83	LN57-102	Size 34 LN83-62
Static torque						
oz-in		14	65	100	130	150
(N-m)		(0.10)	(0.46)	(0.71)	(0.91)	(1.05)
Rotor inertia						
oz-in²		0.081	0.48	1.28	1.75	3.50
(kg-cm²)		(0.015)	(0.088)	(0.234)	(0.320)	(0.64)
Bearings						
Thrust load	lb	—	25	25	25	50
	(kg)	(—)	(11.3)	(11.3)	(11.3)	(22.6)
Radial load	lb	—	15	15	15	25
	(kg)	(—)	(6.8)	(6.8)	(6.8)	(11.3)
End play	in	0.004	0.005	0.005	0.005	0.005
Reversing load (cm)		(0.010)	(0.013)	(0.013)	(0.013)	(0.013)
Equal to 1 lb						
Radial play	in	0.0008	0.0008	0.0008	0.0008	0.0008
Per 0.5 lb load (cm)		(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Weight (net)						
Motor+Cable						
+Connector	lb	.87	1.6	2.4	3.2	3.8
	(kg)	(0.39)	(0.7)	(1.1)	(1.5)	(1.7)

Speed/Torque Curves

LN43-34 Size 17-1 Stack Motor

LN57-51 Size 23-1 Stack Motor

LN57-83 Size 23-2 Stack Motor

LN57-102 Size 23-3 Stack Motor

LN83-62 Size 34-1 Stack Motor
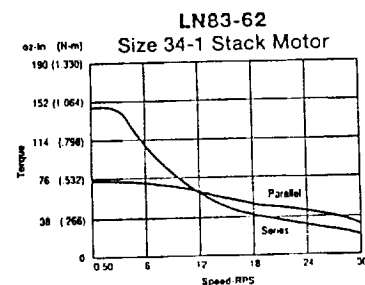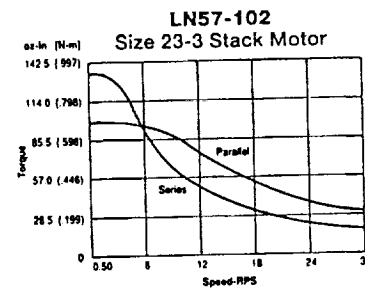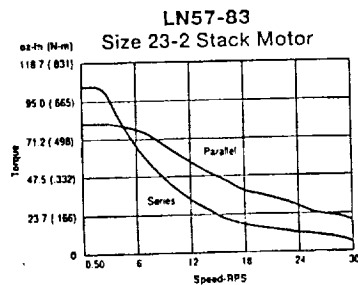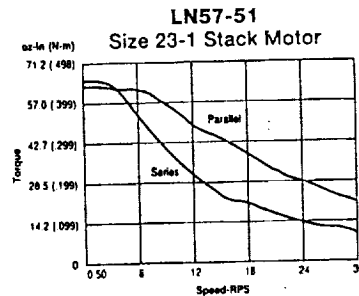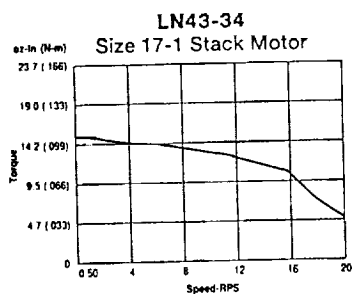
Referenced from (Compumotor, 1991)

LN Series

Low EMI
Microstepping
Systems

Dimensions (—) denotes millimeters

LN43-34
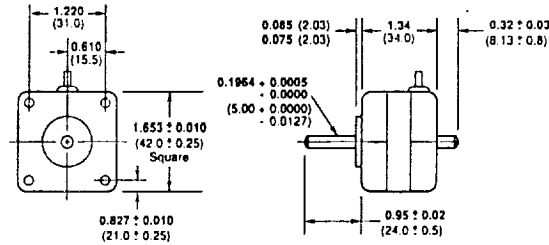
Size 23

Model	A
LN57-51	2.0 (50.8)
LN57-83	3.1 (78.4)
LN57-102	4.0 (101.6)
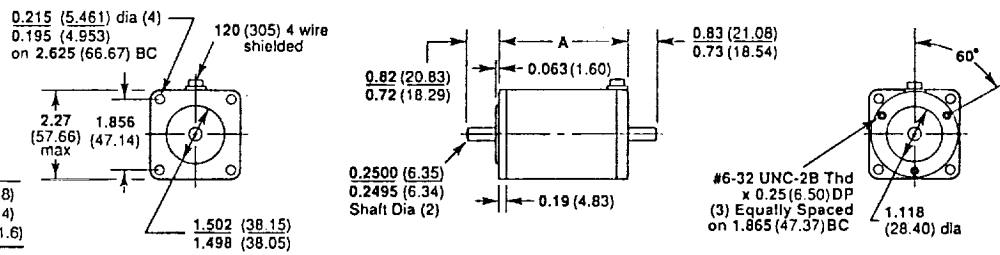
Size 34

Model	A
LN83-62	2.5 (63.5)
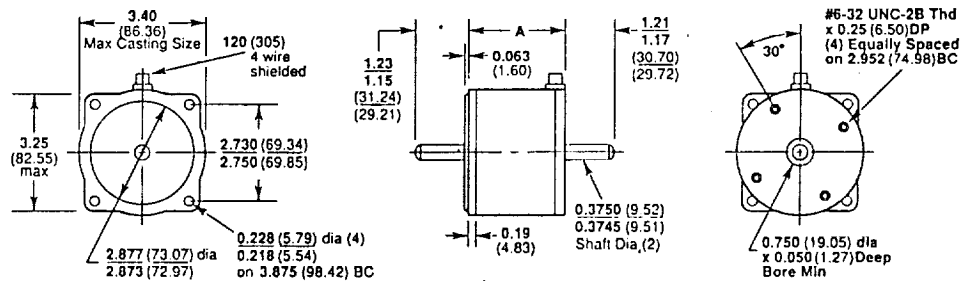
LN Drive Dimensions (—) denotes millimeters
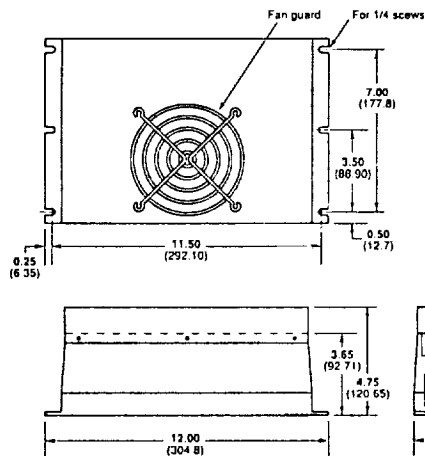
Drive Connections

Motor 9 Pin Phoenix		Indexer 25 Pin "D"	
Pin No.	**Signal**	**Pin No.**	**Signal**
1	INLK	1	Step +
2	A-Ct	2	Direction +
3	A +	9	Fault +
4	A –	14	Step –
5	Earth	15	Direction –
6	B +	16	Shutdown +
7	B –	17	Shutdown –
8	B-Ct	21	Fault –
9	INLK		

Referenced from (Compumotor, 1991)

65

$\mathbf{BA}$ SERIES

SUPERSMALL SYNCHRONOUS MOTOR
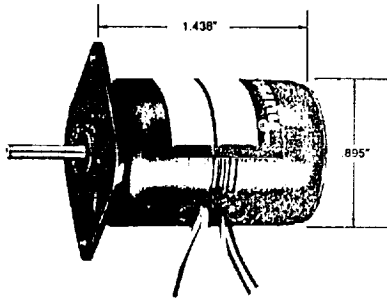
This instrument-grade, SUPERSMALL, synchronous motor is reversible and operates at 720 rpm on 115 VAC, 60 Hz. It weighs just 2.1 ounces and is less than an inch in diameter.

Rated torque is 0.625 ounce-inch and normal operating temperature rise is 30°C.

The new BA Series synchronous motor is a practical solution to control problems in equipment where space is at a premium. It also is suited to products employing variable frequency AC controls.

Dimensional drawing is shown on page 45.

NOTE

1. Capacitor is furnished with motor. 115V

WIRING DIAGRAM

BLUE — RED — CAP — BLACK

S.P.D.T.
REVERSING
SWITCH
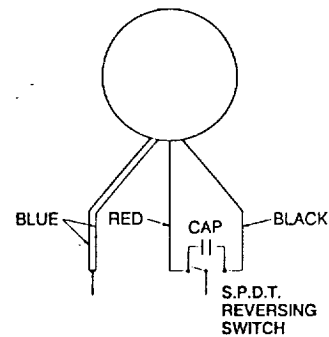
Current applied to the blue and red leads produces CW rotation. Switching the current to the blue and black leads produces CCW rotation. For dual speed versions switching the current produces a change in speed but not in direction of rotation. Direction of rotation must be specified separately.

SPECIFICATIONS:

MODEL	PART NUMBER	STOCK ITEM	SPEED @ OUTPUT SHAFT (rpm)	RATED TORQUE (oz-in)	INPUT POWER (watts)	CAPACITOR VALUE (mfc)	FULL LOAD TEMPERATURE RISE (°C)	WEIGHT (oz)	SHAFT BEARING
BA	4201-001	YES	720	0.625	1.5	0.15 ± 10% 400 VDC	30	2.1	SLEEVE

Referenced from (Emerson Electric Company, 1990)

MODEL 5100 ACCELEROMETER
LOW FREQUENCY - HIGH OUTPUT

Industrial accelerometer designed for industrial mills and plants with low RPM machinery that require low frequency and high sensitivity specifications. The 5100 features rugged top connector, internal isolation, splash-proof construction along with the ability to measure 5 RPM and 10μg vibrations. Internal electronics will allow cable runs up to 1000 feet.

Operating Specifications

Sensitivity ±5% @ 100Hz	500 mv/g
Frequency Range ±5%	0.5 Hz to 500 Hz
±3 db	0.1 Hz to 1000 Hz
Amplitude Range	±10 g
Transverse Sensitivity	7% maximum
Case Noise Rejection	-50 db
Maximum Shock without damage	5,000 g
Mounted Resonant Frequency (nom.)	2.5 KHz
Bias Voltage (nom.)	7 v
Output Impedance	1,000Ω
Isolation	Internally Isolated

Operating Specifications (cont'd.)

Noise Floor (rms)	20 microvolts
Power Requirements	15-30 vdc, 1-4 ma constant current

Physical Specifications

Size (inches)	2.97" high x 1.25" dia
Weight	9.5 oz.
Connector	Top TNC
Material	303 Stainless Steel
Mounting	1/4 - 28 Stud (removeable)
Weatherseal Rating	Splash-Proof
Temperature	-65° to +250°F

Model 5100
Outline Drawing

TNC Connector —

MODEL 5100

2.97"

1/4-28 x .25"
removeable stud —

1.25"

Model 5100
Typical Frequency Response

±5%

±3db

0.5Hz   500Hz   2500Hz
0.1Hz   1000Hz

Accelerometers and instrumentation for vibration monitoring, quality control, modal analysis and structural testing.

Referenced from (Vibra Metrics, 1992)

SIEMENS

<div align="right">

BPW 33
SILICON PHOTODIODE
</div>

Package Dimensions in Inches (mm)

Maximum Ratings

Reverse Voltage (V_R) .... 7 V
Storage Temperature Range .... −40 to +80 °C
Soldering Temperature in a 2 mm Distance
from the Case Bottom ($t \leq 3$ s) (T_S) .... 230 °C
Power Dissipation ($T_{amb} = 25$ °C) (P_{tot}) .... 150 mW

FEATURES

• Very Low Dark Current, 20 pA
• Silicon Planar Photodiode
• Transparent Plastic Package
• 2/10″ Lead Spacing
• High Sensitivity, 75 nA/lx
• Light Measuring Applications
• Lead Bend Option (for SMD)

DESCRIPTION

The BPW 33 is a large area silicon planar photodiode, which is incorporated in a transparent plastic package. Its terminals are soldering tabs, arranged in 5.08 mm (2/10″) lead spacing. Because of its design the diodes can also very easily be assembled on PC boards. The flat back of the epoxy resin case makes rigid fixing of the component feasible.

The BPW 33 has been developed as a detector for low illuminances and is intended for use as a sensor in exposure meters and automatic exposure timers. The component is outstanding for high open circuit voltage at low illuminances. The cathode is marked by an orange dot.

Characteristics ($T_{amb} = 25$ °C)

Photosensitivity (V_R = 5 V, Note 1)	S	75 ($\geq$ 35)	nA/lx
Wavelength of Max. Photosensitivity	λ_{Smax}	800	nm
Spectral Range of Photosensitivity	λ	350...1100	nm
Radiant Sensitive Area	A	7.34	mm²
Dimensions of the Radiant Sensitive Area	L × W	2.71 × 2.71	mm
Distance Between Chip Surface and Package Surface	H	0.5	mm
Half Angle	φ	± 60	Deg
Dark Current (V_R = 1 V)	I_R	20 ($\leq$ 100)	pA
Zero Cross Over (E_V = 0 T_{amb} = 50 °C, Note 2)	S_0	$\geq$ 20	pA/mV
Spectral Photosensitivity (λ = 850 nm)	S	0.59	A/W
Quantum Yield (λ = 800 nm)	η	0.86	Electrons / Photon
Open Circuit Voltage (E_V = 1000 lx, Note 1)	V_0	440 ($\geq$ 375)	mV
Short Circuit Current (E_V = 1000 lx, Note 1)	I_{SC}	72 ($\geq$ 35)	μA
Rise and Fall Time of the Photocurrent from 10% to 90% and from 90% to 10% of the Final Value (R_L = 1 KΩ, V_R = 5 V, λ = 830 nm I_P = 70 μA)	t_r, t_f	1.5	μs
Forward Voltage (I_F = 100 mA, E_a = 0 T_{amb} = 25 °C)	V_F	1.3	V
Capacitance (V_R = 0 V, E = 0, f = 1 MHz)	C_0	630	pF
Temperature Coefficient of V_0	TC_V	−2.6	mV/K
Temperature Coefficient I_K	TC_I	0.2	%/K
Noise Equivalent Power (V_R = 1 V)	NEP	4.3 × 10⁻¹⁵	$\frac{W}{\sqrt{Hz}}$
Detection Limit (V_R = 1 V)	D	6.3 × 10¹³	$\frac{cm \sqrt{Hz}}{W}$

¹ The illuminance indicated refers to unfiltered radiation of a tungsten filament lamp at a color temperature of 2856 K (standard light A in accordance with DIN 5040 and IEC publ. 306·1)

² S_0 is a measure for the lower spectral sensitivity when the photodiode is used in exposure meters. The zero cross over S_0 is defined in the diagram.

<div align="center">

Referenced from (Siemens, 1990)

68
</div>

Referenced from (Siemens, 1990)

69

Package Dimensions in Inches (mm)
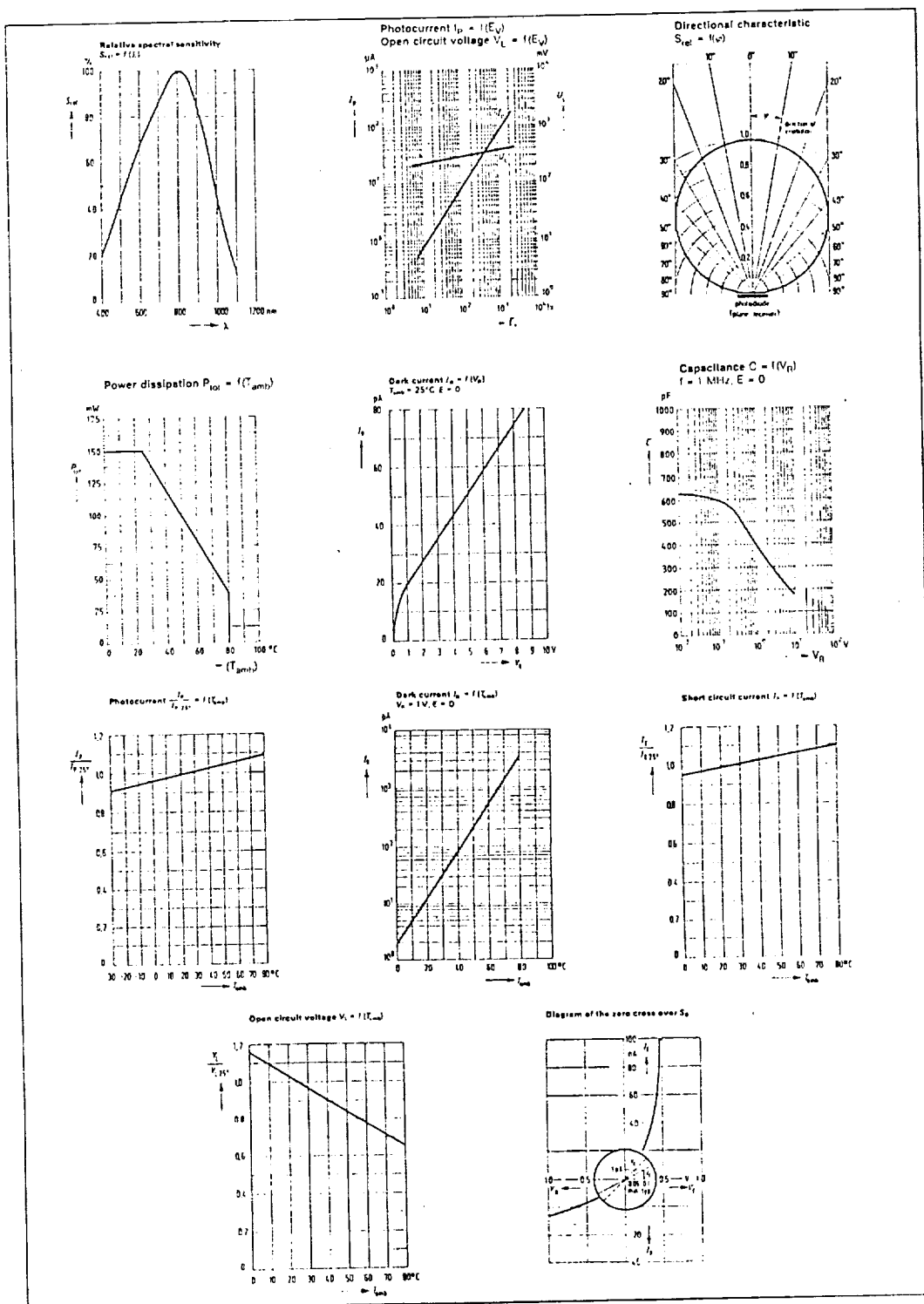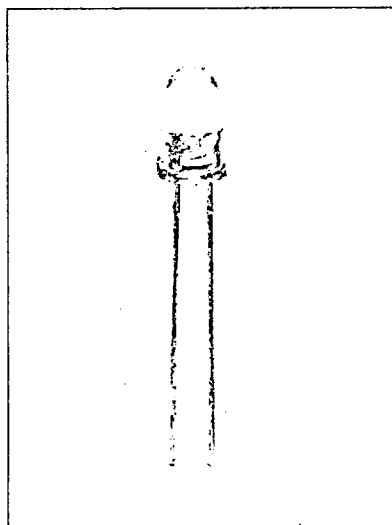
FEATURES

* Three Radiant Intensity Groupings
* Low Cost
* T1¾ Package
* Lightly Diffused Gray Plastic Lens
* Long Term Stability
* Narrow Beam, 20°
* Excellent Match to Silicon Photo-detector BP103B

DESCRIPTION

The GaAs infrared emitting diode LD 274 emits radiation at a wavelength in the near infrared range. It is enclosed in a T 1¾ plastic package of 5 mm diameter. This device is designed for remote control applications requiring extremely high power.
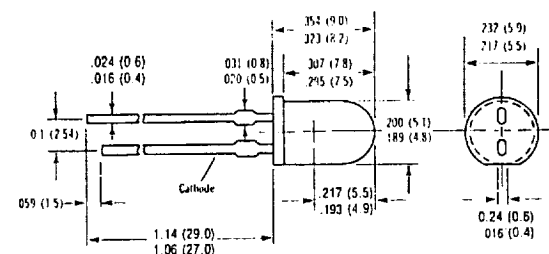
Maximum Ratings

Storage temperature	T	− 55 to + 100	°C
Soldering temperature			
Distance from casing-solder tab ≥2mm			
Dip soldering time ≤5s	T$_{sold}$	260	°C
Iron soldering time ≤3s	T$_{sold}$	300	°C
Junction temperature	T$_j$	100	°C
Reverse voltage	V$_R$	5	V
Forward current	I$_F$	100	mA
Surge current (τ = 10μs)	I$_{FS}$	3	A
Power dissipation (T = 25°C)	P$_{tot}$	165	mW
Thermal Resistance	R$_{thA}$	450	K/W

Characteristics (T$_{amb}$ = 25°)

Wavelength at peak emission at			
I$_F$ = 100 mA, tp = 20ms	λ$_{peak}$	950 ± 20	nm
Spectral bandwidth at 50% of I$_{max}$			
at I$_F$ = 100mA, t$_p$ = 20 ms	Δλ	55	nm
Half angle	φ	± 10	Deg
Active chip area	A	0.09	mm²
Dimensions of active chip area	L × W	0.3 × 0.3	mm
Distance chip surface to case surface	D	4.9 to 5.5	mm
Switching time			
(I$_e$ from 10% to 90%; I$_F$ = 100mA)	t$_r$,t$_f$	1	μs
Capacity (V$_R$ = 0 V)	C$_o$	25	pF
Forward Voltage (I$_F$ = 100mA)	V$_F$	1.30 (≤1.5)	V
(I$_F$ = 1A; t$_p$ = 100μs)	V$_F$	1.9 (≤2.5)	V
Breakdown voltage (I$_R$ = 100 μA)	V$_{BR}$	30 (≥5)	V
Reverse current (V$_R$ = 5V)	I$_R$	0.01 (≤1)	μA
Temperature coefficient of I$_e$ or Φ$_e$	TC	-0.55	%/K
Temperature coefficient of V$_F$	TC	-1.5	mV/K
Temperature coefficient of λ$_{peak}$	TC	+ 0.3	nm/K

Radiant intensity I$_e$ in axial direction at a steradian Ω = 0.01 sr, or 6.65°.

Radiant Intensity I$_E$ In Axial Direction Measured at a Solid Angle of Ω = 0.01sr

Group	LD 274-1	LD 274-2	LD 274-3	
Radiant Intensity I$_e$				
(I$_F$ = 100 mA, T$_p$ = 20 ms)	30-60	50-100	≥ 80	mW/sr
(I$_F$ = 1 A, T$_p$ = 100 μs)	335	560	675	mW/sr
Total Radiant Flux Φ$_F$				
(I$_F$ = 100 mA, T$_p$ = 20 ms)	10	12	14	mW

Referenced from (Siemens, 1990)

Referenced from (Siemens, 1990)

71
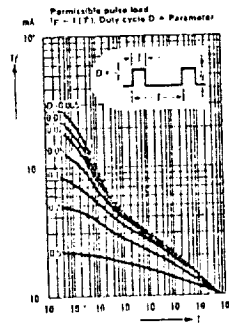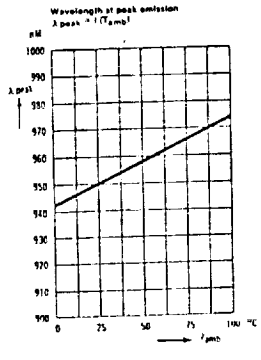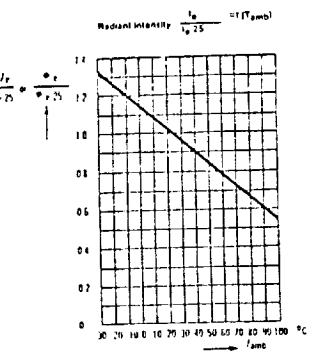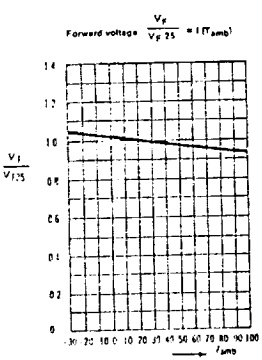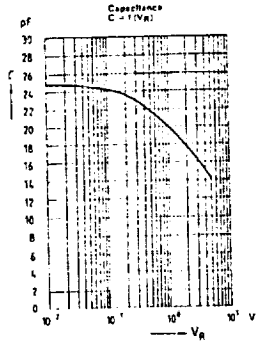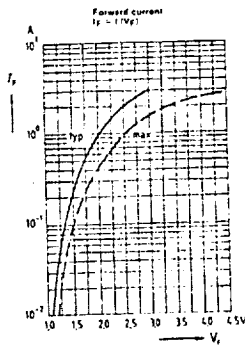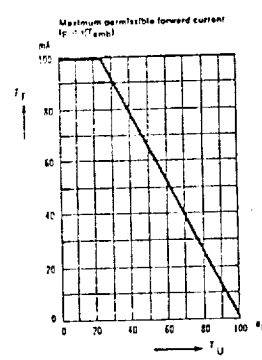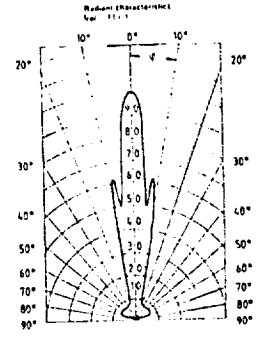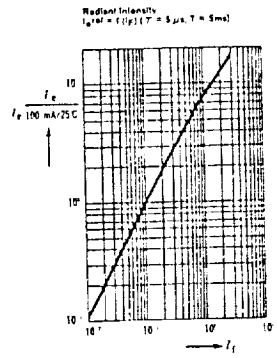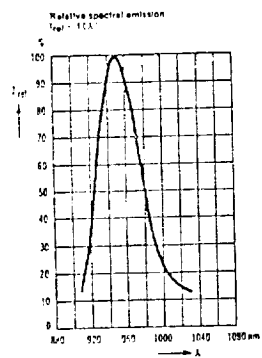
UV AND BLUE-ENHANCED SERIES

UV and Blue-Enhanced Silicon Photodetectors
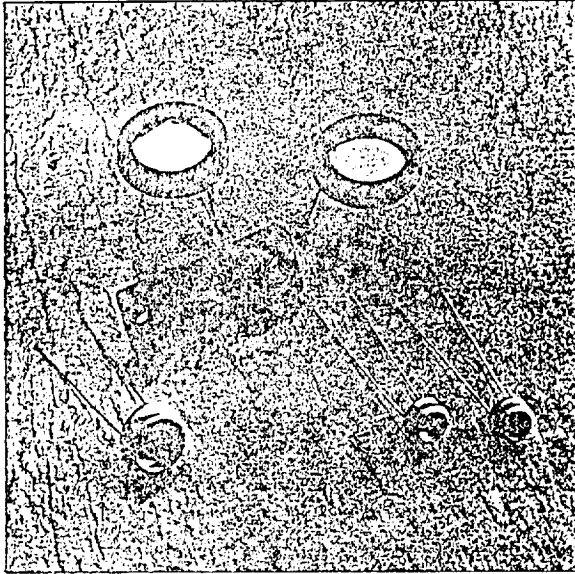
Recent advancements in UDT Sensors' silicon photodiode technology have made possible greatly increased performance and stability in the UV/Blue spectral range.

Two families of devices are available: blue enhanced, optimized for operation in the range of 350 to 1100 nanometers; and inverted channel UV enhanced, optimized for 200 to 400 nanometer use.

The inverted channel structure of UV enhanced photodiodes provides resistance to damage from high energy UV irradiance.

UV exposure tests performed by UDT Sensors and other respected laboratories have proven that UDT UV enhanced photodiodes have the highest reliability and stability of any devices now available.

UV SERIES

Inverted channel UV detectors represent the newest technology in UV devices, both in responsivity (in the 200 to 400 nm range), and unparalleled stability under extended exposure to high-intensity UV radiation. All types have quartz windows to minimize loss in the UV spectral range.

PIN-5DP/SB, 10DP/SB, 10DPI/SB 220DP/SB

Blue enhanced detectors are optimized for near UV to visible (300 to 500 nm) to provide optimized signal-to-noise ratio over a wide dynamic range.

FEATURES

- Photovoltaic (Unbiased)
- Ultra-High Shunt Resistance
- Ultra-Low Noise
- Excellent Responsivity at 250mm
- All Units Are Burned in for Stability and Reliability
- All Devices Have Quartz Windows

APPLICATIONS

- Spectrometers
- Colorimeters
- Densitometers
- Medical Instrumentation
- Fluorescent Analysis
- UV Exposure Meters
- UV Chemical Analysis
- Laboratory Standards

Referenced from (UDT Sensors, 1992)

72

TYPICAL SPECTRAL RESPONSE

(Chart: Responsivity – Amperes/Watt vs Wavelength – Nanometers, showing UV Enhanced, Blue Enhanced, and Normal Photovoltaic curves across Ultraviolet, Visible and Infrared regions)
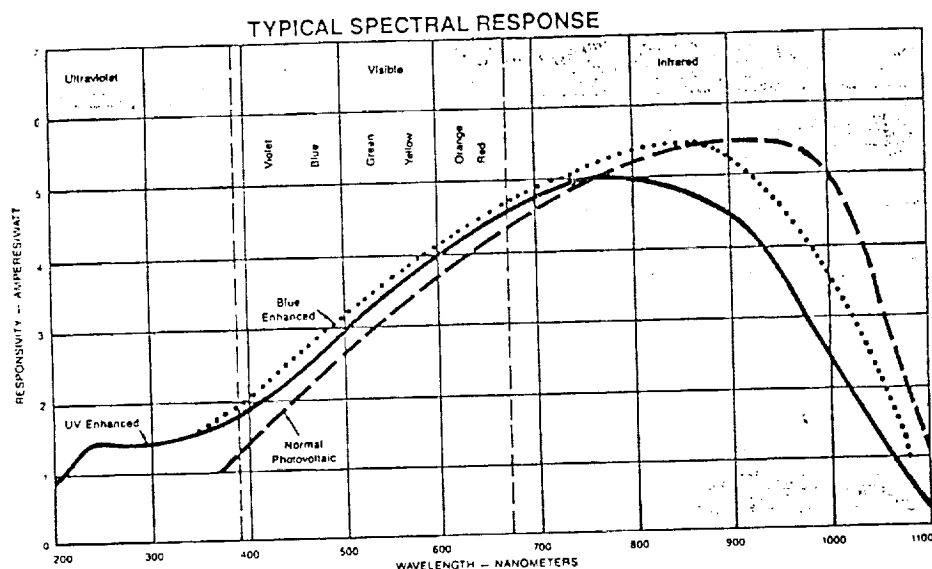
Typical @ 22°C

UV ENHANCED SERIES SPECIFICATIONS

MODEL #	ACTIVE AREA (mm²)	ACTIVE DIA. (INCHES)	RESPONSIVITY @ 254 nm (A/W)		Cj @ 0V (pf)	Rsh (MΩ) TYP.	NEP (w/√Hz)	Tr (μsec)	Isat* (mA)	OPERATING & STORAGE TEMP.	
			MIN.	TYP.						OPERATING	STORAGE
UV001	0.81	040	0.1	0.14	60	500	4×10^{-14}	0.2	0.1	−55 to 125	−65 to 150
UV005	5.1	0.10	0.1	0.14	300	100	8×10^{-14}	0.9	0.1	−55 to 125	−65 to 150
UV015	15	12x.15	0.1	0.14	1425	100	2×10^{-13}	2.0	0.1	−55 to 125	−65 to 150
UV20	20	0.20	0.1	0.14	1000	50	10^{-13}	2.0	0.1	−55 to 125	−65 to 150
UV35	35	28x.24	0.1	0.14	1600	30	1.5×10^{-13}	3.0	0.1	0 to 70	−25 to 85
UV35P	35	.28x.24	0.1	0.14	1600	30	1.5×10^{-13}	3.0	0.1	0 to 70	−25 to 85
UV50	50	0.31	0.1	0.14	2500	20	1.8×10^{-13}	3.5	0.1	−55 to +125	−85 to 150
UV50L	50	0.31	0.1	0.14	2500	20	1.8×10^{-13}	3.5	0.1	−55 to +125	−65 to 150
UV100	100	0.444	0.1	0.14	4500	10	2.5×10^{-13}	5.9	0.2	0 to 70	−25 to 85
UV100L	100	0.444	0.1	0.14	4500	10	2.5×10^{-13}	5.9	0.2	0 to 70	−25 to 85
FIL-UV005	5.1	0.10	0.1	0.14	300	100	8×10^{-14}	0.9	0.1	−55 to +125	−65 to 150
FIL-UV20	20	0.20	0.1	0.14	1000	50	10^{-13}	2.0	0.1	−55 to +125	−65 to 150
FIL-UV50	50	0.31	0.1	0.14	2500	20	1.8×10^{-13}	3.5	0.1	−55 to +125	−85 to 150
FIL-UV100	100	0.444	0.1	0.14	4500	10	2.5×10^{-13}	5.9	0.2	0 to 70	−25 to 85

*Saturation current may be increased by a factor of approximately 10 (to 2-4mA) by applying a reverse bias of 2-5 volts.
"P" suffix on model number indicates plastic package. "L" suffix on model number indicates isolated low profile package.

Typical @ 22°C

BLUE-ENHANCED SERIES SPECIFICATIONS

MODEL #	ACTIVE AREA (mm²)	ACTIVE DIA.	RESPONSIVITY @ 410 nm (A/W)		Cj @ 0V (pf)	Rsh (MΩ) TYP.	NEP (w/√Hz)	Tr (μsec)	Isat* (mA)	OPERATING & STORAGE TEMP.	
			MIN.	TYP.						OPERATING	STORAGE
PIN-5DP/SB	5.1	0.10	0.15	0.2	450	150	7×10^{-14}	0.2	2.0	−55 to 125	−65 to 150°c
PIN-10DP/SB	100	0.444	0.15	0.2	8800	10	4.5×10^{-14}	0.5	10.0	0 to 70	−25 to 85
PIN-10DPI/SB	100	0.444	0.15	0.2	8800	10	4.5×10^{-14}	0.5	10.0	0 to 70	−25 to 85
PIN-220DP/SB	200	0.39 x 0.79	0.15	0.2	17000	5	2.5×10^{-13}	2.0	10.0	0 to 70	−25 to 85

Referenced from (UDT Sensors, 1992)

73

PIN-5DP/SB

ANODE

CATHODE

36 DIA 325 DIA

018

180

15

TO-5

*PIN-10DP/SB, UV50, UV100

098 DIA 0 70 DIA

0175

039   047

625

BNC

PIN-220DP/SB

SILICON PHOTODIODE ACTIVE AREA 1 CM x 2 CM

ANODE PIN

GLASS WINDOW

CATHODE PIN

1 252

45   1 575

56

161

313

626

209

65

1X2cm PLASTIC

UV20, UV35

550 DIA 490 DIA

ANODE

CATHODE

020

195

1 50

TO-8

UV001, UV005, UV015

240 WINDOW APERTURE

45°

CATHODE

030 040

325   200

360

ANODE

42° FOV

040 DIA. MAX   018/ 019 DIA.

025 ± 010/007

015   015

100 ± 015 (DIM TO ACTIVE AREA)

18   15 TYP

TO-5

UV35P

345

285

020

QUARTZ WINDOW

CATHODE

390   275   240

ANODE

018

050

100

40 MIN

ORIENTATION NOTCH

PLASTIC TO-8
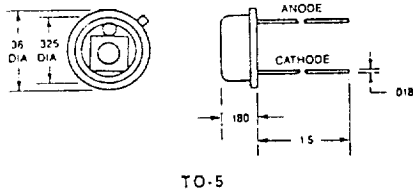
*PIN-10DP/SB OUTER CONTACT IS ANODE.
UV50, UV100 OUTER CONTACT IS CATHODE.

Referenced from (UDT Sensors, 1992)

MECHANICAL DETAILS

PIN-10DPI/SB, UV50L, UV100L

ISOLATED LOW PROFILE

FIL-UV005

FIL-UV100

FIL-UV20

Referenced from (UDT Sensors, 1992)

75
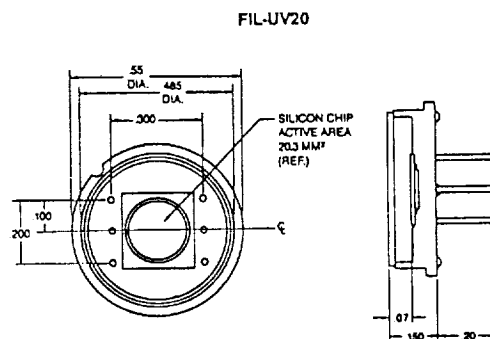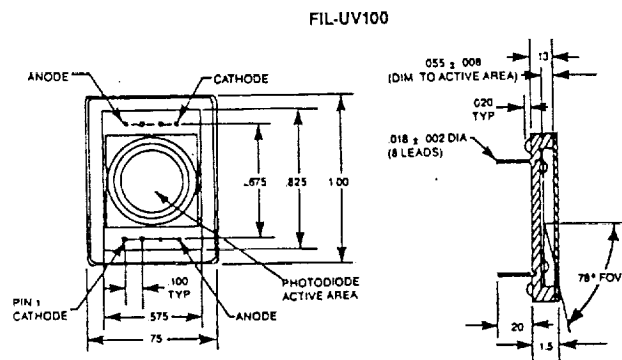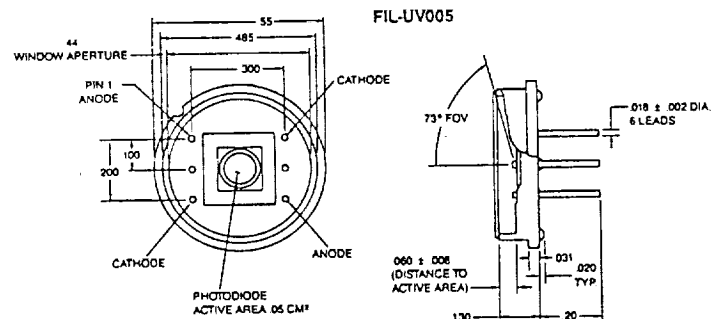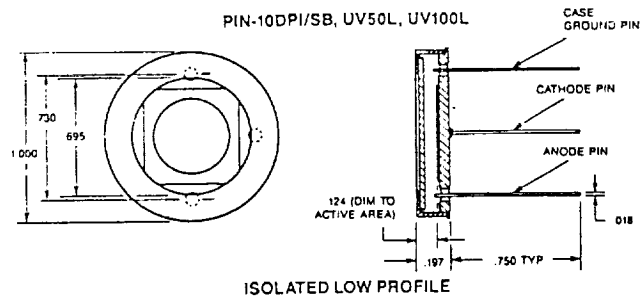
FIBER OPTIC SERIES

InGaAs Detectors and Emitters for Fiber Optics

FEATURES
- FDDI Compatible
- High Quantum Efficiency
- Microlens Option
- Wide Temperature Range

APPLICATIONS
- High Speed Data Communications Systems
- FDDI Local Area Networks

InGaAs PIN PHOTODIODE SERIES

InGaAs PIN PHOTODIODE SERIES   Typical at 25°C

MODEL	ACTIVE AREA DIAMETER mm	RESPONSIVITY A/W	DARK CURRENT nA	RISE TIME ns	FALL TIME ns	CAPACITANCE f = 1MHz pF	MAXIMUM REVERSE VOLTAGE V	MAXIMUM FORWARD CURRENT mA	STORAGE TEMPERATURE °C	OPERATING TEMPERATURE °C
InGaAs-080	.080	0.85	0.5	0.3	0.3	3	20	2	–40 ~ +100	–20 ~ +70
InGaAs-300 InGaAs-300L	.300	0.85	2.0	0.3	0.3	10	20	2	–40 ~ +100	–30 ~ +70

NOTE: InGaAs-300L is the lensed version of InGaAs-300.

Test Conditions: V_R = 5V, λ = 1300nm, R_L = 50Ω unless otherwise specified.

Referenced from (UDT Sensors, 1992)
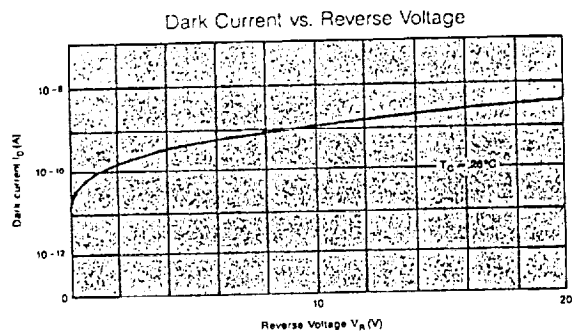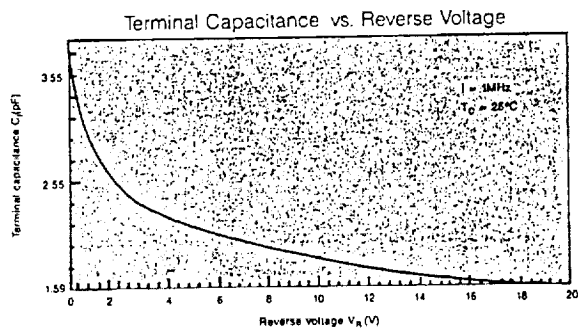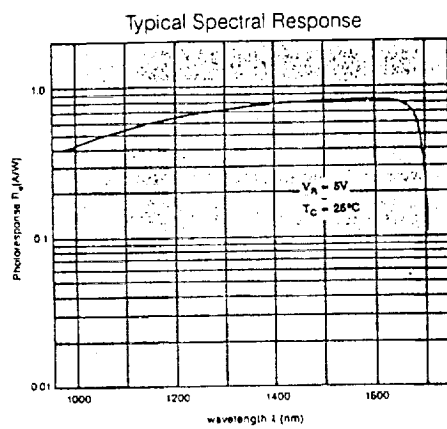
76

Dark Current vs. Reverse Voltage

InGaAs-080

Terminal Capacitance vs. Reverse Voltage

InGaAs-080

Typical Spectral Response

InGaAs-080

Temperature Dependence of Dark Current

InGaAs-080

Temperature Dependence of Dark Current

InGaAs-300, InGaAs-300L

Referenced from (UDT Sensors, 1992)

77

Z-Direction

InGaAs-300L

Dark Current vs. Reverse Voltage

InGaAs-300, InGaAs-300L

X-Direction
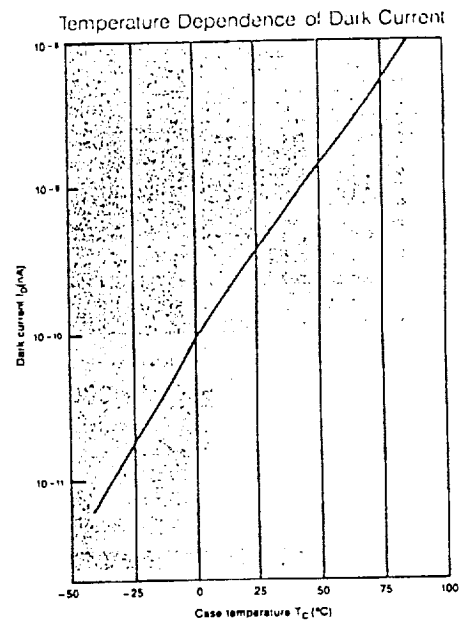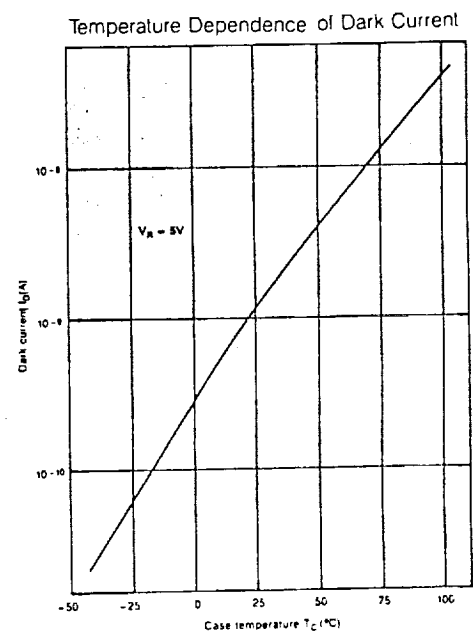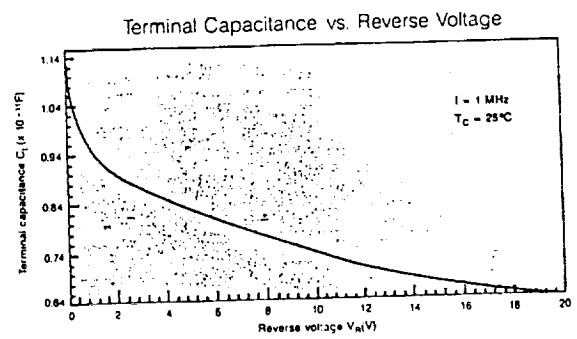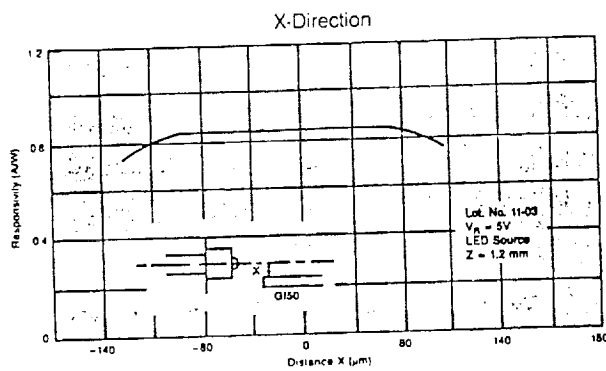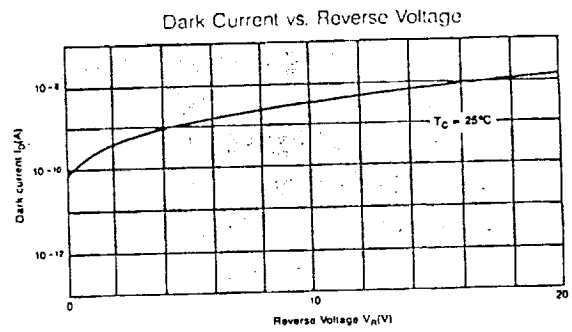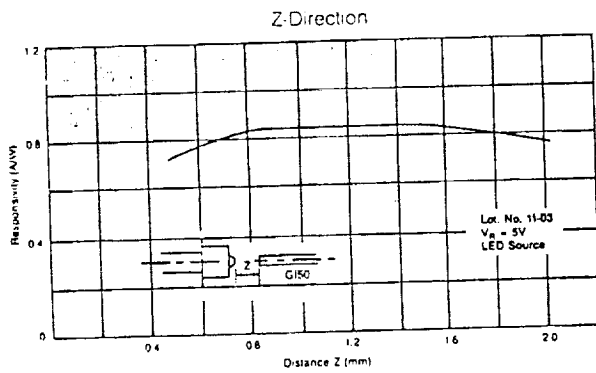
InGaAs-300L

Coupling characteristics of PD (InGaAs-300L) to G150/125 fiber (N.A. = 0.2)

Terminal Capacitance vs. Reverse Voltage

InGaAs-300, InGaAs-300L

Typical Output Photocurrent
vs. Incident Optical Power

InGaAs-300, InGaAs-300L

Referenced from (UDT Sensors, 1992)

78
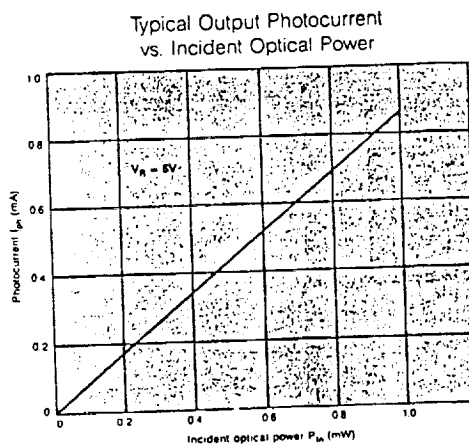
LIGHT EMITTING DIODE SERIES

FEATURES

- FDDI Compatible
- High Power Output
- High Speed Modulation Exceeding 100 mHz.
- Microlens Coupling To Optical Fibers
- High Reliability And Long Life
- Wide Temperature Range

MODEL #	PEAK WAVELENGTH nm		MAXIMUM SPECTRAL WIDTH (FWHM)	OPTICAL OUTPUT [1] μW		CUT-OFF FREQUENCY I_f = 100mA + 8mA P-P MHz		MAXIMUM FORWARD VOLTAGE V	MAXIMUM FORWARD CURRENT mA	MAXIMUM REVERSE VOLTAGE V	STORAGE TEMPERATURE °C	OPERATING TEMPERATURE °C
	MIN.	TYP.		MIN.	TYP.	MIN.	TYP.					
IR-1300	1270	1300	150	15	20	100	130	1.8	150	2	−40 ~ +90	−20 ~ +70
IR-1550	1530	1550	210	7	9	50	100	1.5	100	2	−40 ~ +90	−20 ~ +70

NOTE 1. Optical output power measured at the end of a 1 meter GI 50/125 μm optical fiber for IR-1300, at the end of a 2 meter GI 50/125 μm fiber for IR-1550

Test Conditions: I_f = 100mA for IR-1300B, Case Temperature = 25°C for both, I_f = 50mA for IR-1550

IR-1300
1.3μm LIGHT EMITTING DIODE

Typical Performance Characteristics

(1) Light output vs. input current
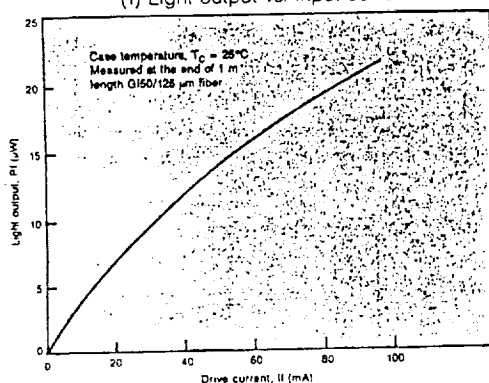
(2) Emission spectrum
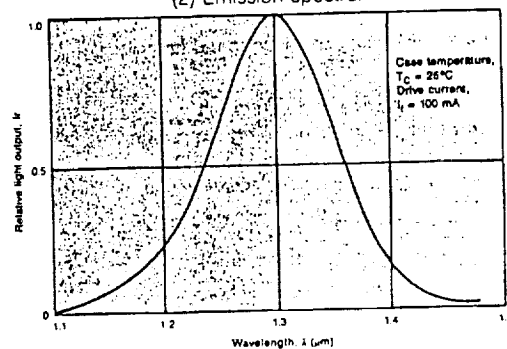
Cautions

1) Do not exceed the specified maximum ratings.
2) Note that any surge current (e.g. 1A/μsec.), could destroy the diode.
3) Avoid causing electrostatic destruction while the diode is in operation.
4) Do not observe the diode directly through a microscope or binocular while it is in operation. The high luminance can injure the eyes.

Referenced from (UDT Sensors, 1992)

79

IR-1550
1.5μm LIGHT EMITTING DIODE
Typical Performance Characteristics

(1) Forward current optical output characteristics

Case temperature (T_C) = 25°C
Measured at the end of 2m
length OI 50/125 μm fiber

Light output P_1 (μW)

Drive current I_f (mA)

(2) Emission spectrum

Case temperature
T_C = 25°C
Drive current.
I_f = 50 mA

Relative light output

Wavelength, λ (μm)
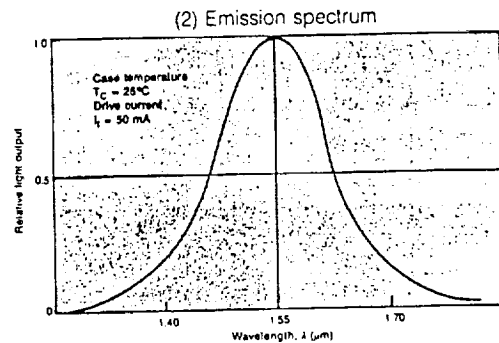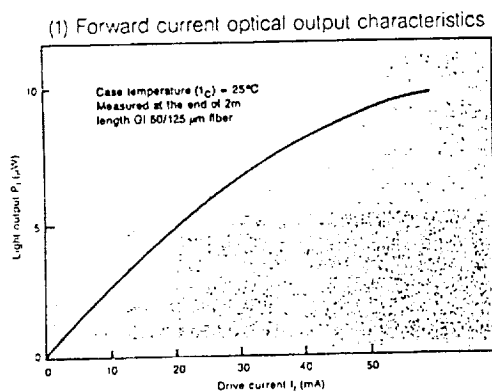
Cautions

1) Do not exceed the specified max. rating.

2) The max. rating is calculated with the case temperature of 25°C. Note that a rise in temperature restricts the operating temperature range due to reduction in the max. allowable current.

3) Below two thirds of the max. rating as recommend for safety operation.

4) Make sure that you know beforehand the transient characteristics of overall drive system including the power source. You'll need an appropriate measure to keep the transient spike current occurred during the power switch ON/OFF below the max. rating.

5) Beware that a surge current (e.g. 1A/μsec.) can destroy the device.

6) Beware of electrostatic damage when handling the device. Be sure to use a conductive mat, conductive shoes, conductive receptacles, and human body grounding. Be sure to ground the solder tip.

7) For soldering keep the following conditions: soldering temperature below 240°C; soldering time below 3 sec.

8) Do not observe the diode directly through a microscope or binocular while it is in operation. The high luminance can injure the eyes.

Referenced from (UDT Sensors, 1992)

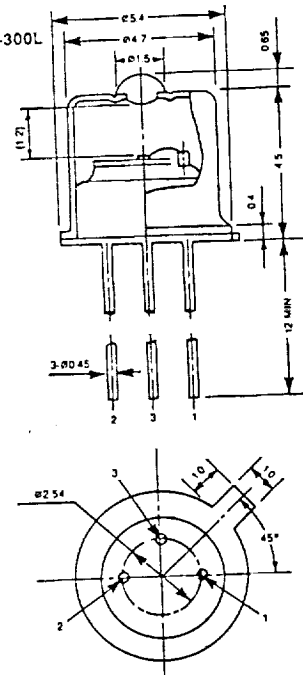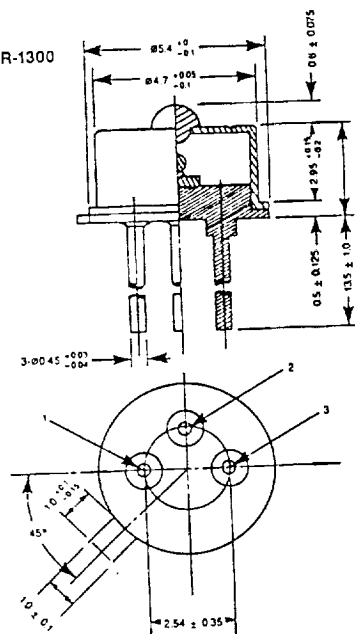# MECHANICAL DETAILS
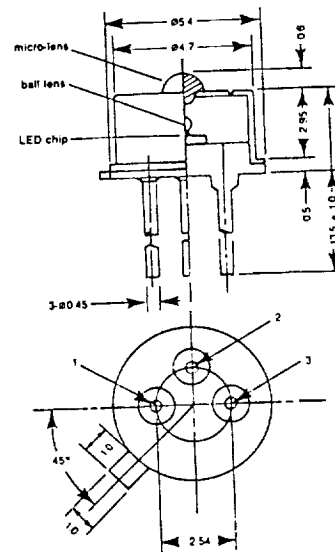
NOTE 1: All units in millimeters

InGaAs-080
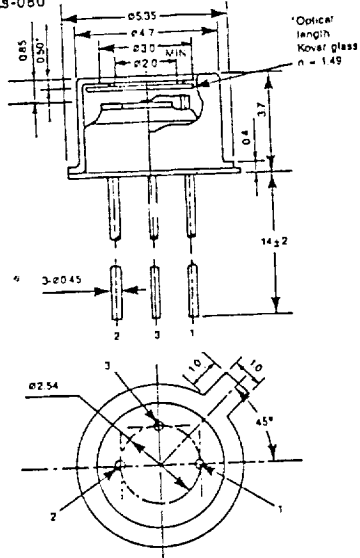
InGaAs-300
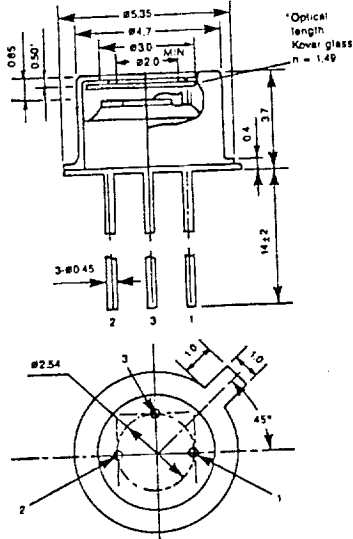
InGaAs-300L

IR-1300

IR-1550

Referenced from (UDT Sensors, 1992)

81

Specifications

ANALOG CHANNELS
- Number of channels: 10 single ended, any pair may be configured for differential inputs
- Auxiliary internal analog channels: 5 volt excitation, temperature, battery voltage
- Sample rates: 76,800 samples per second maximum (no channel switching); 2,500 samples per second maximum switching channels. Mathematical processing of data between scans may slow rates accordingly.
- Common Mode Range: +/− 5V except for +/− 1V on 10V range
- DC Input Characteristics

DC

Range	Resolution	Accuracy*	Output	CMRR
+/− 10 V	5.0 mV	.15 FS	volts	70 dB
+/− 5 V	2.5 mV	.15 FS	volts	75 dB
+/− 1 V	.5 mV	.15 FS	volts	80 dB
+/− 500 mV	250.0 uV	.15 FS	millivolts	85 dB
+/− 250 mV	125.0 uV	.15 FS	millivolts	87 dB
+/− 100 mV	50.0 uV	.15 FS	millivolts	90 dB
+/− 25 mV	12.5 uV	.17 FS	millivolts	92 dB
+/− 10 mV	5.0 uV	.17 FS	millivolts	95 dB

*DC accuracy with anti-aliasing filter is .87%

- AC Accuracy: +/− 1% Full Scale
- Input Resistance:
  - analog power on: 100 Megohms
  - analog power off: 20K ohms
- Input protection: Protected up to +/− 25 Volts in all power states.
- Anti-Alias Filter: 7th order elliptical lowpass
- Pass Bands: 0 (no filter), 10, 100, 1000, 10,000 Hz.
- Stop Band Attenuation: 72dB minimum (at 1.6 x cutoff frequency)
- DC Sensor Excitation: 5 Volt +/− 50mV, 100 ma max current
- Optional Accelerometer Excitation: 20 VDC through a 4 mA constant current diode when option -A1 or -A2 is specified. The signal is capacitively coupled to the input through a 0.47 ufd capacitor with a 330 Kohm load on the input.

DIGITAL INPUTS/OUTPUTS
- Number of channels: 15 total, 8 are dedicated as digital inputs, 3 are dedicated as digital outputs, and 4 may be programmed as inputs or outputs by the user.
- Logic Levels: Vin < 0.8V = Low(0), Vin > 4.0V = High(1)
- Digital Inputs: default is high, tied high through 10 Kohm resistor, input protected by 10 Kohm res.

- Digital Outputs: Nominal 0 to 5 volts, 6 mA maximum drive, source, and sink. State of outputs is indeterminate when the Polycorder is powered down. Digital output protection from external continuous voltages up to +/− 25V.

FREQUENCY COUNTERS
- Number of channels: 3
- Input voltages: +/− 12V maximum
- Signal thresholds: 3.2V positive going
  .9V negative going
- Default level: High tied to 5V through a 10K resistor
- Impedance: 10 Kohm
- Active edge: rising or falling, programmed by the user
- Pulse accumulation operation:
  - Range: 0 to 65535
  - Min. Pulse Width: 500 ns, 10ms w/ debounce option
- Period Mode Operation:
  - Number of Cycles Averaging N user selectable 1 to 65536
  - Range: 2.6 microseconds to 5 seconds
  - Resolution: $(3.255 \times 10^{-7})/N$
  - Measurement Time: Approximately $(N + 1)$ Tin
    [N = number of cycles averaged]
    [Tin = input cycle time]
- Frequency Mode Operation:
  - Range: 1.0 Hz to 1.0 Mhz full scale; user selectable
  - Resolution: 0.001 x (Fin/Fmax) x Fin (in Hertz) where Fin = frequency in and Fmax = maximum frequency
  - Measurement time: 0.00032 sec x (Fmax/Fin) (Freq 3 Khz) (approximate) 1 / Fin (Freq 3 Khz)
  - Accuracy: 0.1% of full scale reading within a user specified range.

COMMUNICATIONS
- Serial Port: RS-232-C with RTS-CTS, DTR-DSR, ring indicator, and ring excitation.
- Software Flow Control: X-on, X-off, with auxiliary user-settable software controls for line wait, repeat line, stop, and continuous transmission of data files. XMODEM package is implemented in user-loadable software. Checksum for line transmit mode is also user selectable.
- Baud Rates: 300, 600, 1200, 2400, 4800, 9600
- Data Bits: 7 or 8
- Parity: Odd, Even, or None
- Stop Bits: 1 or 2
- Input Signal Threshold: Approximately +1 volt, allowing both 0 to 5 volt signals, or negative to positive voltage swing serial communications signals to be used.
- Output Signal: +10 volts (high), −5 volts (low)
- Ring Indicator: Wakes system and automatically executes program named "RING."
- Ring Excitation: Approximately 1v, < 10 mA.

Referenced from (Omnidata, 1988a,b)

82

Specifications (continued)

MICROCOMPUTER OPERATING SYSTEM, UTILITIES, & USER LANGUAGE

- Operating System proprietary Omnidata operating system includes utility routines for:
  - program execution
  - communication protocol set-up
  - data file editing
  - program debug
  - program and data upload/download
  - file/directory management
  - RS-232 terminal emulation
  - digital I/O test
  - analog channel test
  - memory test
  - file & data erase
  - clock check and set
  - autolog selection
  - battery test
- Language: Polycode, a simple data acquisition language developed especially for portable hand-held data recorders. Includes commands for:
  - algebraic computations
  - digital I/O
  - transcendental functions (trigonometric functions, exponentiation, etc.)
  - analog channel scan
  - frequency measurement
  - string manipulation
  - conditional program execution
  - data file I/O
  - RS-232 port transmit/receive
  - keyboard & display I/O

PHYSICAL

- Size: 8" x 4" x 2.1" (20.3 cm x 10.2 cm x 5.3 cm)
- Weight: 2.4 lbs. (1.1 Kg)
- Keyboard: Sealed membrane, tactile response, 21 keys, .625" (1.59 cm) centers. Shift key for alpha characters; characters; function key for special applications.
- Display: 64 character liquid crystal, 4 rows x 16 characters
- Memory: User choice of 128K, 256K, or 448K CMOS static RAM for storage of data and programs. 32K CMOS EPROM contains Polycorder operating system and data collection subroutines.
- Clock: Real time Month, Day, Hours, Minute, Second, and Hundreths of Seconds. +/- 3 minutes per month accuracy.

- Power: Main supply 9 "AA" NiCad rechargeable cells in shrink wrap pack. Operating time per charge varies from 3.5 to 50 hours depending on duty cycle of analog data acquisition. For a typical hand-held application with the analog section on 20% of the time, expect 15 hours of operation between charges.
- Backup Power Supply: 1/2 "AA" LI cell, 5 year memory backup

ENVIRONMENTAL

- Operating Temperature: -4 to +122 F (-20 to +50 C)
- Operating Humidity: 0 to 100% RH (Condensing)
- Enclosure: Impact resistant polycarbonate case, sealed with neoprene rubber gasket to protect against moisture, EMI shielded.
- Connectors: 37 and 25 Pin, D-type, sealed against moisture and fitted with a soft plastic plug to protect the pins.

Contact Omnidata Today . . .

Omnidata offers reliable, cost effective solutions to data acquisition needs. We welcome the opportunity to discuss your unique data collection application. Contact us today for further information:

phone: (801) 753-7760
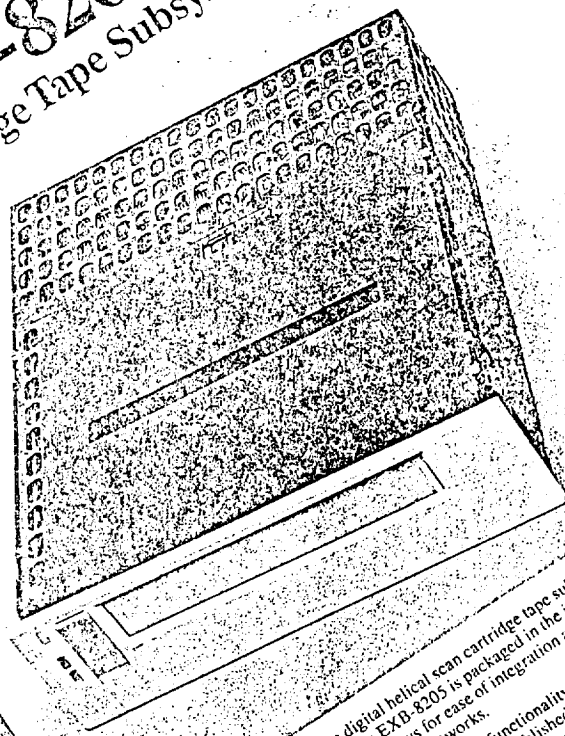fax: (801) 753-6756
telex: 3725960

OMNIDATA *INTERNATIONAL, INC.*
P. O. Box 3489
Logan, Utah 84321 USA

Referenced from (Omnidata, 1988a,b)

EXB-8205
8mm Cartridge Tape Subsystem

The EXB-8205 is an *enhanced* 8mm digital helical scan cartridge tape subsystem. Designed to meet the demand for smaller form factors, the EXB-8205 is packaged in the industry standard 5.25-inch half-high form factor. The smaller size allows for ease of integration across a multitude of platforms, including workstations, minicomputers, and networks.

Not only does the EXB-8205 offer high-speed search functionality and short filemarks, but it also offers a maximum data compression ratio of 5:1. Using the established Improved Data Recording Capability (IDRC) algorithm licensed from IBM, the EXB-8205 can store from 2,500 megabytes (2.5 gigabytes) up to 12,500 megabytes (12.5 gigabytes). Compression boosts native sustainable transfer rates up to 1.3 MBytes/second.

The EXB-8205 maintains data interchange with the industry standard EXB-8200 through full read and write compatibility. Other EXB-8205 enhancements include: SCSI-2 compatibility, synchronous data transfer, integrated 1 megabyte speed-matching buffer, multi-host support, full disconnect/reconnect arbitration support, variable block packing, and LED indications for time-to-clean as well as compression.

To ensure data integrity, the EXB-8205 performs onboard Error Correction Code and Error Recovery Procedures, along with full read-after-write verification. Combined with an integral SCSI controller, the EXB-8205 8mm Cartridge Tape Subsystem is designed to meet your backup, restore, journaling, archiving, data interchange, data acquisition, imaging, and software distribution needs — at a competitive price.

EXABYTE®
The Capacity to Succeed

Referenced from (Exabyte, 1991a)

EXB-8205

Product Description and Specifications

Full-width erase head

SCSI controller/formatter and drive electronics are implemented in ASICs and Surface Mount Technology (SMT)

Status LEDs

Cartridge load/unload switch

Rotary Drum Assembly contains read, write, and servo heads in read-after-write configuration

Cartridge door/linear skate load mechanism

Industry-standard 5¼-inch half high form factor
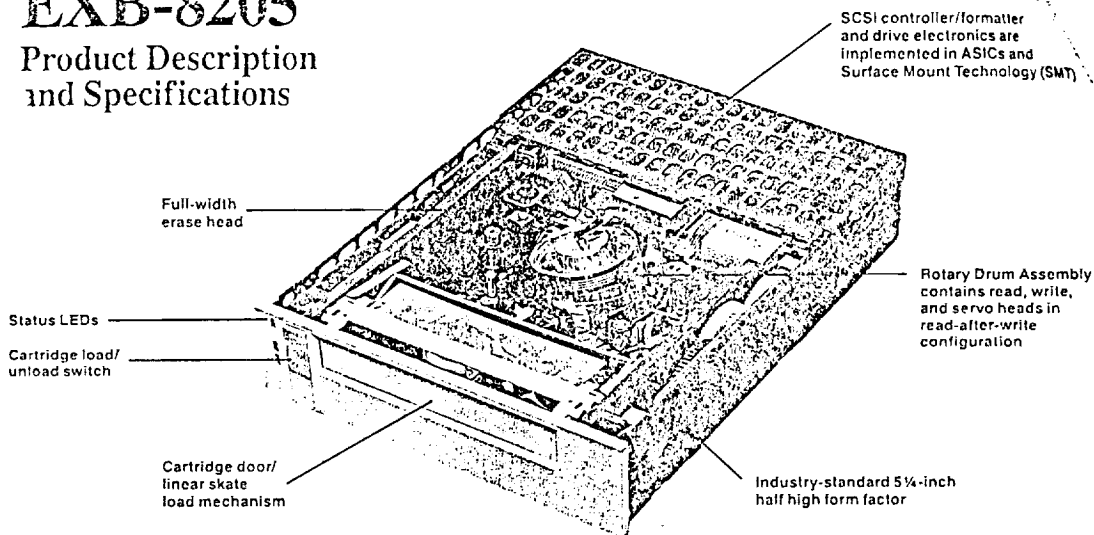
Models

Compression is standard on EXB-8205 models.
EXB-8205S — Single Ended SCSI
EXB-8205D — Differential SCSI

Read and Write Format

Recording Format	8mm Helical Scan Digital Computer Tape
Industry Standard	EXB-8200 Format and Compressed EXB-8200 Format (EXB-8200c)
Head Configuration	Read-after-Write head with separate full width erase head
Track Density	819 tracks/in.
Linear Density	8200 mode 43,271 bits/in. 8200c mode 45,434 bits/in.
Areal Density	8200 mode 35 million bits/in.² 8200c mode 37 million bits/in.²

Formatted Capacity

User-selectable 8mm metal particle data cartridges
8200 mode — from 150 MB to 2,500 MB (2.5 Gigabytes)
8200c mode — a capacity increase of up to 5x may be realized*

Reliability

Non-recoverable error rate in data interchange mode: 10¹³
MTBF: 40,000 hours
MTTR: < 30 minutes

Performance

Peak Transfer rate: 4.0 MB/sec synchronous; 1.5 MB/sec asynchronous
8200 mode Transfer rate (sustained): 262.5 KB/sec
8200c mode Transfer rate: a throughput increase of up to 5x may be realized*
Power on diagnostics: ~10 seconds
Minimum Search Speed: 19 MB/sec**
Buffer size: 1 MB

Tape Motion

Tape speed:
8200 mode — .458 in/sec
8200c mode — .436 in/sec
Effective Head to tape speed:
8200 mode — 158 in/sec
8200c mode — 150 in/sec
Max. Rewind speed: 75 times nominal

Controller Features

Integrated SCSI Controller and Formatter
Standard SCSI Interface Connection (single-ended or differential)
Onboard Error Correction Code (ECC) and Error Recovery Procedures (ERP)
ECC: Reed-Solomon Product Code

SCSI Characteristics

SCSI-2 Specification — ANSI X3.131-1990
Sequential Access Device
SCSI Bus Parity — Configurable
Full Disconnect, Arbitration, Reconnect
Asynchronous and Synchronous Data Transfer Supported
Connector Type — ANSI Spec Non-Shielded
SCSI Address Switch — Remote and local
Termination — Internal, Removable

SCSI Command Set

Test Unit Ready
Rewind
Request Sense
Read Block Limits
Read
Write
Write Filemarks
Inquiry
Space
Mode Select
Reserve Unit
Release Unit
Erase
Mode Sense
Load/Unload
Receive Diagnostic Results
Send Diagnostics
Prevent/Allow Medium Removal
Verify
Locate**
Read Position**

Physical Dimensions

Standard 5.25-inch half-height form factor
Height: 1.625 in.
Width: 5.750 in.
Depth: 8.000 in.
Weight: 2.57 lbs.

Power

+5/+12 volts ± 5%
15 watts

Environmental

Operating temperature: +5°C to +40°C (+41°F to +104°F)
Non-operating temperature: −40°C to +60°C (−40°F to +140°F)
Relative humidity (noncondensing): 20% to 80%

Recommended Media/Cleaning Cartridge(s)

ANSI Helical-Scan 8mm Digital Computer Tape Cartridge, x3B5/89-136
EXATAPE™ 8mm Data Cartridge
EXABYTE 8mm Cleaning Cartridge

All specifications are subject to change without notice.

*Compression capacity and throughput ratios will vary dependent upon type of data.
**Accessible in EXB 8200c mode. Searching speed will vary dependent upon actual compression ratio.

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MKT-097-00 November 1991 Printed in U.S.A.

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1685 38th Street
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Phone (303) 447-7359
Fax (303) 447-7689

Referenced from (Exabyte, 1991a)

85

Referenced from (Exabyte, 1991b)

EXATAPE™
Product Description and Specifications

Magnetic Material

Metal Particles

Base Material

Super-Smooth Polyethylene
Terephthalate Film

Backcoating

Anti-Static Agent

Cartridge Dimensions

(WxHxD)

95x62.5x15mm (3.7x2.5x0.6 in.)

Physical Properties

| Yield Strength | 0.5 kg |
| Transparency | Less than 5% |

Magnetic Properties

| Coercivity (Hc) | > 1,450 Oe |
| Retentivity (Brs) | > 2,300 Gauss |

Environmental

Operating temperature: +5°C to +45°C
(+41°F to +113°F)
Relative humidity (noncondensing):
20% to 80%
Maximum wet bulb temperature:
26°C (79°F)

Storage Case Material

Polypropylene

Cartridge Weight

34.3 grams (1.2 oz.)

Cartridge Weight (with case)

42.9 grams (1.5 oz.)

Cartridge Capacity

	Cartridge Size		
	15m	54m	112m
EXB-8200	300 MB	1.2 GB	2.5 GB
EXB-8205	600 MB*	2.4 GB*	5.0 GB*
EXB-8500	600 MB	2.4 GB	5.0 CB
EXB-8500c	1.2 GB*	4.8 GB*	10.0 GB*

*Assumes 2:1 compression ratio.

Dimensional Properties (Typical)	Cartridge Size(s)	
	15m-54m	112m
Tape width	8.00mm	8.00mm
Tape width tolerance	+/- 0.004mm	+/0.004mm
Total tape thickness	13.0µm	10.0µm
Magnetic layer thickness	3.0µm	3.0µm
Base thickness	9.0µm	6.0µm
Backcoating thickness	1.0µm	1.0µm

All specifications are subject to change without notice.

EXABYTE®

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Referenced from (Exabyte, 1991b)